DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

Subject Name: Transmission and Distribution

Subject Code: EE T53

Unit-1

Distribution Systems: ***Structure of electric power systems - one Line Diagram - generation, transmission and distribution systems, comparison of distribution systems – radial and ring – two wire dc, ac single phase and three phase systems – current and voltage calculations in distributors with concentrated and distributed loads – Kelvin's law for the design of feeders and its limitations.***

TWO MARKS QUESTIONS & ANSWER

1) State Kelvin's law for the design of feeders (APRIL/2015) (or)
State Kelvin's law. (APRIL/2012)(NOV/2013) (or)
Define Kelvin's Law (APRIL/2013)

Statement: "The annual expenditure on the variable part of the transmission system should be equal to the annual cost of energy wasted in the conductor used in that system."

2) What are the limitations of Kelvin's Law? (NOV/2014) (APRIL/2014)

It is difficult to estimate accurately the annual charge on the capital outlay. It does not give the exact economical size of the conductor.

3) What do you understand by distribution system? (NOV/2014)

Distribution is to deliver power from generating stations or substations to various consumers. It consists of distribution transformers which step down the voltage from 11KV to 400V for 3 ph. And 230 V for single phase. Distribution can be classified as primary distribution and secondary distribution.

i) According to supply: DC distribution and AC distribution
ii) According to construction: Overhead system and Underground system
iii) Acc. To connection: Radial, Ring Main and Interconnected systems.

4) Mention the various types of DC distributors (NOV/2013)

i) DC 2 wire system ii) DC 2 wire system Mid-point Earthed
iii) DC 3 wire system

5) List out the practical transmission and distribution voltage levels commonly used. (APRIL/2014)

Primary transmission :110KV/132 KV/220 KV/400 KV/765 KV
Secondary transmission :66 KV/33 KV
Primary distribution :11 KV/6.6 KV
Secondary distribution :400V for 3Ø ; 230V for 1Ø

6) Define the term feeder, distributor and service mains. (APRIL/2013) (NOV/2012) (APRIL/2012)

Feeder: A feeder is a conductor which helps in transfer of power from receiving station to the substations.

Distributor: It is the conductor from which tapings are taken for supply to the consumers.

Service mains: it is generally a small cable which connects the distributor to the consumers terminals.

7) Why all transmission and distribution systems are three phase systems. (APRIL/2012)

A three phase A.C circuit using the same size conductors as the single phase circuit can carry three times the power which can be carried by a single phase circuit and uses three conductors for the two phases and one conductor for the neutral. Thus a three phase circuit is more economical than a single phase circuit in terms of initial cost as well as the losses. Therefore all transmission and distribution systems are in three phase systems.

8) Explain the term Regional grid.

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

11 marks questions

1) Draw and explain the structure of modern power system including the voltage levels in each transmission line. (NOV/2012) (or) Write in detail about the structure of electric power. (NOV/2012)-(or) Draw and explain the line diagram of a typical transmission and distribution scheme, indicate clearly the voltage levels used at different stages. (NOV/2014)

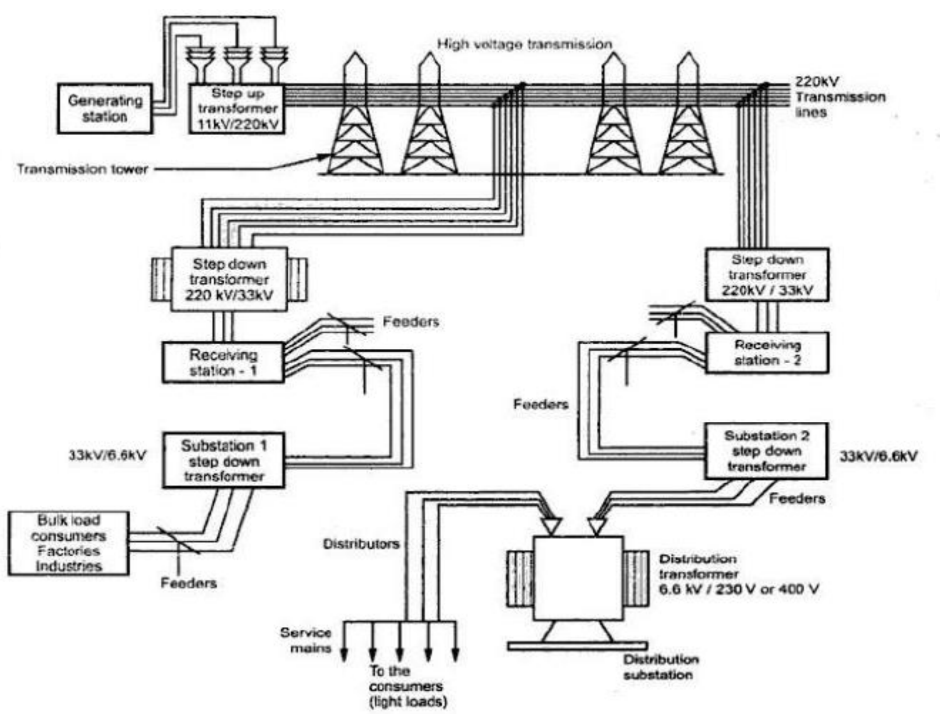
A Typical Transmission and Distribution Scheme:

The flow of electrical power from the generating station to the consumer is called an electrical **power system**. It consists of the following important components:

- Generating station
- Transmission network
- Distribution network

All these important networks are connected with the help of conductors and various steps up and down transforms.

A typical transmission and distribution scheme is shown in the figure. A scheme shows a generating station which is located too far away from cities and towns. It is generating an electrical power at 11 KV. It is required to increase this level for the transmission purpose. Hence a step up transformer is used which steps up the voltage level to 220 KV. This level may be 132 KV, 220KV or more as per the requirement.



Then with the help of transmission lines and the towers, the power is transmitted at very long distances. Design of the transmission lines is based on the factors like transmission voltage levels constants like resistance, reactance of the lines, line performance interference with the neighbouring circuits etc. Its mechanical features are strength of the supports, sag calculations, tension etc. Transmission of power by the overhead lines is very much cheaper.

Similarly the repairs also can be carried out comparatively more easily. The transmission is generally along with additional lines in parallel. These lines are called duplicate lines. Thus two sets of three phase lines work in parallel. This ensures the continuity during maintenance and also can be used to satisfy future demand.

The power is then transmitted to the receiving station via step down transformer. This transformer is 220/33 KV or 220/22 KV transformer. The power is then transmitted to the substations.

A substation consists of a step down transformer of rating 33 KV to 6.6 KV or 3.3 KV. The transfer of power from receiving station to the substation is with the help of conductors called feeders. This is called secondary transmission.

From the substations, power is distributed to the local distribution centers with the help of distributors. Sometimes for bulk loads like factories and industries, the distributors transfer power directly. For the light loads, there are distribution centers consisting of distribution transformers which step down the voltage level to 230 V or 400 V. This is called primary distribution.

In the crowded areas like cities, overhead system of bare conductors is not practicable. In such cases insulated conductors are used in the form of underground cables, to give supply to the consumers. These cables are called service mains. This is called secondary distribution. This is the complete flow of an electrical power from the generating station to the consumer premises

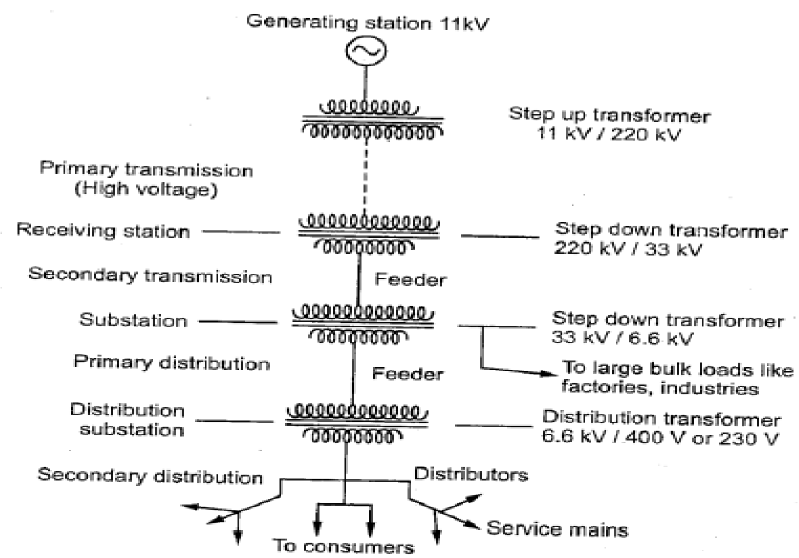


Figure shows the line diagram of a typical transmission and distribution scheme

At the generating station an electrical power is generating with the help of three phase alternators running in parallel, also in this scheme shown the voltage level is 11 KV. But the voltage level may be 6.6 KV, 22 KV, or 33 KV, depending upon the capacity of the generating station actual transmission and distribution starts the overall scheme can be divided into four sections which are:

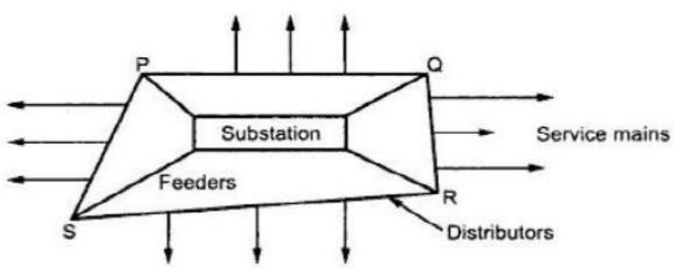
- **Primary transmission** : it is basically with the help of overhead transmission lines for the economic aspects the voltage level is increased to 132KV,220 KV Or more with the help of step up transformer . Hence this transmission is also called high voltage transmission .the primary transmission uses 3 phase wire system.
- **Secondary transmission**: The primary transmission lines continues via transmission towers till the receiving stations at the receiving stations the voltage level is reduced to 22 KV or 33 KV using the step down transformer there can be more than one receiving stations then at reduced voltage level of 22 KV or 33 KV the power is then transmitted to various substations using overhead 3 phase 3 wire system this is secondary transmission. The conductors used for the secondary transmission are called feeders.

- **Primary distribution**: at the substation the voltage level is reduced to 6.6 KV, 3.3 KV or 11KV with the help of step down transformers it uses three phase three wire underground system and the power is further transmitted to the local distribution for the large consumers like factories and industries, the power is directly transmitted to such loads from a substation such big loads have their own substations.
- **Secondary distribution**: at the local distribution centers there are step Down distribution transformers .the voltage level of 6.6 KV 11 KV is further reduced to 400 V using distribution transforms. Sometimes it may be reduced to 230 V. the power is then transmitted using distributors and service mains to the consumers this is secondary distribution, also called low
voltage distribution this uses 3 phase 4 wire system the voltage between any two lines is 400 V while the voltage between any of the three lines and a neutral is 230 V the single phase lighting loads are supplied using a line and neutral while loads like motors are supplied using three phase lines.

COMPONENTS OF DISTRIBUTION:

The distribution scheme consists of following important components:

- **Substation** : Transmission lines bring the power up to the substations at a voltage level of 22 KV or 33 KV at the substations the level is reduced to 3.3 KV or 6.6 KV then using feeders the power is given to local distribution
- **Local distribution station**: it consists of distribution transformer which steps down the voltage level from 3.3 KV 6.6 to 400 V or 230 V then it is distributed further using distribution Substation.
- **Feeders**: these are the conductors which are of large current carrying capacitor. the feeders connect the Substation to the area where power is to be finally distributed to the consumers no tapping's are taken from the feeders the feeders current always remains constant the voltage drop along the feeder is compensated by compounding the generators.
- **Distribution:** these are the conductors used to transfer power from Distribution Centre to the consumers .the voltage drop along the distributors is the main criterion to design the distributors.
- **Service mains** : these are the small cables between the distributors and the actual consumer premises



The interconnection of feeders distributors and service mains is shown in the figure

There is no tapping on feeders on feeders PQ, QR, RS and PS are the distributors which are supplied by the feeders no consumer is directly connected to the feeder the service mains are used to supply the consumers from the distributors tapings are taken from the distributors.

2) a) Compare AC and DC transmission (APRIL/2013)

The electric power can be transmitted either by means of D.C or A.C Each system has its own merits and demerits. It is, therefore, desirable to discuss the technical advantages and disadvantages of the two systems for transmission of electric power.

D.C TRANSMISSION

For some years past, the transmission of electric power by D.C has been receiving the active consideration of engineers due to its numerous advantages as follows

Advantages:

The high voltage D.C transmission has the following advantages over high voltage A.C transmission

- It requires only two conductors as compared to three for A.C transmission.
- There is no inductance, capacitance, phase displacement and surge problems in D.C transmission.

- Due to the absence of inductance, the voltage drop in a D.C transmission line is less than the A.C line for the same load and sending end voltage. For this reason, a D.C transmission line has better voltage regulation.
- There is no skin effect in a D.C system. Therefore, entire cross-section of the line conductor is utilized.
- For the same working voltage, the potential stress on the insulation is less in case of D.C system than that in A.C system. So, a D.C line requires less insulation.
- A D.C line has less corona loss and reduced interference with communication circuits.
- The high voltage D.C transmission is free from the dielectric losses, particularly in the case of cables.
- In D.C transmission, there are no stability problems and synchronizing difficulties.

Disadvantages:

- Electric power cannot be generated at high D.C voltage due to commutation problems.
- The D.C voltage cannot be stepped up for transmission of power at high voltages.
- The D.C switches and circuit breakers have their own limitations.

A.C TRANSMISSION

Now-a-days, electrical energy is almost exclusively generated, transmitted and distributed in the form of alternating current (AC).

Advantages:

- The power can be generated at high voltages.
- The maintenance of A.C sub-stations is easy and cheaper.
- The A.C voltage can be stepped up or stepped down by transformers with ease and efficiency. This permits to transmit power at high voltages and distribute it at safe potentials.

Disadvantages:

- An A.C line requires more copper than a D.C line.
- The construction of A.C transmission line is more complicated than a D.C transmission line.
- Due to skin effect in the A.C system, the effective resistance of the line is increased.
- An A.C line has capacitance. Therefore, there is a continuous loss of power due to charging current even when the line is open

From the above comparison, it is clear that high voltage D.C transmission is superior to high voltage A.C transmission. Although at present, transmission of electric power is carried by A.C, there is an increasing interest in D.C transmission.

2b) List out advantages of High Voltages transmission (APRIL/2013)

The transmission of electric power is carried at high voltages due to the following reasons:

(i) Reduces volume of conductor materials.

(ii) Increases transmission efficiency.

(i) **Reduces volume of conductor material.**

Consider the transmission of electric power by at three-phase line.

$$P = Power\ transmitted\ in\ watts$$
$$V = line\ voltage\ in\ volts$$
$$\cos\Phi = power\ factor\ of\ the\ load$$
$$l = length\ of\ the\ line\ in\ metres$$
$$R = Resistance\ per\ conductor\ in\ ohms$$
$$\rho = Resistivity\ of\ conductor\ material$$
$$a = area\ of\ X - section\ of\ conductor$$

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

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

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

$$\therefore Area\ of\ cross-section, a = \frac{P^2\rho l}{WV^2\cos^2\Phi}$$

Total volume of conductor material required

$$= 3a\,l = 3\left(\frac{P^2\rho l}{WV^2\cos^2\Phi}\right)$$
$$= \frac{3P^2\rho l^2}{WV^2\cos^2\Phi}$$

It is clear from above expression that for given values of P, l, ρ and W, the volume of conductor material required is inversely proportional to the square of transmission voltage and power factor. In other words, the greater the transmission voltage, the lesser is the conductor material required.

(ii) **Increases transmission efficiency.**

$$Input\ power = P + Total\ losses = P + \frac{P^2\rho l}{V^2\cos^2\Phi a}$$

Assuming J to be the current density of the conductor. Then,

$$a = I/J$$

$$Input\ power = P + \frac{P^2\rho lJ}{V^2\cos^2\Phi} \times \frac{1}{I}$$
$$= P + \frac{P^2\rho lJ}{V^2\cos^2\Phi} \times \frac{*\sqrt{3}V\cos\Phi}{P}$$

$$= \left[1 - \frac{\sqrt{3}J\rho l}{V\cos\Phi}\right] approx$$

As J, ρ and l are constants, therefore, transmission efficiency increases when the line voltage is increased.

(iii) Decreases percentage line drop :

$$Line\ drop = IR = I \times \frac{\rho l}{a}$$

$$= I \times \rho l \times \frac{J}{I} = \rho\, I\, J \qquad [\therefore a = I/J]$$

$$percentage\ line\ drop = \frac{J\rho l}{V} \times 100$$

As J, ρ and l are constants, therefore, percentage line drop decreases when the transmission voltage increases.

3) Explain: the various systems of power transmission.

VARIOUS SYSTEMS OF POWER TRANSMISSION: For transmission of electric power, three phases, three wires A.C system is universally adopted. However, other systems can also be used for transmission under special circumstances. The different possible systems of transmission are

D.C SYSTEM:
(i) D.C two-wire.
(ii) D.C two-wire with mid-point earthed.
(iii) D.C three-wire.

SINGLE-PHASE A.C SYSTEM:
(i) Single-phase two-wire.
(ii) Single-phase two-wire with mid-point earthed
(i) Single-phase three-wire.

TWO-PHASE A.C SYSTEM:
(i) Two-phase four-wire.
(ii) Two-phase three wire.

THREE-PHASE A.C SYSTEM:
(i) Three-phase three-wire.
(ii) Three-phase four-wire.

From the above possible systems of power transmission, it is difficult to say which the best system is unless and until some method of comparison is adopted. Now, the cost of conductor material is one of the most important charges in a system. Obviously, the best system for transmission of power is that for which the volume of conductor material required is minimum. Therefore, the volume of conductor material required forms the basis of comparison between different systems. While comparing the amount of conductor material required in various systems, the proper comparison shall be on the basis of equal maximum stress on the dielectric. There are two cases

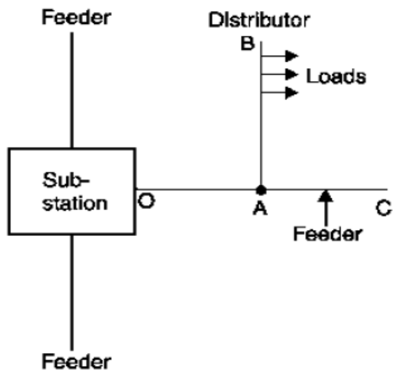
(i) When transmission is by overhead system:-
In the overhead system, the maximum disruptive stress exists between the conductor and the earth. Therefore, the comparison of the system in this case has to be made on the basis of maximum voltage between conductor and earth.

(ii) **When transmission is by underground system**:-
In the underground system, the chief stress on the insulation is between conductors. Therefore, the comparison of the systems in this case should be made on the basis of maximum potential difference between conductors.

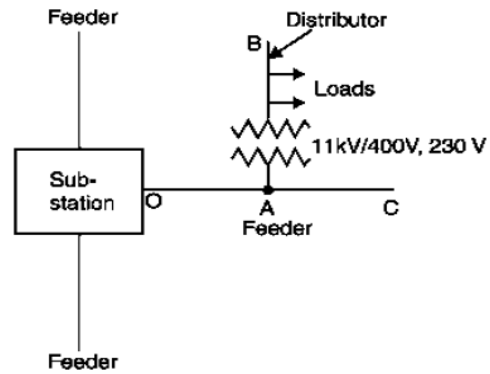
4) Discuss and compare Radial and Ring main distribution system. What is the role of interconnectors in distribution system? (APRIL/2014) (or)

Discuss connection schemes of the following distribution systems. (APRIL/2012)

a) Radial system
b) Ring Main system.
RADIAL SYSTEM:
"In this system, separate feeders radiate from a single substation and feed the distributors at one end only"
Figure (i) show a single line diagram of a radial system for D.C distribution where a feeder OC supplies a distributor AB at point A. obviously, the distributor is fed at one end only i.e., point A is this case.



(i)

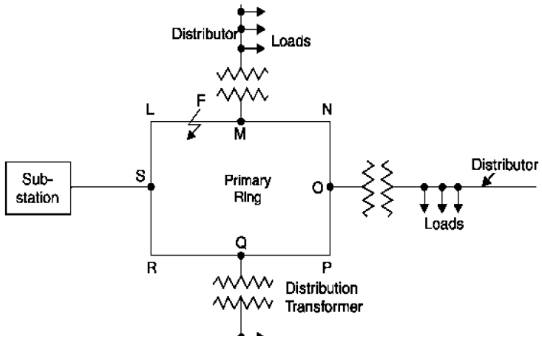


(ii)

Figure (ii) show a single line diagram of radial system for A.C distribution.
The radial system is employed only when power is generated at low voltage and the substation is located at the center of the load.
Advantages:
- This is the simplest distribution circuit
- Lowest initial cost

Disadvantages:
- The end of the distributor nearest to the feeding point will be heavily loaded.
- The consumers are dependent on a single feeder and single distributor. Therefore, any fault on the feeder or distributor cuts off supply to the consumers who are on the side of the fault away from the substation.
- The consumers at the distant end of the distributor would be subjected to serious voltage fluctuations when the load on the distributor changes. Due to these limitations, this system is used for short distances only.

RING MAIN SYSTEM:
"In this system, the primaries of distribution transformers form a loop. The loop circuit starts from the substation bus-bars, makes a loop through the area to be served, and returns to the substation"
Figure shows the single line diagram of ring main system for A.C distribution where substation supplies to the closed feeder LMNOPQRS. The distributors are tapped from different points M, O and Q of the feeder through distribution transformers.



Advantages:

- There are less voltage fluctuations at consumer's terminals.
- The system is very reliable as each distributor is fed via two feeders. In the event of fault on any section of the feeder, the continuity of supply is maintained. (For example, suppose that fault occurs at any point F of section SLM of the feeder. Then section SLM of the feeder can be isolated for repairs and at the same time continuity of supply is maintained to all the consumers via the feeder SRQPONM).

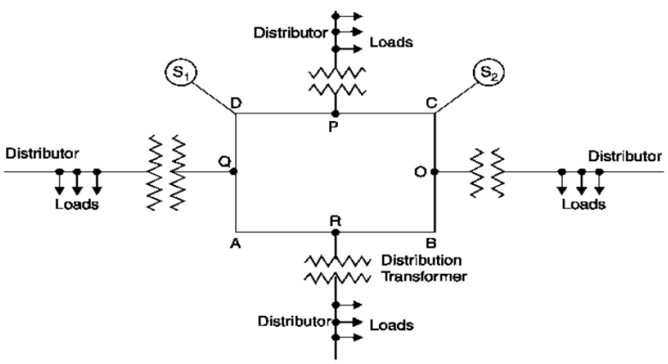
INTERCONNECTED SYSTEM:

"When the feeder ring is energized by two or more than two generating stations or substations, it is called inter-connected system"

Figure shows the single line diagram of interconnected system where the closed feeder ring ABCD is supplied by two substations S_1 and S_2 at points D and C respectively. Distributors are connected to points O, P, Q and R of the feeder ring through distribution transformers.

Advantages

- It increases the service reliability.
- Any area fed from one generating station during peak load hours can be fed from the other generating station. This reduces reserve power capacity and increases efficiency of the system.



5) Mention the basic requirements of a Distribution System and the design consideration on Distribution system

REQUIREMENTS OF A DISTRIBUTION SYSTEM:

A considerable amount of effort is necessary to maintain an electric power supply within the requirements of various types of consumers. Some of the requirements of a good distribution system are

- ***Proper voltage,***
- ***Availability of power on demand***
- ***Reliability***

(i) ***PROPER VOLTAGE***

One important requirement of a distribution system is that voltage variations at consumer's terminals should be as low as possible. The changes in voltage are generally caused due to the variation of load on the system.

Low voltage causes loss of revenue, inefficient lighting and possible burning out of motors. High voltage causes lamps to burn out permanently and may cause failure of other appliances. Therefore, a good distribution system should ensure that the voltage variations at consumer's terminals are within permissible limits.

The statutory limit of voltage variations is ± 6% of the rated value at the consumer's terminals. Thus, if the declared voltage is 230 V, then the highest voltage of the consumer should not exceed 244 V while the lowest voltage of the consumer should not be less than 216 V.

(ii) ***AVAILABILITY OF POWER ON DEMAND***

Power must be available to the consumers in any amount that they may require from time to time. For example, motors may be started or shut down, lights may be turned on or off, without advance warning to the electric supply company. As electrical energy cannot be stored, therefore, the distribution system must be capable of supplying load demands of the consumers.

(iii) ***RELIABILITY***

Modern industry is almost dependent on electric power for its operation. Homes and office buildings are lighted, heated, cooled and ventilated by electric power. This calls for reliable service. Unfortunately, electric power, like everything else that is man-made, can never be absolutely reliable. However, the reliability can be improved to a considerable extent by (a) interconnected system (b) reliable automatic control system (c) providing additional reserve facilities.

DESIGN CONSIDERATIONS IN DISTRIBUTION SYSTEM:

Good voltage regulation of a distribution network is probably the most important factor responsible for delivering good service to the consumers. For this purpose, design of feeders and distributors requires careful consideration.

- **Feeders**

A feeder is designed from the point of view of its current carrying capacity while the voltage drop consideration is relatively unimportant. It is because voltage drop in a feeder can be compensated by means of voltage regulating equipment at the substation.

- **Distributors**

A distributor is designed from the point of view of the voltage drop in it. It is because a distributor supplies power to the consumers and there is a statutory limit of voltage variations at the consumer's terminals (± 6% of rated value). The size and length of the distributor should be such that voltage at the consumer's terminals is within the permissible limits.

Problem 1: **A 2-wire D.C ring distributor is 300 m long and is fed at 240 V at point A. At point B, 150 m from A, a load of 120 A is taken and at C, 100 m in the opposite direction, a load of 80 A is taken. If the resistance per 100 m of single conductor is 0·03 Ω, find:**

(i) Current in each section of distributor

(ii) Voltage at points B and C

Solution:

Resistance per 100 m of distributor

$$Resistace\ of\ section\ AB, R_{AB} = 0.06 \times \frac{150}{100} = 0.09\Omega$$

$$Resistace\ of\ section\ BC, R_{BC} = 0.06 \times \frac{50}{100} = 0.03\Omega$$

$$Resistace\ of\ section\ CA, R_{CA} = 0.06 \times \frac{100}{100} = 0.06\Omega$$

i) *Let us suppose that a current IA flows in section AB of the distributor. Then currents in sections BA and CA will be (IA - 120) and (IA - 200) respectively as shown in figure (i) According to Kirchhoff's voltage law, the voltage drop in the closed loop ABCA is zero. i.e.*

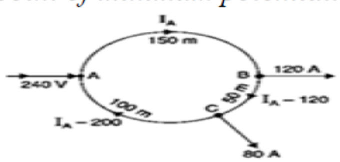
$$I_{AB}R_{AB} + I_{BC}R_{BC} + I_{CA}R_{CA} = 0$$

$$0.09\, I_A + 0.03(I_A - 120) + 0.06(I_A - 200) = 0$$

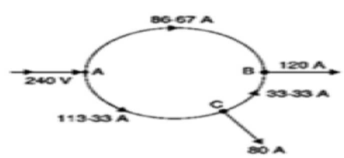
$$0.18 I_A = 15.6$$

$$I_A = \frac{15.6}{0.18} = 86.67A$$

The actual distribution of currents is as shown in figure (ii) from where it is seen that B is the point of minimum potential.



(i)



(ii)

$$Current\ in\ section\ AB, I_{AB} = I_A = 86.67A\ from\ A\ to\ B$$

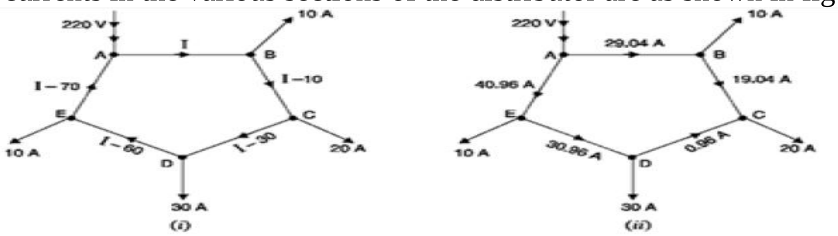
$$Current\ in\ section\ BC, I_{BC} = I_A - 120 = 86.67 - 120 = -33.33A$$
$$= 33.33\ A\ from\ C\ to\ B$$

$$Current\ in\ section\ CA, I_{CA} = I_A - 200 = 86.67 - 200 = -113.33A$$
$$= 113.33\ A\ from\ A\ to\ C$$

ii) $Voltage\ at\ point\ B,\ V_B = V_A - I_{AB}R_{AB} = 240 - 86.67 \times 0.09 = 232.2V$

$Voltage\ at\ point\ C, V_C = V_B + I_{BC}R_{BC} 232.2 + 33.33 \times 0.03 = 233.3V$

Problem 2: **A 2-wire D.C distributor ABCDEA in the form of a ring main is fed at point A at 220 V and is loaded as under : 10A at B ; 20A at C ; 30A at D and 10 A at E. The resistances of various sections (go and return) are : AB = 0·1 Ω ; BC = 0·05 Ω ; CD = 0·01Ω ; DE = 0·025 Ω and EA = 0·075 Ω. Determine :**
(i) The point of minimum potential
(ii) Current in each section of distributor
Solution:
Figure (i) show the ring main distributor. Let us suppose that current I flow in section AB of the distributor. Then currents in the various sections of the distributor are as shown in figure



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

$$0.1I + 0.05(I - 10) + 0.01(I - 30) + 0.025(I - 60) + 0.075(I - 70) = 0$$

Or

$$0.26I = 7.55 \implies I = \frac{7.55}{0.26} = 29.04A$$

The actual distribution of currents is as shown in figure (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 = 29·04 − 10 = 19·04 A from B to C
Current in section CD = I − 30 = 29·04 − 30 = − 0·96 A = 0·96 A from D to C
Current in section DE = I−60 = 29·04 − 60 = − 30·96 A = 30·96 A from E to D
Current in section EA = I−70 = 29·04 − 70 = − 40·96 A = 40·96 A from A to E

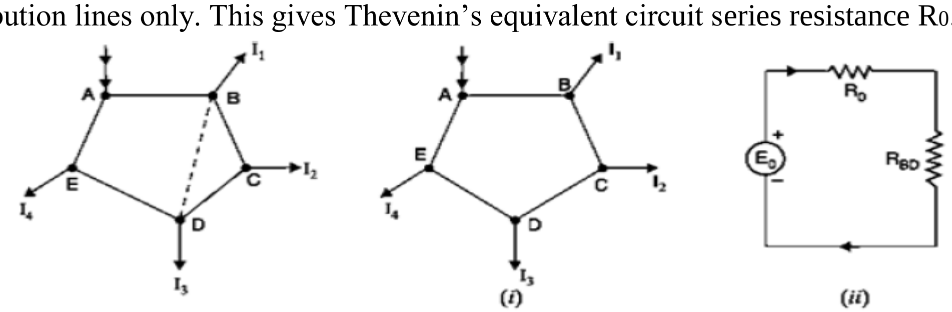
6) Write a short notes on Ring Main Distributor with Interconnector

RING MAIN DISTRIBUTOR WITH INTERCONNECTOR:

Sometimes a ring distributor has to serve a large area. In such a case, voltage drops in the various sections of the distributor may become excessive. "***In order to reduce voltage drops in various sections, distant points of the distributor are joined through a conductor called interconnector***". Figure shows the ring distributor ABCDEA. The points B and D of the ring distributor are joined through an interconnector BD. There are several methods for solving such a network. However, the solution of such a network can be readily obtained by applying Thevenin's theorem. The steps of procedure are

(i) Consider the interconnector BD to be disconnected [See figure (i)] and find the potential difference between B and D. This gives Thevenin's equivalent circuit voltage E_0.

(ii) Next, calculate the resistance viewed from points B and D of the network composed of distribution lines only. This gives Thevenin's equivalent circuit series resistance R_0.



(iii) If RBD is the resistance of the interconnector BD, then Thevenin's equivalent circuit will be as shown in figure (ii).

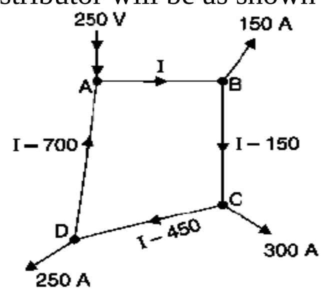
$$\therefore\ Current\ in\ interconnector\ BD = \frac{E_0}{R_0 + R_{BD}}$$

Therefore, current distribution in each section and the voltage of load points can be calculated.

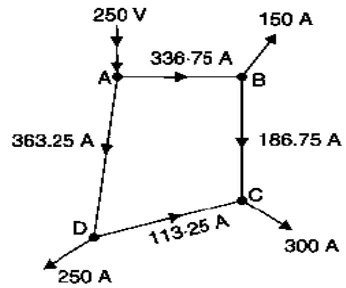
Problems related to Ring Main Distributor:

Problem1: **A D.C ring main ABCDA is fed from point A from a 250 V supply and the resistances (including both lead and return) of various sections are as follows: AB = 0·02 Ω; BC = 0·018 Ω; CD = 0·025 Ω and DA = 0·02 Ω. The main supplies loads of 150 A at B, 300 A at C and 250 A at D. Determine the voltage at each load point. If the points A and C are linked through an interconnector of resistance 0·02 Ω, determine the new voltage at each load point.**

Solution: Without Interconnector. Figure (i) show the ring distributor without interconnector. Let us suppose that a current I flows in section AB of the distributor. Then currents in various sections of the distributor will be as shown in figure (i).



(i)



(ii)

According to Kirchhoff's voltage law, the voltage drop in the closed loop ABCDA is zero i.e.

$$I_{AB}R_{AB} + I_{BC}R_{BC} + I_{CD}R_{CD} + I_{DA}R_{DA} = 0$$

$$0.02I + 0.018(I - 150) + 0.025(I - 450) + 0.02(I - 700) = 0$$

$$0.083I = 27.95 \implies I = \frac{27.95}{0.083} = 336.75A$$

The actual distribution of currents is as shown in figure (ii).

Voltage drop in AB = 336·75 × 0·02 = 6·735 V

Voltage drop in BC = 186·75 × 0·018 = 3·361 V

Voltage drop in CD = 113·25 × 0·025 = 2·831 V

Voltage drop in DA = 363·25 × 0·02 = 7·265 V

Voltage at point B = 250 − 6·735 = 243·265

Voltage at point C = 243·265 − 3·361 = 239·904 V

Voltage at point D = 239·904 + 2·831 = 242·735 V

With Interconnector, Figure (iii) shows the ring distributor with interconnector AC. The current in the interconnector can be found by applying Thevenin's theorem.

$$E_0 = Voltage\ between\ points\ A\ and\ C = 250 - 239.904 = 10.096V$$

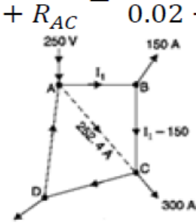
$$R_0 = Resistance\ viewed\ from\ points\ A\ and\ C$$

$$= \frac{(0.02 + 0.018)(0.02 + 0.025)}{(0.02 + 0.018) + (0.02 + 0.025)} = 0.02\Omega$$

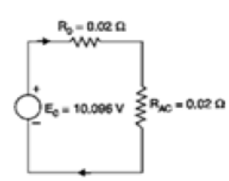
$$R_{AC} = Resistance\ of\ interconnector = 0.02\Omega$$

Thevenin's equivalent circuit is shown in figure (iv). Current in interconnector AC

$$= \frac{E_0}{R_0 + R_{AC}} = \frac{10.096}{0.02 + 0.02} = 252.4A\ from\ A\ to\ C$$



(iii)



(iv)

Thevenin's equivalent circuit is shown in figure (iv). Current in interconnector AC

Let us suppose that current in section AB is I_1. Then the current in section BC will be I_1-150. As the voltage drop round the closed mesh ABCA is zero.

$$\therefore 0.02I_1 + 0.018(I_1 - 150) - 0.02 \times 252.4 = 0$$

$$0.038I_1 = 7.748$$

$$\therefore I_1 = \frac{7.748}{0.038} = 203.15A$$

The actual distribution of currents in the ring distributor with interconnector will be as shown in figure (v)

$$Drop\ in\ AB = 203.15 \times 0.02 = 4.063V$$

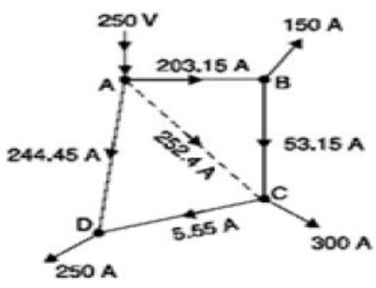
$$Drop\ in\ BC = 53.15 \times 0.018 = 0.960V$$

$$Drop\ in\ AD = 244.45 \times 0.02 = 4.9V$$

Potential of B = 250-4.063 = 245.93V

Potential of C = 245.93 – 0.96 = 244.97V

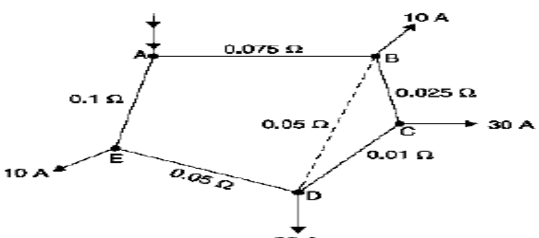
Potential of D = 250 – 4.9 = 245.1 V



(v)

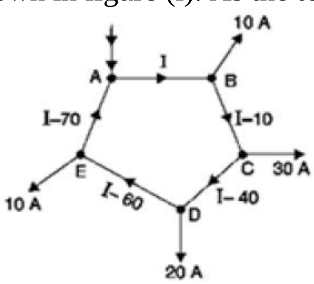
It may be seen that with the use of interconnector, the voltage drops in the various sections of the distributor are reduced.

Problem 2: **Figure shows a ring distributor with interconnector BD. The supply is given at point A. The resistances of go and return conductors of various sections are indicated in the figure. Calculate: (i) Current in the interconnector (ii) Voltage drop in the interconnector**

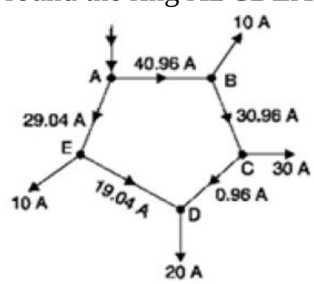


Solution:

When interconnector BD is removed, let the current in branch AB be I. Then current distribution will be as shown in figure (i). As the total drop round the ring ABCDEA is zero,



(i)



(ii)

$$0.075I + 0.025(I-10) + 0.01(I-40) + 0.05(I-60) + 0.1(I-70) = 0$$
$$0.26I = 10.65$$
$$I = 10.65/0.26 = 40.96A$$

The actual distribution of currents will be as shown in figure (ii)

$$Voltage\ drop\ along\ BCD = 30.96 \times 0.025 + 0.96 \times 0.01 = 0.774 + 0.0096 = 0.7836V$$

This is equal to Thevenin's open circuited voltage E_0 i.e.

$$E_0 = 0.7836\ V$$
$$R_0 = Resistance\ viewed\ from\ B\ and\ D$$
$$= \frac{(0.075+0.1+0.05)(0.025+0.01)}{(0.075+0.1+0.05)+(0.025+0.01)} = 0.03\Omega$$

i) *Current in interconnector BD is*

$$I_{BD} = \frac{E_0}{R_0 + R_{BD}} = \frac{0.7836}{0.03+0.05} = 9.8A$$

ii) *Voltage drop along interconnector BD*

$$= I_{BD}R_{BD} = 9.8 \times 0.05 = 0.49V$$

7) Compare various systems of transmission.

COMPARISON OF VARIOUS SYSTEMS OF TRANSMISSION:

Below is given the table which shows the ratio of conductor-material in any system compared with that in the corresponding 2-wire D.C system. Cos φ is the power factor in an A.C system.

The following points may be noted from the below table:

System	Same maximum voltage to earth	Same maximum voltage between conductors
1. D.C. system		
(i) Two-wire	1	1
(ii) Two-wire mid-point earthed	0·25	1
(iii) 3-wire	0·3125	1·25
2. Single phase system		
(i) 2 wire	$2/\cos^2\phi$	$2/\cos^2\phi$
(ii) 2-wire with mid-point earthed	$\frac{0\cdot5}{\cos^2\phi}$	$\frac{2}{\cos^2\phi}$
(iii) 3-wire	$\frac{0\cdot625}{\cos^2\phi}$	$\frac{2\cdot5}{\cos^2\phi}$
3. Two-phase system		
(i) 2-phase, 4-wire	$\frac{0\cdot5}{\cos^2\phi}$	$\frac{2}{\cos^2\phi}$
(ii) 2-phase, 3-wire	$\frac{1\cdot457}{\cos^2\phi}$	$\frac{2\cdot914}{\cos^2\phi}$
4. Three-phase system		
(i) 3-phase, 3-wire	$\frac{0\cdot5}{\cos^2\phi}$	$\frac{1\cdot5}{\cos^2\phi}$
(ii) 3-phase, 4-wire	$\frac{0\cdot583}{\cos^2\phi}$	$\frac{1\cdot75}{\cos^2\phi}$

1. There is a great saving in conductor material if D.C system is adopted for transmission of electric power. However, due to technical difficulties, D.C system is not used for transmission.

2. Considering the A.C system, the 3-phase A.C system is mostly suitable for transmission due to two reasons. Firstly, there is considerable saving in conductor material. Secondly, this system is convenient and efficient.

8) Explain the various elements of transmission line and the economics of power transmission.

ELEMENTS OF A TRANSMISSION LINE:

For reasons associated with economy, transmission of electric power is done at high voltage by 3-phase, 3-wire overhead system. The principal elements of a high-voltage transmission line are:

- **Conductors,** usually three for a single-circuit line and six for a double-circuit line. The usual material is aluminum reinforced with steel.
- **Step-up and step-down transformers**, at the sending and receiving ends respectively. The use of transformers permits power to be transmitted at high efficiency.
- **Line insulators**, which mechanically support the line conductors and isolate them electrically from the ground.
- **Support**, which are generally steel towers and provide support to the conductors.
- **Protective devices**, such as ground wires, lightning arrestors, circuit breakers, relays etc. They ensure the satisfactory service of the transmission line.
- **Voltage regulating devices,** which maintain the voltage at the receiving end within permissible limits. All these elements will be discussed in detail in the subsequent chapters.

ECONOMICS OF POWER TRANSMISSION:

While designing any scheme of power transmission, the engineer must have before him the commercial aspect of the work entrusted to him. He must design the various parts of transmission scheme in a way that maximum economy is achieved. The economic design and layout of a complete power transmission scheme is outside the scope of this book. However, the following two fundamental economic principles which closely influence the electrical design of a transmission line will be discussed

- Economic choice of conductor size
- Economic choice of transmission voltage

Economic choice of conductor size:

The cost of conductor material is generally a very considerable part of the total cost of a transmission line. Therefore, the determination of proper size of conductor for the line is of vital importance. The most economical area of conductor is that for which the total annual cost of transmission line is minimum. This is known as Kelvin’s Law after Lord Kelvin who first stated it in 1881. The total annual cost of transmission line can be divided broadly into two parts viz., annual charge on capital outlay and annual cost of energy wasted in the conductor.

(i) Annual charge on capital outlay. This is on account of interest and depreciation on the capital cost of complete installation of transmission line. In case of overhead system, it will be the annual interest and depreciation on the capital cost of conductors, supports and insulators and the cost of their erection. Now, for an overhead line, insulator cost is constant, the conductor cost is proportional to the area of cross-section and the cost of supports and their erection is partly constant and partly proportional to area of cross -section of the conductor. Therefore, annual charge on an overhead† transmission line can be expressed as :

$$Annual\ charge = P1 + P2\,a \qquad \dots\dots\dots(i)$$

Where, P_1 and P_2 are constants and a is the area of cross -section of the conductor.

ii) Annual cost of energy wasted. This is on account of energy lost mainly in the conductor due to I^2R losses. Assuming a constant current in the conductor throughout the year, the energy lost in the conductor is proportional to resistance. As resistance is inversely proportional to the area of cross section of the conductor, therefore, the energy lost in the conductor is inversely proportional to area of cross -section. Thus, the annual cost of energy wasted in an overhead transmission line can be expressed as:

$$Annual\ cost\ of\ energy\ wasted = \frac{P_3}{a} \qquad \dots\dots\dots(ii)$$

Where, P_3 is a constant.

$$Total\ annual\ cost.\ C = \exp(i) + \exp(ii)$$

$$C = (P_1 + P_2 a) + \frac{P_3}{a} \qquad \dots\dots\dots\dots(iii)$$

In exp (iii), only area of cross section **a** is variable. Therefore the total annual cost of transmission line will be minimum if differentiation of C w.r.t **a** is zero i.e

$$\frac{d}{da}(C) = 0$$

$$\frac{d}{da}\left((P_1 + P_2 a) + \frac{P_3}{a}\right) = 0$$

$$P_2 - \frac{P_3}{a^2} = 0$$

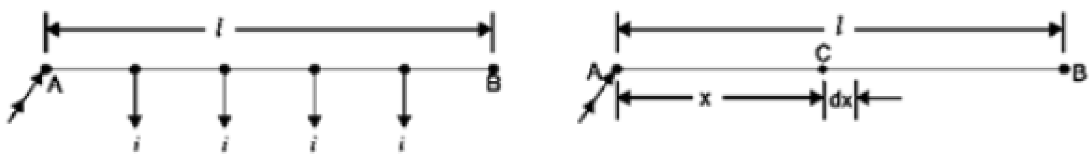
$$P_2 a = \frac{P_3}{a}$$

i.e., variable part of annual charge = annual cost of energy wasted

Therefore Kelvin's law can be also stated in another way i.e., the most economical area of conductor is that for which the variable part of annual charge is equal to the cost of energy losses per year.

9) a) Derive an expression for the voltage drop for a uniformly distributed fed at one end

Figure shows the single line diagram of a 2-wire D.C distributor AB fed at one end A and loaded uniformly with i amperes per meter length. It means that at every 1 m length of the distributor, the load tapped is i amperes. Let l meters be the length of the distributor and r ohm is the resistance per meter run.



(i) (ii)

Consider a point C on the distributor at a distance x meters from the feeding point A as shown in Figure (ii). Then current at point C is = i l − i x amperes = i (l − x) amperes Now, consider a small length dx near point C. Its resistance is r dx and the voltage drop over length dx is dv = i (l − x) r dx = i r (l − x) dx

Total voltage drop in the distributor upto point C is

$$V = \int_0^x ir\,(1 - x)dx = ir\,(lx - \frac{x^2}{2})$$

The voltage drop upto point B (i.e. over the whole distributor) can be obtained by putting x = l in the above expression.

Voltage drop over the distributor AB

$$= ir\,(lx - \frac{x^2}{2})$$

$$= \frac{1}{2}\,irl^2 = \frac{1}{2}\,(i\,l)(r\,l)$$

$$= \frac{1}{2}\,IR$$

Where

i l = I, the total current entering at point A

r l = R, the total resistance of the distributor

Thus, in a uniformly loaded distributor fed at one end, the total voltage drop is equal to that produced by the whole of the load assumed to be concentrated at the middle point.

b) A 2 wire dc distributor 200 meters long is uniformly loaded with 2A/metre. Resistance of single wire is 0.3 Ω /Km. If the distributor is fed at one end, calculate

i) The voltage drop upto a distance of 150m from the feeding point

ii) The maximum voltage drop (APRIL/2013)

Given: Current loading, i = 2 A/m Resistance of distributor per meter run, r = 2 × 0·3/1000 = 0·0006 Ω Length of distributor, l = 200 m

Solution:

(i) Voltage drop upto a distance x meters from feeding point

$$= ir\ (lx - \frac{x^2}{2})$$

x= 150 m

Here ,

$$\therefore \quad Desired\ voltage\ drop = 2 \times 0.0006\ \left(200 \times 150 - \frac{150 \times 150}{2}\right) = 22.5\ V$$

(ii) *Total voltage entering the distributor*

$$I = i \times l = 2 \times 200 = 400A$$

Total resistance of the distributor,

$$R = r \times l = 0.0006 \times 200 = 0.12\Omega$$

Total resistance of the distributor

$$= \frac{1}{2}\ IR = \frac{1}{2} \times 400 \times 0.12 = 24V$$

10) A 2 wire DC distributor cable AB is 2 km long and supplies loads of 100A, 150A, 200 A and 50A situated 500 m, 1000m, 1600m and 2000m from the feeding point A. Each conductor has a resistance of 0.01 Ω per 1000m. Calculate the potential difference at each load point of a potential difference of 300 V is maintained at point A. (APRIL/2014)

11) A two wire DC distributor of 1km long and it supplies a load of 90A, 70A, 50A and 40A at a distance of 200m, 600m, 900m and 1000m from the feeding point A. The resistance of the distributor is 0.003 Ω per km length. Determine the voltage at each load point when the voltage at point A is 220V. (NOV/2012)

12) Explain about AC three phase system. (NOV/2012)

3 PHASES. 3 WIRE SYSTEMS:

This system is almost universally adopted for transmission of electric power. The 3-phase, 3wire system may be star connected or delta connected. Figure shows 3-phase, 3 wire star connected system. The neutral point N is earthed.

$$\text{RMS voltage per phase} = \frac{V_m}{\sqrt{2}}$$

$$\text{Power transmitted per phase} = \frac{P}{3}$$

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

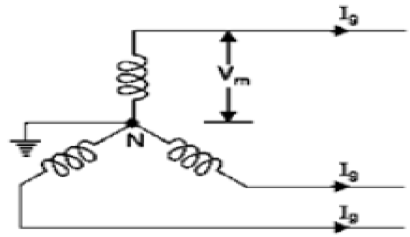
Let a_9 be the area of X-section of each conductor

$$\text{Line losses, } W = 3I_9^2R_9 = 3\left(\frac{\sqrt{2}P}{3V_m\cos\emptyset}\right)^2\frac{\rho l}{a_9} = \frac{2P^2\rho l}{3a_9V_m^2\cos^2\emptyset}$$

$$\therefore \text{Area of X section, } a_9 = \frac{2P^2\rho l}{3WV_m^2\cos^2\emptyset}$$

Volume of conductor material required

$$= 3a_9 l = 3\left(\frac{2P^2\rho l}{3WV_m^2\cos^2\emptyset}\right)l = \frac{2P^2\rho l^2}{WV_m^2\cos^2\emptyset} = \frac{0.5K}{\cos^2\emptyset}\left[\because K = \frac{4P^2\rho l}{WV_m^2}\right]$$



Hence the volume of the conductor material required for this system is 1.457/$\cos^2$ Φ times that the required for 2 wire D.C system with one conductor earthed.

3-PHASE, 4-WIRE SYSTEM:

In this case, 4th or neutral wire taken from the neutral point as shown in figure, the area of X-section of the neutral wire is generally one-half that of the line conductor. If the loads are balanced, then current through the neutral wire is zero. Assuming balanced loads and p.f. of the load are cos Φ.

$$\text{Line losses, } W = \text{Same as in 3 phase, 3} - \text{wire}$$

$$= \frac{2P^2\rho l}{3a_{10}V_m^2\cos^2\emptyset}$$

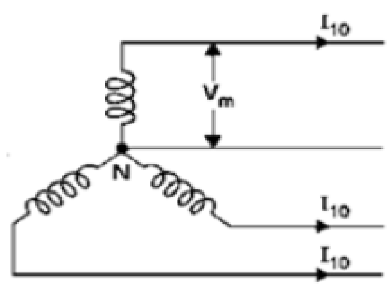
$$\therefore \text{Area of X} - \text{section, } a_{10} = \frac{2P^2\rho l}{3WV_m^2\cos^2\emptyset}$$

As the area of X-section of neutral wire is one-half that of any line conductor.

Volume of conductor material required

$$= 3.5a_{10}l = 3.5\left(\frac{2P^2\rho l}{3WV_m^2\cos^2\emptyset}\right)l$$

$$= \frac{7P^2\rho l}{3WV_m^2\cos^2\emptyset} = \frac{7}{3\cos^2\emptyset}\times\frac{P^2\rho l}{WV_m^2}$$



Hence, the volume of conductor material required for this system is 7/12 $\cos^2$Φ times that required for 2-wire D.C system with one conductor earthed.

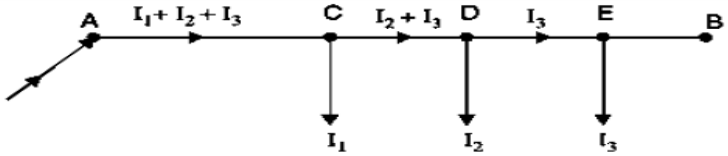
13) a) Describe briefly the different types of d.c. distributor (NOV/2014)

TYPES OF DC DISTRIBUTORS:

The most general method of classifying D.C distributors is the way they are fed by the feeders. On this basis, D.C distributors are classified as:

- Distributor fed at one end
- Distributor fed at both ends
- Distributor fed at the centre
- Ring distributor.

DISTRIBUTOR FED AT ONE END.

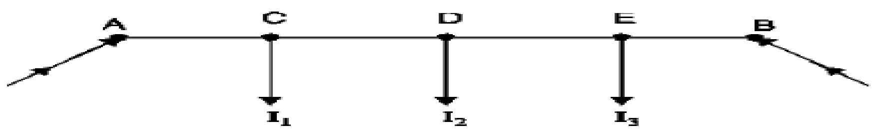


In this type of feeding, the distributor is connected to the supply at one end and loads are taken at different points along the length of the distributor. Above figure shows the single line diagram of a D.C distributor AB fed at the end A (also known as singly fed distributor) and loads I_1, I_2 and I_3 tapped off at points C, D and E respectively.

The following points are worth noting in a singly fed distributor:

- The current in the various sections of the distributor away from feeding point goes on decreasing. Thus current in section AC is more than the current in section CD and current in section CD is more than the current in section DE.
- The voltage across the loads away from the feeding point goes on decreasing. Thus in Fig. 1.42, the minimum voltage occurs at the load point E.
- In case a fault occurs on any section of the distributor, the whole distributor will have to be disconnected from the supply mains. Therefore, continuity of supply is interrupted.

DISTRIBUTOR FED AT BOTH ENDS.

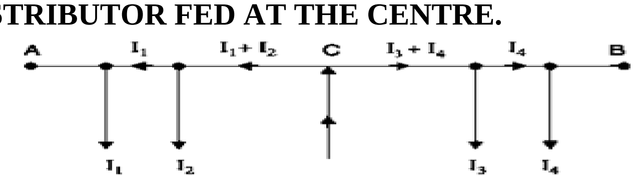


In this type of feeding, the distributor is connected to the supply mains at both ends and loads are Tapped off at different points along the length of the distributor. The voltage at the feeding points may or may not be equal. Figure shows a distributor AB fed at the ends A and B and loads of I_1, $I_2$and I_3 tapped off at points C, D and Irrespectively. Here, the load voltage goes on decreasing as we move away from one feeding point say A, reaches minimum value and then again starts rising and reaches maximum value when we reach the other feeding point B. The minimum voltage occurs at some load point and is never fixed. It is shifted with the variation of load on different sections of the distributor.

Advantages

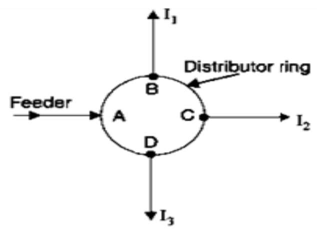
- If a fault occurs on any feeding point of the distributor, the continuity of supply is maintained from the other feeding point.
- In case of fault on any section of the distributor, the continuity of supply is maintained from the other feeding point.
- The area of X-section required for a doubly fed distributor is much less than that of a singly fed distributor

DISTRIBUTOR FED AT THE CENTRE.



In this type of feeding, the centre of the distributor is connected to the supply mains as shown in figure It is equivalent to two singly fed distributors, each distributor having a common feeding point and length equal to half of the total length.

RING MAINS.



In this type, the distributor is in the form of a closed ring as shown in below figure.
It is equivalent to a straight distributor fed at both ends with equal voltages, the two ends being brought together to form a closed ring. The distributor ring may be fed at one or more than one point.

b) A uniform 2-wire dc distributor 500 meters long is loaded with 0.4 A/m and is fed at one end. If the maximum permissible voltage drop is not to exceed 10V. Find the cross section area of the distributor. Take P=1.7 x 10-6Ω cm. (NOV/2014)

Solution:

Current entering the distributor,

$$I = i \times l = 0.4 \times 500 = 200A$$

Max. Permissible voltage =10 V

Let r ohm be the resistance per meter length of the distributor

Max. voltage drop = ½ IR

$$10 = \frac{1}{2} Irl \qquad [\because R = rl]$$

$$r = \frac{2 \times 10}{I \times l} = \frac{2 \times 10}{200 \times 500} = 0.2 \times 10^{-3}$$

Area of cross section of the distributor conductor is

$$a = \frac{\rho l}{\frac{r}{2}} = \frac{1.7 \times 10^{-6} \times 100 \times 2}{0.2 \times 10^{-3}} = 1.7\ cm^2$$

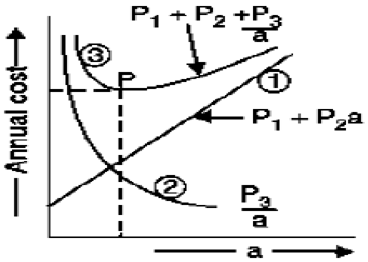
14) a) Explain the need of HV transmission. (APRIL/201

b) What are the limitations of Kelvin's law? (APRIL/2012)

LIMITATIONS OF KELVIN'S LAW.

Although theoretically Kelvin's law holds well, there is often considerable difficulty in applying it to a proposed scheme of power transmission. In practice, the limitations of this law are:

- It is not easy to estimate the energy loss in the line without actual load curves, which are not available at the time of estimation.
- The assumption that annual cost on account of interest and depreciation on the capital out lay is in the form $P_1 + P_2a$ is strictly speaking not true. For instance, in cables neither the cost of cable dielectric and sheath nor the cost of laying vary in this manner.
- This law does not take into account several physical factors like safe current density, mechanical strength, corona loss etc.
- The conductor size determined by this law may not always be practicable one because it may be too small for the safe carrying of necessary current.
- Interest and depreciation on the capital outlay cannot be determined accurately.

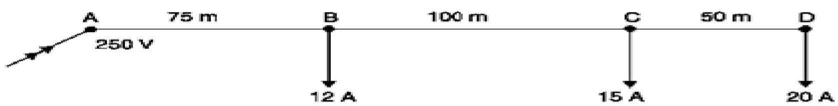


15) a) Distinguish between OH and UG distribution system (8) (APRIL/2015)
b) Write the merits and demerits of radial system (3) (APRIL/2015)
Advantages:
- This is the simplest distribution circuit ➢ Lowest initial cost

Disadvantages:
- The end of the distributor nearest to the feeding point will be heavily loaded.
- The consumers are dependent on a single feeder and single distributor. Therefore, any fault on the feeder or distributor cuts off supply to the consumers who are on the side of the fault away from the substation.

- The consumers at the distant end of the distributor would be subjected to serious voltage fluctuations when the load on the distributor changes. Due to these limitations, this system is used for short distances only.

16) The load distribution on a two wire dc distributor is shown in the below figure. The cross sectional area of each conductor is 027 cm^2. The end A is supplied at 250 V. resistivity of the wire is ρ = 1.78μΩ cm. calculate (i) the current in each section of the conductor (ii) two-core resistance of each section (iii) the voltage at each tapping point. (11) (APRIL/2015)



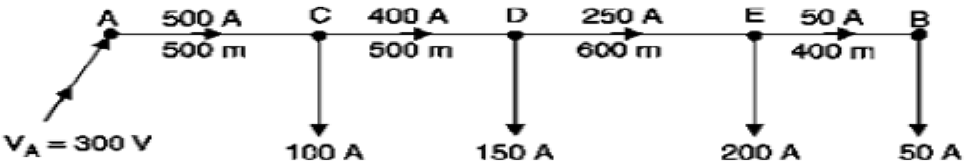
Solution:
(i) currents in the various sections are:
Section CD, I_{CD} = 20 A;
Section BC, I_{BC} =20+15 = 35 A;
Section AB, I_{AB} = 20+15+12 = 47 A
(ii) single core resistance of the section of 100m length
The resistances of the various sections are:
$R_{AB} = 0{\cdot}066 \times 0{\cdot}75 \times 2 = 0{\cdot}099\ \Omega$;
$R_{BC} = 0{\cdot}066 \times 2 = 0{\cdot}132\ \Omega$
$R_{CD} = 0{\cdot}066 \times 0{\cdot}5 \times 2 = 0{\cdot}066\ \Omega$
(iii) Voltage at tapping point B is
$V_B = V_A - I_{AB} R_{AB} = 250 - 47 \times 0{\cdot}099 = 245{\cdot}35$ V
Voltage at tapping point C is
$V_C = V_B - I_{BC} R_{BC} = 245{\cdot}35 - 35 \times 0{\cdot}132 = 240{\cdot}73$ V
Voltage at tapping point D is
$V_D = V_C - I_{CD} R_{CD} = 240{\cdot}73 - 20 \times 0{\cdot}066 = 239{\cdot}41$ V

17) a) Draw a single line diagram showing the essential parts of a power system network.(5) (NOV/2013)

b) A two wire DC distributor cable AB is 2 Km long and supplies loads of 100 A, 150A, 200 A and 50A situated 500 m, 1000m, 1600m and 2000 m from the feeding point A. each conductor has a resistance of 0.01Ω per 1000m. Calculate the potential difference at each load point if a p.d. of 300 V is maintained at point A (6) (NOV/2013)

Solution:

Figure shows the single line diagram of the distributor with its tapped currents.



Resistance per 1000 m of distributor = 2 × 0·01 = 0·02 Ω
Resistance of section AC, RAC = 0·02 × 500/1000 = 0·01 Ω
Resistance of section CD, RCD = 0·02 × 500/1000 = 0·01 Ω
Resistance of section DE, RDE = 0·02 × 600/1000 = 0·012 Ω
Resistance of section EB, REB = 0·02 × 400/1000 = 0·008 Ω
Referring to figure, the currents in the various sections of the distributor are
I_{EB} = 50 A;
I_{DE} = 50 + 200 = 250
I_{CD} = 250 + 150 = 400 A
I_{AC} = 400 + 100 = 500 A
P.D at load point C,

$$V_c = voltage\ at\ A - voltage\ drop\ in\ AC$$
$$= V_A - I_{AC}R_{AC}$$
$$= 300 - 500 \times 0.01 = 295\ V$$

P.D at load point D,

$$V_D = V_C - I_{CD}R_{CD}$$
$$= 295 - 400 \times 0.01 = 291\ V$$

P.D at load point E,

$$V_E = V_D - I_{DE}R_{DE}$$
$$= 291 - 250 \times 0.012 = 288\ V$$

P.D at load point B,

$$V_B = V_E - I_{EB}R_{EB}$$
$$= 288 - 50 \times 0.008 = 287.6\ V$$

TRANSMISSION AND DISTRIBUTION / UNIT I QUESTION BANK

University Two marks Questions:

1) State kelvin's law for the design of feeders (APRIL/2015)

2) What is proximity effect (APRIL/2015)

3) What are the limitations of Kelvin's Law? (NOV/2014)

4) What do you understand by distribution system? (NOV/2014)

5) List out the practical transmission and distribution voltage levels commonly used. (APRIL/2014)

6) What are the limitations of Kelvin's law? (APRIL/2014)

7) Mention the various types of DC distributors (NOV/2013)

8) State kelvin law (NOV/2013)

9) Define Kelvin's Law (APRIL/2013)

10) Define the term feeder, distributor and service mains. (APRIL/2013)

11) Draw the single line diagram of a ring main distributor (NOV/2012)

12) Distinguish between concentrated load and distributed load (NOV/2012)

13) Define one line diagram (NOV/2012)

14) What is feeder? (NOV/2012)

15) What are distributors and service mains? (APRIL/2012)

16) What are the advantages of bundled conductors? (APRIL/2012)

17) Why all transmission and distribution systems are three phase systems. (APRIL/2012)

18)State kelvin's law. (APRIL/2012)

11 marks questions:

1) a) Compare AC and DC transmission (APRIL/2013)

b) List out advantages of High Voltages transmission (APRIL/2013)

2) a) Derive an expression for the voltage drop for a uniformly distributed fed at one end

b) A 2 wire dc distributor 200 meters long is uniformly loaded with 2A/metre. Resistance of single wire is 0.3 Ω /Km. If the distributor is fed at one end, calculate

i) The voltage drop upto a distance of 150m from the feeding point

ii) The maximum voltage drop (APRIL/2013)

3) Discuss and compare Radial and Ring main distribution system. What is the role of interconnectors in distribution system? (APRIL/2014)

4) A 2 wire DC distributor cable AB is 2 km long and supplies loads of 100A, 150A, 200 A and 50A situated 500 m, 1000m, 1600m and 2000m from the feeding point A. Each conductor has a resistance of 0.01 Ω per 1000m. Calculate the potential difference at each load point of a potential difference of 300 V is maintained at point A. (APRIL/2014)

5) Draw and explain the structure of modern power system including the voltage levels in each transmission line. (NOV/2012)

6) A two wire DC distributor of 1km long and it supplies a load of 90A, 70A, 50A and 40A at a distance of 200m, 600m, 900m and 1000m from the feeding point A. The resistance of the distributor is 0.003 Ω per km length. Determine the voltage at each load point when the voltage at point A is 220V. (NOV/2012)

7) Write in detail about the structure of electric power. (NOV/2012)

8) Explain about AC three phase system. (NOV/2012)

9) Draw and explain the line diagram of a typical transmission and distribution scheme, indicate clearly the voltage levels used at different stages. (NOV/2014)

10) a) Describe briefly the different types of d.c. distributor (NOV/2014)

b) A uniform 2-wire dc distributor 500 meters long is loaded with 0.4 A/m and is fed at one end. If the maximum permissible voltage drop is not to exceed 10V. Find the cross section area of the distributor. Take P=1.7 x $10^{-6}\Omega$ cm. (NOV/2014)

11) a) Explain the need of HV transmission. (APRIL/2012)

b) What are the limitations of Kelvin's law? (APRIL/2012)

12) Discuss connection schemes of the following distribution systems. (APRIL/2012)

a) Radial system b) Ring Main system.

13) a) Distinguish between OH and UG distribution system (8) (APRIL/2015)

b) Write the merits and demerits of radial system (3) (APRIL/2015)

14) The load distribution on a two wire dc distributor is shown in the below figure. The cross sectional area of each conductor is 027 cm^2. The end A is supplied at 250 V. resistivity of the wire is ρ = 1.78$\mu\Omega$ cm. calculate (i) the current in each section of the conductor (ii) two-core resistance of each section (iii) the voltage at each tapping point. (11) (APRIL/2015)

15) a) Draw a single line diagram showing the essential parts of a power system network.(5) (NOV/2013)

b) A two wire DC distributor cable AB is 2 Km long and supplies loads of 100 A, 150A, 200 A and 50A situated 500 m, 1000m, 1600m and 2000 m from the feeding point A. each conductor has a resistance of 0.01Ω per 1000m. Calculate the potential difference at each load point if a p.d. of 300 V is maintained at point A (6) (NOV/2013)

16) a) Write the comparison of various distribution systems. (6) (NOV/2013)

b) Explain the application of Kelvin's law for the design of feeders (5) (NOV/2013)

Unit-II

TRANSMISSION LINE PARAMETERS: *Resistance, inductance and capacitance of single and three phase transmission lines-symmetrical and unsymmetrical spacing–transposition-single and double circuits-stranded and bundled conductors-application of self and mutual GMD–Skin and Proximity effect-inductive interference-Corona-characteristics.*

TWO MARKS QUESTIONS:

1) What are the various factors affecting skin effect (APRIL/2015) (or) On what factors does the skin effect depend? (NOV/2012)

The skin effect depends upon the following factors:

- Nature of material,
- Resistivity
- Frequency
- Conductor size

2) What are the classifications of OH transmission lines (APRIL/2015)

3) What is meant by skin effect? (NOV/2014)

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

4) Define self GMD. (NOV/2014)

GMR is also called as self GMD. GMR is defined as the limit of geometric mean of distances between all the pairs of elements in that area as the number or elements increase without limit. Self GMD of a conductor depends upon the size and shape of the conductor and is independent of spacing between the conductors.

5) Give the expression for the inductance per phase of three phase overhead line in which conductor are symmetrically placed. (APRIL/2014)

6) Distinguish between stranded and bundled conductors (APRIL/2014)

STRANDED CONDUCTOR	BUNDLED CONDUCTOR
Stranded conductors are composed of two or more elements of strands electrically in parallel with alternate layers spiralled in opposite direction to prevent unwinding.	A bundled conductor is a conductor made up of two or more sub conductors and is used as one phase conductor. Bundled conductors are separated from each other by 30cm or more and conductors of each phase are connected by connecting wires at particular length.
It is used for voltages less than 230kv	It is used for voltages above 230kv

7) What is meant by transposition of the power conductors (NOV/2013) (or) Why is transmission lines transposed? (NOV/2012)

To avoid the unbalancing effect due to unsymmetrical spacing, the positions of the line conductors are interchanged at regular intervals along the line so that each conductor occupies the original position of every other conductor over an equal distance. This exchanging of positions of conductors is called transposition.

8) What are bundled conductors (NOV/2013) (or) Write about bundled conductor. (NOV/2012)

The conductors of any one bundle are in parallel and charge per bundle is assumed to divide equally between the conductors of bundle.

9) What is meant by corona? (APRIL/2013) (or) What is corona discharge? (NOV/2012

When the potential difference is increased, a potential gradient is set up. If the potential gradient is above 30 kV/cm the conductors get ionized. The phenomenon of faint violet glow, hissing noise and production of ozone gas is known as corona.

10) Define mutual GMD. (APRIL/2013)

GMD is defined as the geometric mean of the distances from one end of the conductor to the other end. It is also called as mutual GMD.

11) What is the necessity for double circuit line (APRIL/2012)

In an overhead system there may be more than one circuit running in parallel on the same towers. A transmission line has two circuits connected in parallel called a double circuit line. Each circuit will have three conductors lying along its length. The necessity for a double circuit line in overhead transmission system is to reduce the inductance per phase, improves transmission capability.

12) Distinguish between GMD and GMR? Explain the influence of power factor on the regulation of a transmission line (APRIL/2012)

13) What is proximity effect (APRIL/2015)

The alternating magnetic flux in a conductor caused by the current flowing in a neighbouring conductor gives rise to circulating currents which causes non uniformity of current and an apparent increase in the resistance of a conductor. This phenomenon is called proximity effect.

14) What are the advantages of using bundled conductor? (APRIL/2012)

The advantages of using bundled conductors are:

- Reduced reactance,
- Reduced voltage gradient,
- Reduced corona loss,
- Reduced radio interference,
- Reduced surge impedance,
- Reduced inductance.

15) Define the term “Interference with neighboring circuits”.

If the power line is running along the communication line, there will be interference in the communication line due to both electrostatic and electromagnetic effects. The electrostatic effect induces voltage in communication line, which is dangerous to human body, vehicles, buildings and objects of comparable size. The electromagnetic effect produces currents, which is superimposed on the true speech currents in the communication signal and cause distortion.

11 marks

1) Write a note on the transmission line parameters/constants:

Transmission Line Constants:

Transmission lines are the circuits with the distributed constants such as resistance, inductance, conductance and capacitance distributed along the length of transmission line. These constants are not concentrated at any point. Their values are normally expressed as pet kilometer length of line.

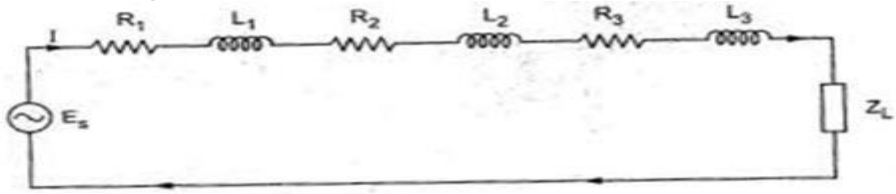
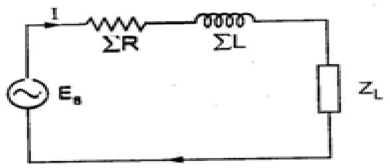
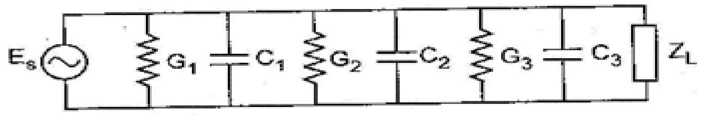


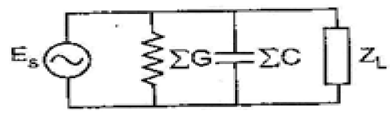
Fig 2.1

Consider the distributed circuit shown in the Fig. 2.1. The analysis of this circuit can be made by lumping the parameters which is shown in Fig 2.2 the analysis of circuit becomes easier. By lumping the parameters as the same current is passing through each element of resistance and inductance. Fig 2.2





(a)



(b)

Fig 2.3

Similarly the' circuits shown in the Fig. 2.3 (a) and (b) are seen to be equivalent as the same voltage is applied across each conductance and capacitance. But if the elements are distributed as shown in the Fig. 2.4 then the elements cannot be lumped as the same current is not flowing through series element and the voltage across different elements changes from one section to other. Consider the equivalent circuit of a 2-wire transmission line having resistance, inductance, capacitance and conductance associated with it as shown in the Fig 2.4

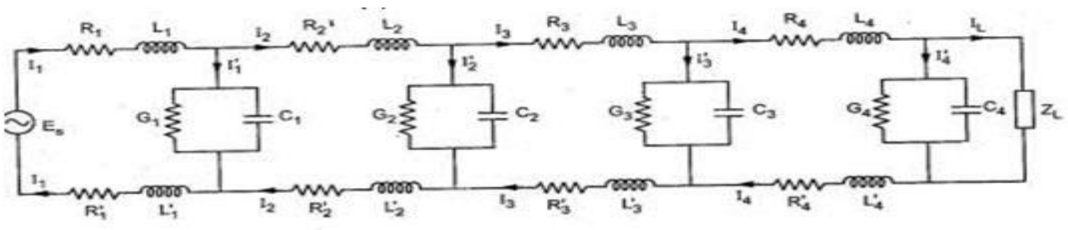


Fig 2.4

The line is divided into large number of small sections of unit length. The upper and lower part of each section carries same current. Hence we have the equivalent circuit as shown in the Fig 2.5

Here

$R_{1T} = R_1 + R_1', R_{2T} = R_2 + R_2'$

$L_{1T} = L_1 + L_1', L_{2T} = L_2 + L_2'$etc

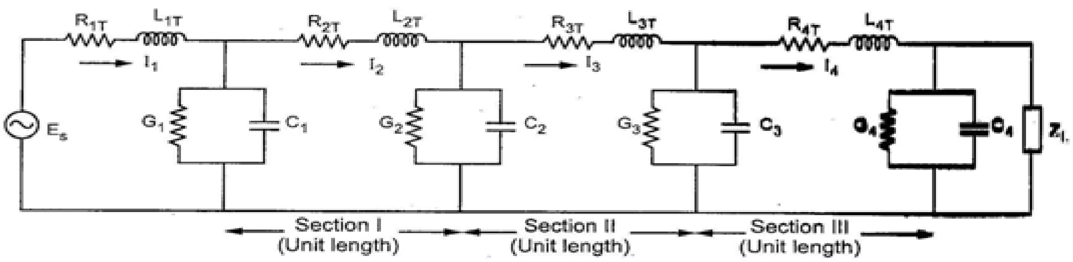


Fig 2.5

The resistance per unit length of the line is say R where R1T = R2T=R:nR-1T…=R, ohm/meter. We have L1T=L2T=L3T=…=L, henry/meter
G1 = G2 = … G, mho, meter
C1 = C2 = … C, Farad/meter
In case of 2 wire transmission system the line parameters are expressed on loop basis while in case of 3 phase transmission system the parameters are represented on per conductor basis. The physical length of the transmission line does not indicate that the line is short or long but it is based on comparison with the wavelength (A) of the source
2) What are the factors to be considered while deciding a transmission line?
Factors to be considered while Deciding Transmission Line:
Following are some of the important factors that need to be considered while deciding the transmission system.

1. Type and size of a conductors.
2. Voltage level.
3. Line regulation and control of voltage.
4. Efficiency of transmission.
5. Corona loss.
6. Power flow capability and stability.
7. Requirement of compensation.
8. Levels of faults at various bus bars and requirement of new circuit breakers.
9. Grounding needs.
10. Protection schemes for new lines.

11. Co-ordination of insulation.
12. Mechanical design aspects which include stress and sag calculations, composition of conductor, spacing of conductor, and configurations for insulators .
13. Design of power system structure.
14. Economical aspects.

3) Mention the major types of conductors used in transmission systems.
Conductor Types:
When the conductors are used in transmission system for bulk power transfer, then they should full following requirements.
1. They should have low weight.
2.They should have high tensile strength.
3.They should have low co-efficient of expansion, low corona loss .
4.They should have less resistance and low cost.
The normally used materials for conductors are copper and aluminum. The advantages of using aluminum conductors over copper conductors are given below.
1.They have low cost
2.Less resistance and corona loss.
3. Less weight.
But aluminum has less tensile strength, high coefficient of expansion and large area which restricts its use alone as a conductor. In order to increase the tensile strength of a conductor, one or more central conductors of different materials are used. These materials give high tensile strength, The different types of aluminum conductors used in power systems with full forms of their abbreviations are as given below.
AAC : All aluminum conductor.
AAAC : All aluminum alloy conductor.
ACSR :Aluminum conductor with steel reinforcement.
ACAR : Aluminum conductor with alloy reinforcement.
The ACSR conductors are more commonly used as they have following advantages,
1. They have low corona loss.
2. Skin effect is to reduced extent.
3. Due to high mechanical strength, the line span can be increased. The minimizes cost of erection and maintenance.
4. These conductors are inexpensive as compared to (copper conductors having equal resistance without reduction in efficiency,useful life span and durability.
The conductors used in transmission system are stranded except for small cross section. These conductors are electrically in parallel and spiralled together. Due to use of stranded conductors, the skin effect is reduced.
The conductor size is decided based on its current carrying ability and voltage level on which it is working. The total number of strands N for n layers of strands In a Conductor for uniform each strand is given by,
$N = 3n^2 - 3n + 1$
The overall outer diameter D if the diameter of one strand is d is given by
$D=(2n-1)d$
4) Explain in details the constants of transmission systems.
Resistance:
The resistance of a transmission line is an important parameter as it is the main cause of power loss in a transmission line. It is defined as the opposition offered by the transmission

line conductors flow of current. The resistance of the line is uniformly distributed along its whole length. But the performance of the line can be conveniently analyzed by considering the distributed resistance as lumped one as Shown in the Fig.2.2

The effective resistance of a conductor is given by

$$R = \frac{\text{Power loss in conductor}}{(I^2)} \ (\Omega)$$

R = Power loss in conductor (Ω)

(I^2) = current through the conductor (A)

Where the power loss in conductor is in watts and current flowing through the conductor in amperes. When the distribution of current in a conductor is uniform then the effective resistance is equal to d.c. resistance of the conductor. This direct resistance is given by,

$$R = \frac{\rho l}{a} \ (\Omega)$$

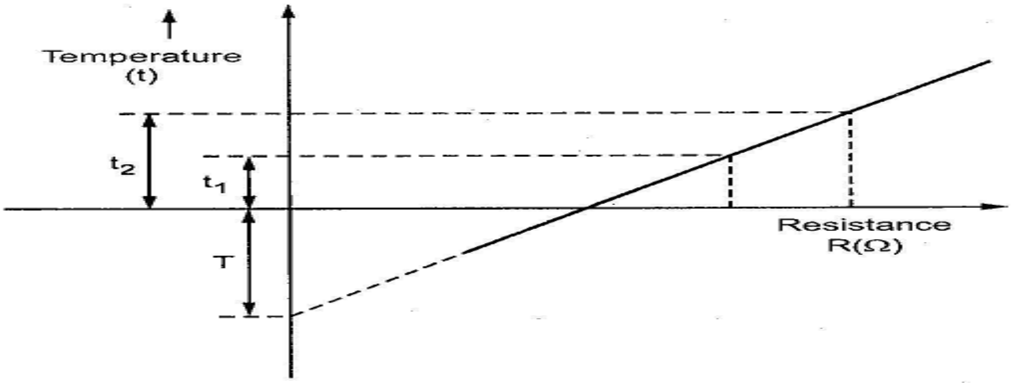
p = resistivity of conductor (Ω - m)

I = length of conductor (m)

a = cross-sectional area of conductor (m2)

The d.c. resistance computed from the above equation of the standard conductors is greater as spiraling of the strands makes them longer than the conductor itself. This increase in resistance is taken as 1% for 3 strand conductors and 2% for concentrically stranded conductors.

Temperature is also one of the factor which will change the d.c. resistance of metallic conductor. Its variation with resistance is as shown in the Fig. 2.6. It is seen to be linear over normal range of operation.



Fg 2.6

$$\frac{R2}{R1} = \frac{T + t2}{T + t1}$$

rom the above Fig.2.6 it can be seen that

Where R1 ,R2 are the resistances of the conductor at temperatures t1 and t2 in degrees C and T is the constant obtained from the graph. The value of T is 234.5¤C for annealed copper of 100% conductivity.

Inductance:

An alternating flux is produced by the alternating current when flowing through a conductor. This flux links with the conductor. The conductor possesses inductance due to these flux linkage. The flux linkages per ampere is called the inductance.

Thus inductance is given by

L=Ψ/I

Where,

Ψ=Flux linkage in Weber-turns
I=Current in amperes
The inductance of a transmission line is also a distributed parameter over the length of line. For convenience in analysis it is taken as lumped as shown in the Fig 2.2
The fundamental equation used to define inductance is given by

$$e = \frac{d\tau}{dt}$$

Where e is induced voltage in volts and τ is number of flux linkage of the circuit in weber-turns. The number of weber turns is the product of each weber of flux and the number of turns of the circuit linked. Each of line of flux is multiplied by the number of turns it links and these products are added to determine total flux linkages.
If constant permeability is assumed for the medium in which the magnetic field is set up then we have

$$N\tau \; \alpha \; i$$

$$N\tau = Li$$

The constant of proportionality is called inductance

$$\tau = \frac{Li}{N}$$

Substituting this value in the fundamental equation we have,

$$e = \frac{d}{dt}\left[\frac{Li}{N}\right] = \frac{L}{N}\frac{di}{dt}$$

For N number of turns,

$$e = L\frac{di}{dt}$$

If permeability is-not constant then above equation may also be used but then the inductance is not constant.
Solving equations (1) and (2) we get,

$$L = \frac{d\tau}{dt} H$$

$$\therefore \qquad \tau = Li \qquad Wb - turns$$

In this equation, i is the instantaneous value of current. So τ represents instantaneous flux linkages. For sinusoidal alternating current, flux linkages are also sinusoidal. Hence we have

$$\Psi = LI$$

The voltage drop due to flux linkage is

$$V = j\omega LI \qquad Volts$$

$$\therefore \; V = j\omega\Psi \qquad Volts$$

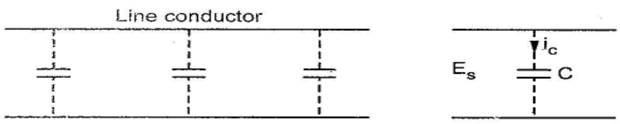
The mutual inductance between the two circuits is defined as the flux linkages of one circuit due to current in the second circuit per ampere of current in the second circuit. If current I_2 produces Ψ_{12}flux linkages with circuit1, the mutual inductance is $M_{12}=\Psi_{12}/I_2$
The voltage drop in circuit 1 is given by

$$V_1 = j\omega M_{12} I_2 = j\omega \Psi_{12} \qquad Volts$$

Mutual inductance is important in considering the influence of power lines telephone lines and the coupling between parallel power lines.

Capacitance:

When any two conductors are separated by an insulating material it will form a capacitor. In case of overhead transmission line air acts as an insulating medium between two conductors, So there will be capacitance between two conductors which is defined as charge per unit potential difference Capacitance = C = q/v fared Unlike resistance and, inductance, the capacitance of transmission line is also uniformly distributed along the whole length of the line. It may be treated as a uniform series of capacitors connected between the conductors as shown in the Fig



The charge on the conductors at any point increases and decreases with increase and decrease of the instantaneous value of the voltage between conductors at that point. Due to this a current known as charging current flows through the conductor even though the line is open circuited. The voltage drop, efficiency and power factor of line depends on the value of capacitance.

5. Derive an expression for inductance of a conductor due to the internal flux.

Inductance of a Conductor due to the Internal Flux:

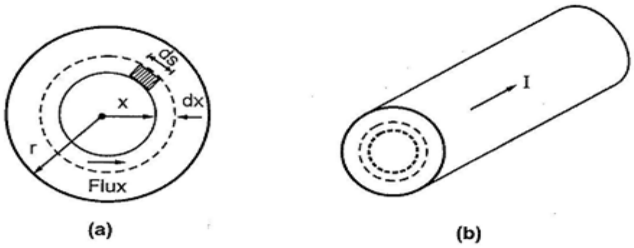


Fig. 2.9

Consider a long, straight conductor with radius 1meters and carrying a current I amperes as shown in the Fig. 2.9(a). The magnetic field will be established due to this current. The magnetic flux lines will change inside the conductors which will contribute to induced voltage and hence inductance. The magnetic flux lines exist outside the conductor also. We may assume that the return path for.

The current in this conductor is far away and the magnetic field of the conductor is not affected. The value of inductance due to internal flux is given by the ratio of flux linkages to current by taking into account the fact that each line of internal flux links only a fraction of total current.

The exact value of inductance of transmission line is obtained by considering the flux inside each conductor as well as external flux. The lines of flux are concentric with the conductor. The mmf in ampere turns around any closed path is equal to the current in amperes enclosed by the path. Thus we have $mmf = \oint H.ds = I$

$\oint$ where H is magnetic field intensity in At/m .Let the magnetic field .
Intensity at a point x meters from the center of the conductor be H This is constant at all points as field is symmetrical. Thus integration of ds around the closed circular path is 2πx $\oint$

$$\oint ds = 2\pi x$$

As H_x is constant

$$H_x 2\pi x = I_x$$

$$H_x = \frac{I_x}{2\pi x}$$

As the current density is uniform

$$\frac{I_x}{\pi x^2} = \frac{I_x}{\pi r^2}$$

Substituting the value of I_x *in expression for* H_x

$$H_x = \frac{x^2}{r^2}.I.\frac{1}{2\pi x} = \frac{x}{2\pi r^2}I \quad AT/m$$

If $\mu = \mu_0\mu_r$, *then flux density at the given point is given by,*

$$B_x = \mu H_x = \mu_0\mu_r H_x$$

$$= \frac{\mu_0\mu_r x}{2\pi r^2}I$$

$$\mu_r = 1 \ \text{for the non} - \text{magnetic material}$$

$$B_x = \frac{\mu_0 x}{2\pi r^2}.I$$

For the element having thickness dx, the flux will be product of ex and the cross-sectional area of the element normal to the flux lines. This area is dx times axial length. If the axial length considered is 1m then the flux per meter of length is

$$d\phi = B_x \times 1 \times dx = \frac{\mu_0 \times I}{2\pi r^2}dx$$

This flux links with current I_x. Hence flux linkage per meter length of conductor is given by,

$$d\Psi = \frac{x^2}{r^2}d\phi = \frac{\mu_0 x^3 I}{2\pi r^4}dx$$

To find internal flux or the total flux linkage inside the conductor we have to carry the integration from the center of conductor to its outside edge.

$$\Psi_{int} = \int_0^r d\Psi = \int_0^r \frac{\mu_0 x^3 I}{2\pi r^4}dx$$

$$\Psi_{int} = \frac{\mu_0 I}{8\pi} \ Wb - \frac{turn}{m}$$

But $\mu_0 = \text{permeability of free space} = 4\pi \times 10^{-7} \ H/m$

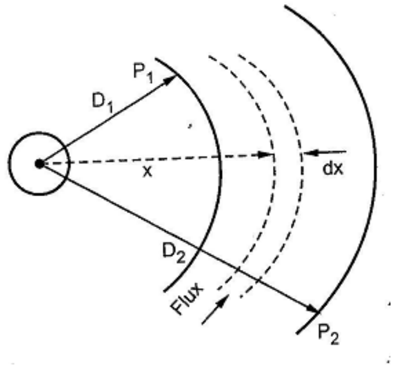
$$\Psi_{int} = \frac{I}{2} \times 10^{-7} \ Wb - t/m$$

$$L_{int} = \frac{\Psi_{int}}{I} = \frac{10^{-7}}{2} H/m$$

Thus we have obtained inductance per unit length of a round conductor due to flux inside the conductor. Inductance per unit length is referred as simply inductance for convenience and simplicity.

6. Derive an expression for inductance of a conductor due to the external flux.

Inductance of a Conductor due to External Flux: Now we shall estimate the flux linkages of the conductor due to the external flux. For this we will consider the flux linkages of an isolated conductor due to that portion of the external flux which lies between two points distant D1, and D2 meters from center of conductor P1 and P 2 are two such points as shown in the Fig.2.10 The conductor showed in the Fig. 2.10 .carries current I. The flux paths are concentric circles around the conductor between P 1 andP2 Consider a tubular element which is x meters from center of conductor. The field Intensity at this point is Hx The mmf around the element is $2\pi H_x = I$



The flux density Bx at this point is given by

$$B_x = \mu H_x = \frac{\mu I}{2\pi x} wb/m^2$$

The flux dΦ in the tabular element is given by,

$$d\emptyset = B_x \times dx \times 1m \ (Axial\ length\ is\ considered\ as\ 1m)$$

$$d\emptyset = \frac{\mu I}{2\pi x} . dx$$

The flux linkages dΨ per meter are equal to dφ since flux external to the conductor links all the current in the conductor. The total flux linkage between P1 and P2 are Obtained by integrating dΨ from D1 to D2

$$\Psi_{12} = \int_{D_1}^{D_2} \frac{\mu I}{2\pi x} dx$$

$$= \frac{\mu I}{2\pi} \int_{D_1}^{D_2} \frac{dx}{x}$$

$$= \frac{\mu I}{2\pi} ln\left(\frac{D_2}{D_1}\right)$$

$$\because \quad \mu = \mu_0 \mu_r$$

For Relative permeability, $\mu_r = 1$

$$\Psi_{12} = \frac{\mu_0 I}{2\pi} ln\left(\frac{D_2}{D_1}\right)$$

$$= \frac{4\pi \times 10^{-7} I}{2\pi} \left(\frac{D_2}{D_1}\right)$$

$$\Psi_{12} = 2 \times 10^{-7} I ln\left(\frac{D_2}{D_1}\right)$$

The inductance due to flux included between P_1 and P_2 only is,

$$L_{12} = \frac{\Psi_{12}}{I} = 2 \times 10^{-7} ln\left(\frac{D_2}{D_1}\right)$$

In the external flux is considered to be extended from the surface of conductor to infinity then total flux linkages is given by,

$$\Psi_{12} = \int_r^\infty \frac{\mu_0 I}{2\pi x} dx \qquad weber - turns$$

Overall flux linkages is given by

$$Total\ flux\ linkage = \frac{\mu_0 I}{8\pi} + \int_r^\infty \frac{\mu_0 I}{2\pi x} dx$$

$$= \frac{\mu_0 I}{2\pi}\left[\frac{1}{4} + \int_r^\infty \frac{dx}{x}\right]$$

7. Derive an expression for inductance of a single phase two wire line. (APRIL/2013) (NOV/2012) (NOV/2014)

Inductance of a Single Phase Two Wire Line :

Consider a single phase line consisting, of two parallel conductors. These conductors are forming a rectangular loop of one turn. These conductors are solid conductors of radii r1 and r2 respectively. One conductor is forming a return circuit for the other. The two conductors are carrying currents I1 and I2 respectively. In a single phase circuit we have I1 + I2 = 0 I2= -I1 Here we are neglecting the effect of earth's presence of magnetic field geometry as earth's relative permeability is same as that of air and its conductivity is relatively small.

The arrangement of the conductors and variation of flux density due to each conductor is shown in the Fig 2.11 & 2.12In the beginning, let us consider only the flux linkages of the circuit caused by the current in conductor 1. The flux line set up by the current flowing in conductor 1 at a distance equal to or greater than D + R2 from the center of conductor 1 does not link the circuit and hence is not responsible for inducing any voltage in the circuit.

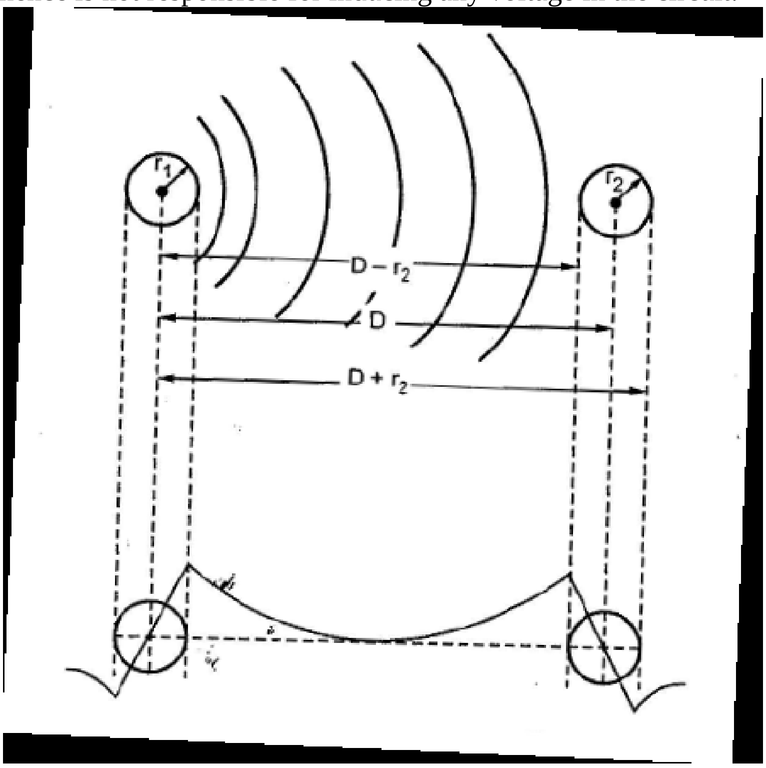


Fig 2.11&2.12

This is because conductor 2 carries current which is equal and opposite to that in conductor1. The external flux from R_1 to D - R_2 links all the current I_1 in conductor 1. Over the surface of conductor 2 i.e. between (D - r_2) and (D + r_2)' the external flux links a current whose magnitude is progressively reduces from I_1 to zero because of negative current in conductor 2. The total inductance of the current carrying in conductor 1 can be calculated by assuming that D is much greater than $f_1$and f_2.

Under this condition it can be assumed that flux from (D – r_2) to the center of conductor 2 links current II and flux from the center of conductor 2 to (D + r_2) links zero current. The inductance due to current in conductor 1 can be calculated by using the relation,

$$L_{12} = 2 \times 10^{-7} ln \left(\frac{D_2}{D_1}\right) H/m$$

$$L_{12} = 2 \times 10^{-7} ln \left(\frac{D}{r_1}\right) H/m$$

This expression is valid for external flux only. For internal flux we have

$$L_{1int} = \frac{1}{2} \times 10^{-7} H/m$$

The total inductance of the circuit due to current in conductor 1 only is,

$$L_1 = L_{1int} + L_{12} = \frac{1}{2} \times 10^{-7} + 2 \times 10^{-7} ln \left(\frac{D_2}{r_1}\right)$$

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

The above equation can conveniently be written as

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

$$where \qquad \frac{1}{4} = ln \epsilon^{1/4}$$

$$L_1 = 2 \times 10^{-7} ln \left[\frac{\epsilon^{1/4} D}{r_1}\right] = 2 \times 10^{-7} ln \left[\frac{D}{r_1 \epsilon^{-1/4}}\right]$$

Let us consider $r_1' = r_1 \epsilon^{-1/4}$, then we have

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

The radius r1is that of an imaginary or fictitious conductor assumed to have no internal flux. The quantity Є-1/4 equals to 0.7778.The value of inductance given by equation (2) is same as that given by equation (1).The difference is that equation (2) omits the term on account of internal flux. But it is compensated by adjusted value of radius of conductor.

The above equation is derived by considering solid round conductors. Equation II is algebraic manipulation of equation (1). Hence the multiplying factor of 0.7778 is applicable only to solid round conductors in order to account for internal flux.

The conductor 2 carries current in opposite direction to that in conductor 1. The flux linkages produced by current in conductor 2 considered alone are in the same direction as those produced by current in conductor 1.

The resultant flux for the two conductors is determined by sum of mmfs of the two conductors. If permeability is assumed to be constant then the flux linkages and inductances of the two conductors calculated separately may be added. The inductance of conductor 2 in comparison with equation (2) can be written as, L2=2X

$$L_2 = 2 \times 10^{-7} ln \left[\frac{D}{r_2{'}}\right] H/m$$

For the total circuit

$$L = L_1 + L_2 = 4 \times 10^{-7} ln \left[\frac{D}{\sqrt{r_1' r_2'}}\right] H/m$$

If we have

$$r_1' = r_2' = r'$$

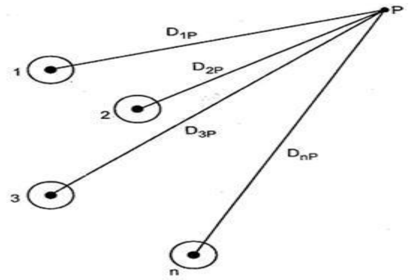
Total inductance, $\qquad L = 4 \times 10^{-7} ln \left[\frac{D}{r'}\right] H/m$

The above equation gives the inductance of two wire single phase line taking into consideration the flux linkages caused by current in both the conductors. The value of inductance obtained is the inductance per loop meter or per loop mile. The inductance given by equation (2) is one half of the total inductance of single phase line and is called inductance per conductor.

7. Derive an expression for flux linkages of one conductor in a group.

Flux Linkages of One conductor in a Group :

Consider a composite conductor which is made up of two or more strands which are in parallel. For simplicity let us assume that all the strands are identical and share the current equally. The sum of the currents in all the conductors is zero. Such a grow of conductors is shown in the Fig. 2.13 The conductors 1, 2, 3, ... n carry the currents I1,I2,I3....In Let the distances of the conductors from a point P be D1P, D2P, D3p respectively. Let Ψ P1be flux linkages of conductor 1 due to its own current II due to internal and external flux. The flux beyond point P is excluded.



$$\Psi_{1p1} = \left[\frac{I_1}{2} + 2I_1 ln\frac{D_{1p}}{r_1}\right] \times 10^{-7} I_1 ln\frac{D_{1p}}{r_1'}$$

Now ΨIp2 is the, flux linkage of conductor 1 due to current I2is equal to flux produced by I2between the point P and conductor 1. Again flux beyond P is neglected

$$\Psi_{1p2} = 2 \times 10^{-7} I_2 ln\frac{D_{2p}}{D_{12}}$$

Similarly the flux linkages $\Psi_{1p}$with conductor 1 due to all the conductors in the group but the flux beyond point P is neglected.

$$\Psi_{1p} = 2 \times 10^{-7}\left[I_1 ln\frac{D_{1p}}{r_1'} + I_2 ln\frac{D_{2p}}{D_{12}} + I_3 ln\frac{D_{3p}}{D_{13}} + \cdots + I_n ln\frac{D_{np}}{D_{1n}}\right]$$

By expanding the logarithmic terms and rearranging the terms

$$\Psi_{1p} = 2 \times 10^{-7}\left[I_1 ln\frac{1}{r_1'} + I_2 ln\frac{1}{D_{12}} + I_3 ln\frac{1}{D_{13}} + \cdots + I_n ln\frac{1}{D_{1n}} + I_1 lnD_{1p} + I_2 lnD_{2p} + I_3 lnD_{3p} + \cdots + I_n lnD_{np}\right]$$

The sum of all currents is zero.

$$I_1 + I_2 + I_3 + \cdots + I_n = 0$$
$$I_n = -(I_1 + I_2 + \cdots + I_{n-1})$$

Substituting this value in above equation

$$\Psi_{1p} = 2 \times 10^{-7}\left[I_1 ln\frac{1}{r_1'} + I_2 ln\frac{1}{D_{12}} + \cdots + I_n ln\frac{1}{D_{1n}} + I_1 lnD_{1p} + I_2 lnD_{2p} + \cdots (-I_1 - I_2 - \cdots - I_{n-1}) lnD_{np}\right]$$

If point P is at infinite distance so that $\ln\frac{D_{1p}}{D_{np}}, \ln\frac{D_{2p}}{D_{np}}$ etc will approach to zero (since ln1=0) then we have,

$$\Psi_{1p} = 2 \times 10^{-7}\left[I_1 ln\frac{1}{r_1'} + I_2 ln\frac{1}{D_{12}} + \cdots + I_n ln\frac{1}{D_{1n}}\right]$$

If $r_1' = D_{11}$ then

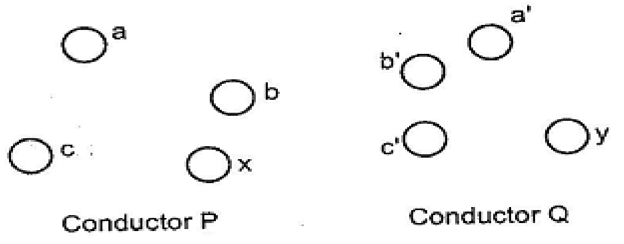
$$\Psi_{1p} = 2 \times 10^{-7}\left[I_1 ln\frac{1}{D_{11}} + I_2 ln\frac{1}{D_{12}} + \cdots + I_n ln\frac{1}{D_{1n}}\right]$$

All the flux linkages of conductor 1 are included in the above derivation. The above expression is valid only if sum of the currents is zero.

8. Derive an expression for inductance of composite conducting lines.

Inductance of Composite Conductor Lines:

Now we will consider a single phase 2 wire system. It consists of two conductors say P and Q which are composite conductors. The arrangement of conductors is shown in the Fig



Conductor P is consisting of x identical, parallel filaments. Each of the filament carries a current of l /x. Conductor Q consists of y filament with each filament carrying a current of - I/y. The conductor Y carries a current of I amps in opposite direction to the current in conductor X as it is forming return path. The flux linkages of filament say a due to all currents in all the filaments is given

$$\Psi_a = 2\times10^{-7}\left[\frac{I}{x}\ln\frac{1}{D_{aa}}+\frac{I}{x}\ln\frac{1}{D_{ab}}+\frac{I}{x}\ln\frac{1}{D_{ac}}+\cdots+\frac{I}{x}\ln\frac{1}{D_{ax}}\right]$$

$$+2\times10^{-7}\left[\frac{-I}{y}\ln\frac{1}{D_{aa'}}+\frac{-I}{y}\ln\frac{1}{D_{ab'}}+\frac{-I}{y}\ln\frac{1}{D_{ac'}}+\cdots+\frac{-I}{y}\ln\frac{1}{D_{ay}}\right]$$

$$=2\times10^{-7}\frac{I}{x}\left[\ln\frac{1}{D_{aa}}+\ln\frac{1}{D_{ab}}+\ln\frac{1}{D_{ac}}+\cdots+\ln\frac{1}{D_{ax}}\right]$$

$$-2\times10^{-7}\frac{I}{y}\left[\ln\frac{1}{D_{aa'}}+\ln\frac{1}{D_{ab'}}+\ln\frac{1}{D_{ac'}}+\cdots+\ln\frac{1}{D_{ay}}\right]$$

$$=2\times10^{-7}I\left[\ln\left(\frac{1}{D_{aa}}\right)^{1/x}+\ln\left(\frac{1}{D_{ab}}\right)^{1/x}+\cdots+\ln\left(\frac{1}{D_{ax}}\right)^{1/x}\right]$$

$$-2\times10^{-7}I\left[\ln\left(\frac{1}{D_{aa'}}\right)^{1/y}+\ln\left(\frac{1}{D_{ab'}}\right)^{1/y}+\cdots+\ln\left(\frac{1}{D_{ay}}\right)^{1/y}\right]$$

$$=2\times10^{-7}I\left[\ln\frac{\sqrt[y]{D_{aa'}D_{ab'}\ldots\ldots D_{ay}}}{\sqrt[x]{D_{aa}D_{ab}\ldots\ldots D_{ax}}}\right]$$

The inductance of filament a is given by,

$$L_a=\frac{\Psi_a}{I/x}=2x\times10^{-7}\ln\frac{\sqrt[y]{D_{aa'}D_{ab'}\ldots\ldots D_{ay}}}{\sqrt[x]{D_{aa}D_{ab}\ldots\ldots D_{ax}}}$$

The average inductance of the filaments of conductor P is

$$L_{av}=\frac{L_a+L_b+L_c+\cdots+L_x}{x}$$

The conductor P consists of x number of parallel filaments. If all the filaments are of equal inductances then inductance of the conductor would be l/x times inductance of one filament. All the filaments have different inductances but the inductance of all of them in parallel is l/x times the average inductance. Inductance of conductor P is given by,

$$L_p=\frac{L_{av}}{x}=\frac{L_a+L_b+L_c\ldots\ldots L_x}{x^2}$$

Substituting the values of L_a, L_b, ….L_x in the equation and simplifying the expression we have,

$$L_p=2\times10^{-7}ln\left[\frac{\sqrt[xy]{(D_{aa'}D_{ab'}\ldots D_{ay})(D_{ba'}D_{bb'}\ldots D_{by})\ldots(D_{xa'}D_{xb'}\ldots D_{xy})}}{\sqrt[x^2]{(D_{aa'}D_{ab'}\ldots D_{ax})(D_{ba'}D_{bb'}\ldots D_{bx})\ldots(D_{xa'}D_{xb'}\ldots D_{xx})}}\right]$$

In the above expression the numerator of argument of logarithm is the xy, the root of xy terms. These terms are nothing but products of distances from all the x filaments of conductor P to all the y filaments of the conductor Q. For each filament in conductor P there are y distances to filaments in conductor Q and there are x filaments in conductor P.

The xy terms are formed as a result of product of y distances for each of x filaments. The xyth root of the product of the xy distances is called the geometric mean distance between conductor P and Q. His termed as Dm or GMD and is called mutual GMD between the conductors.

The denominator of the above expression is the x2root of x2terms. There are x filaments and for each filament there are x terms consisting of r' (denoted by Daa' Dbb, etc) for that filament times the distances from that filament to every other filament in conductor P.

If we consider the distance Daa then it is the distance of the filament from itself. which is also denoted as r. This r' of a separate filament is called the self GMD of the filament. It is also called geometric mean radius GMR and identified as Ds. Thus the above expression now becomes

$$L_p = 2 \times 10^{-7} ln \left[\frac{D_m}{D_s}\right] H/m$$

Comparing this equation with the expression obtained for inductance of a single phase two wire line. The distance between solid conductors of single conductor line is substituted by the GMD between conductors of the composite conductor line. Similarly the GMR (r') of the single conductor is replaced by GMR of composite conductor .The composite conductors are made up of number of strands which are in parallel. The inductance of composite conductor Q is obtained in a similar manner. Thus the inductance of the line is,

$$L = L_p + L_Q$$

An Alternative Approach for Finding the Expression for Inductive Reactance:

For standard conductors generally the values for GMR are available. These tables are also useful for calculating inductive reactance as well as shunt capacitive reactance and resistance. The units used in these tables are inches, feet and miles as used by the industries in the United States. Normally value of inductive reactance is required rather than the inductance. The inductive reactance of one conductor of a single phase two conductor is given by,

$$X_L = 2\pi f L = 2 \times 10^{-7} ln\left(\frac{D_m}{D_s}\right) \times 2\pi f$$

$$= 4\pi f \times 10^{-7} ln\left(\frac{D_m}{D_s}\right)$$

$$X_L = 2.022 \times 10^{-7} f \ln\left(\frac{D_m}{D_s}\right)$$

The GMR found from the tables is an equivalent D, which takes into account skin effect which affects the value of inductance appreciably. Expanding the above equation we have,

$$X_L = 2.022 \times 10^{-3} f \ln\left(\frac{1}{D_s}\right) + 2.022 \times 10^{-3} f \ln D_m$$

Considering both Dm and D, to be expressed in feets, the first term in the equation is the inductive reactance of one conductor of a two conductor line having a distance of 1ft between them. Hence the first term is called inductive reactance at 1ft spacing Xa.

It depends upon the GMR of the conductor and frequency. The second term is called inductive reactance spacing factor Xd. This term is independent of type of. conductor and depends only on frequency and spacing. When Dm = 1, the spacing factor is equal to zero. When it is less than 1, the spacing factor value is negative.

The inductive reactance at 1ft spacing value is available from the table. To that value.uhe value of inductive reactance spacing factor is added which is also available at desired line frequency.

9. Derive an expression for flux linkages in parallel current carrying conductors. Flux Linkages in Parallel Current Carrying Conductors:

Consider a group' of parallel conductors A, B, C etc as shown in the Fig. 2.15. Each of these conductors carry current I_A, I_B, I_C etc. Consider the flux linkages with anyone conductor say A. There will be flux linkages with conductor A due to its own current. Also there will be flux linkages with this conductor due to mutual inductance effects. Flux linkages with conductor A due to its own current,

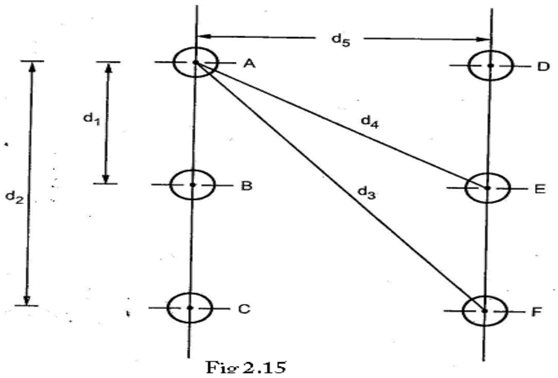


Fig 2.15

$$\Psi_{1A} = \frac{\mu_0 I_a}{2\pi}\left[\frac{1}{4} + \int_r^{\infty} \frac{dx}{x}\right]$$

Flux linkages with conductor A due to the current I_B, Flux linkages with conductor A due to the current I_C,

$$\Psi_{1C} = \frac{\mu_0 I_C}{2\pi}\left[\int_{d2}^{\infty} \frac{dx}{x}\right]$$

By adding all the above expressions we will get total flux linkages with conductor A.

$$Total\ flux\ linkages\ with\ conductor\ A = \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4} + \int_r^{\infty} \frac{dx}{x}\right] + \frac{\mu_0 I_B}{2\pi}\int_{d_1}^{\infty} \frac{dx}{x} + \frac{\mu_0 I_C}{2\pi}\int_{d_2}^{\infty} \frac{dx}{x}$$

In the similar way flux linkages with other conductors can be determined. This will form basis for finding inductance of any circuit.

11. Derive an expression for inductance of Three Phase Lines with Equilateral and Symmetrical Spacing. (NOV/2012)

Inductance of Three Phase Lines with Equilateral and Symmetrical Spacing:

Consider a three phase line consisting of three conductors a, band c as shown in the Fig. 2.16. These three conductors are equally spaced at the corners of an equilateral triangle having radius r. The flux linkages of conductor a are given by,

$$\Psi_a = 2\times10^{-7}\left(I_a ln\frac{1}{r'} + I_b ln\frac{1}{D} + I_c ln\frac{1}{D}\right)$$

If the currents are assumed to be balanced then

$$I_a + I_b + I_c = 0$$
$$\therefore \ I_a = -(I_b + I_c)$$
$$or\ (I_b + I_c) = -I_a$$

The above equation becomes,

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

The inductance of conductor a is given by,

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

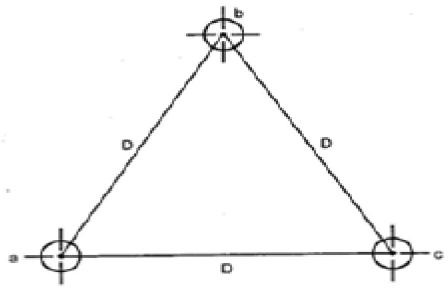


Fig 2.16

Because of symmetry, conductors band c will have same inductance as that of conductor a. Each phase consists of only one conductor. So the above equation gives inductance per phase of the three phase lines. For stranded conductor we write D, whereas for single conductor it is replaced by r'.

12. Derive an expression for inductance of Transmission Line with Unsymmetrical Spacing. (APRIL/2014)

Inductance of Transmission Line with Unsymmetrical Spacing:

Consider the same three conductors a, b, c having radius r but unsymmetrical spaced as shown in the Fig.2.17 Flux linkage of conductor a is given by

$$\Psi_a = 2\times10^{-7}\left[I_a ln\frac{1}{r'} + I_b ln\frac{1}{D_{ab}} + I_c ln\frac{1}{D_{ca}}\right]$$

Inductance of conductor a, L_a =

$$\frac{\Psi_a}{I_a} = 2\times10^{-7}\left[ln\frac{1}{r'} + \frac{I_b}{I_a} ln\frac{1}{D_{ab}} + \frac{I_c}{I_a} ln\frac{1}{D_{ca}}\right]$$

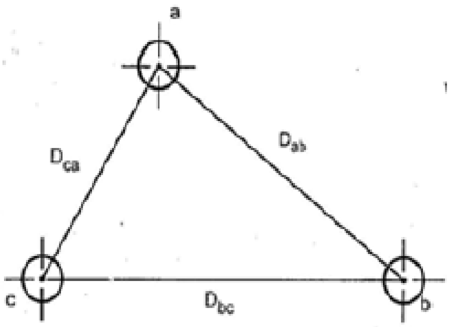


Fig 2.17

If all the three currents are assumed to be balanced with I_a as a reference phasor.

$$\overline{I_a} = I_a\angle 0°; \overline{I_b} = I_b\angle 240° = I_a\angle 240°; \overline{I_c} = I_c\angle 120° = I_a\angle 120°$$

$$\frac{I_b}{I_a} = 1\angle 240° = \cos 240° + j\sin 240° = -\frac{1}{2} - \frac{j\sqrt{3}}{2}$$

$$\frac{I_c}{I_a} = 1\angle 120° = \cos 120° + j\sin 120° = -\frac{1}{2} + \frac{j\sqrt{3}}{2}$$

Substituting this in equation for L_a,

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

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

Similarly we have,

$$\Psi_b = 2\times10^{-7}\left[I_a \ln\frac{1}{D_{ab}} + I_b \ln\frac{1}{r'} + I_c \ln\frac{1}{D_{bc}}\right]$$

$$L_b = 2\times10^{-7}\left[\ln\frac{1}{r'} + \frac{I_a}{I_b}\ln\frac{1}{D_{ab}} + \frac{I_c}{I_b}\ln\frac{1}{D_{bc}}\right]$$

$$L_b = 2\times10^{-7}\left[\ln\frac{1}{r'} + (1\angle-240°)\ln\frac{1}{D_{ab}} + (1\angle-120°)\ln\frac{1}{D_{bc}}\right]$$

$$= 2\times10^{-7}\left\{\ln\frac{1}{r'}\left[-\frac{1}{2}+j\frac{\sqrt{3}}{2}\right]\ln\frac{1}{D_{ab}} + \left[-\frac{1}{2}-j\frac{\sqrt{3}}{2}\right]\ln\frac{1}{D_{bc}}\right\}$$

$$= 2\times10^{-7}\left\{\ln\frac{1}{r'} + \ln\sqrt{D_{ab}D_{bc}} + j\sqrt{3}\ln\sqrt{\frac{D_{bc}}{D_{ab}}}\right\}$$

Also we have,

$$\Psi_c = 2\times10^{-7}\left[I_a \ln\frac{1}{D_{ca}} + I_b \ln\frac{1}{D_{bc}} + I_c \ln\frac{1}{r'}\right]$$

Which on simplifying gives,

$$\Psi_c = 2\times10^{-7}\left[\ln\frac{1}{r'} + \ln\sqrt{D_{ca}D_{bc}} + j\sqrt{3}\ln\sqrt{\frac{D_{ca}}{D_{bc}}}\right]$$

The inductances of the three phases are respectively as follows,

$$L_a = 2\times10^{-7}\left[\ln\frac{1}{r'} + \ln\sqrt{D_{ab}D_{ca}} + j\sqrt{3}\ln\sqrt{\frac{D_{ab}}{D_{ca}}}\right]$$

$$L_b = 2\times10^{-7}\left[\ln\frac{1}{r'} + \ln\sqrt{D_{ab}D_{bc}} + j\sqrt{3}\ln\sqrt{\frac{D_{bc}}{D_{ab}}}\right]$$

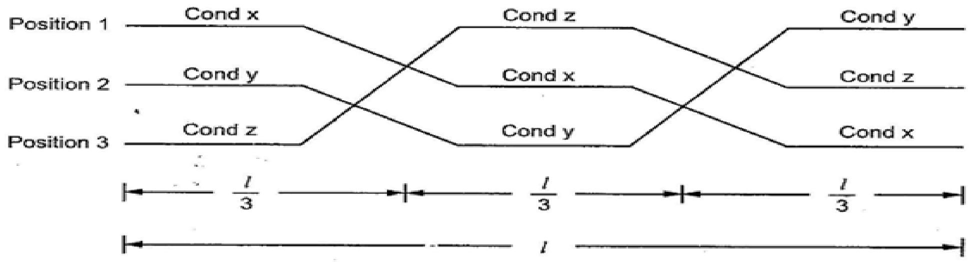
$$L_c = 2\times10^{-7}\left[\ln\frac{1}{r'} + \ln\sqrt{D_{ca}D_{bc}} + j\sqrt{3}\ln\sqrt{\frac{D_{ca}}{D_{bc}}}\right]$$

From the above expressions it can be seen that the individual phase inductance of a line which is unsymmetrically spaced is a complex number. The imaginary part in the expression for inductance represents exchange of energy between phases.

13. Derive an expression for inductance of Three phase Unsymmetrical spacing but transposed.

Inductance of Three Phase Line with Unsymmetrical Spacing but Transposed:

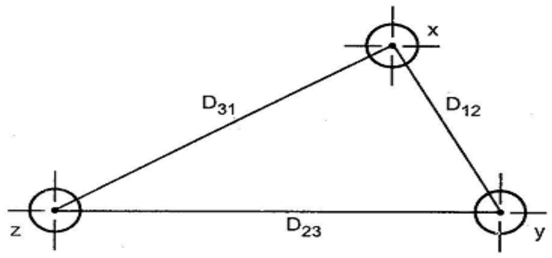
Now consider a three phase line having three conductors but not spaced equilaterally. The problem of finding the inductance in this case is difficult. The flux linkage and the corresponding inductance will not be same in each phase. Due to this different inductance per phase there is unbalance in the circuit though' the currents in each phases are balanced. The drops in the three phases due to these inductances are observed to be different. Thus at the receiving end we will not get the same voltage. In order to achieve balance under this case, transposition of transmission line is preferred after a certain fixed distance. This is shown in the Fig.



The positions of the conductors are exchanged at regular interval along the line so that each conductor occupies the original position of every other conductor over. an equal distance.

This exchange of conductor positions is called transposition. Thus balance in the three phase is restored. The Fig. shows complete transposition cycle. The conductors in the individual phases are denoted by x..y. and z where the positions are given by I, 2, and 3.

The same average inductance over the complete cycle is obtained due to the transposition. The average inductance of one conductor is obtained by finding the flux linkages of a conductor for each position that is occupied during a complete cycle of transposition. Then the average flux linkages are obtained.



Now let us find the flux linkages of conductor x which till in position 1 whereas conductor y and z are in positions 2 and 3 respectively.

$$\Psi_{x1} = 2 \times 10^{-7}\left(I_x ln\frac{1}{r'} + I_y ln\frac{1}{D_{12}} + I_z ln\frac{1}{D_{31}}\right)$$

Conductor x is in position 2 whereas conductor y and z are in positions 3 and 1 respectively.

$$\Psi_{x2} = 2 \times 10^{-7}\left(I_x ln\frac{1}{r'} + I_y ln\frac{1}{D_{23}} + I_z ln\frac{1}{D_{12}}\right)$$

Conductor x is in position 3 whereas conductor y and z are in positions 1 and 2 respectively.

$$\Psi_{x3} = 2 \times 10^{-7}\left(I_x ln\frac{1}{r'} + I_y ln\frac{1}{D_{31}} + I_z ln\frac{1}{D_{23}}\right)$$

The average value of flux linkage of conductor x is

$$\Psi_x = \frac{\Psi_{x1} + \Psi_{x2} + \Psi_{x3}}{3}$$

$$\Psi_x = \frac{2 \times 10^{-7}}{3}\left(3I_x ln\frac{1}{r'} + I_y ln\frac{1}{D_{12}D_{23}D_{31}} + I_z ln\frac{1}{D_{12}D_{23}D_{31}}\right)$$

$$\Psi_x = \frac{2 \times 10^{-7}}{3}\left(3I_x ln\frac{1}{r'} + (I_y + I_z) ln\frac{1}{D_{12}D_{23}D_{31}}\right)$$

But we have $I_x + I_y + I_z = 0$

$$\therefore \qquad I_y + I_z = -I_x$$

$$\Psi_x = \frac{2 \times 10^{-7}}{3}\left(3I_x ln\frac{1}{r'} - I_x ln\frac{1}{D_{12}D_{23}D_{31}}\right)$$

$$\Psi_x = 2 \times 10^{-7} I_x \ln\left[\frac{\sqrt[3]{D_{12}D_{23}D_{31}}}{r'}\right]$$

Thus the average inductance per phase is

$$L_x = 2 \times 10^{-7} \ln\left[\frac{\sqrt[3]{D_{12}D_{23}D_{31}}}{r'}\right]$$

$$L_x = 2 \times 10^{-7} \ln\left[\frac{D_{eq}}{r'}\right]$$

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

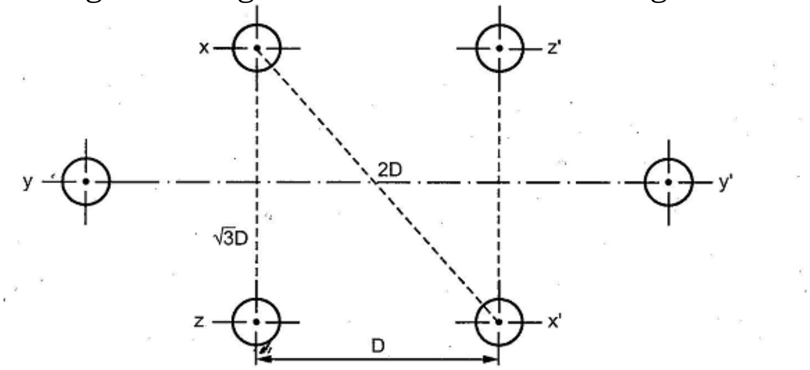
In modem power lines, transposition of lines is not done at regular intervals even though an exchange in conductor positions can be made at switching stations to balance the inductance per phase. The inequality in the phases of an untransposed line is small and neglected in many cases.

If the dissymmetry is neglected, the inductance of the untransposed line is the average value of the inductive reactance of one phase of the same line correctly transposed.

14. Derive an expression for inductance of a single phase two wire line.

Inductance of single phase two wire line:

Consider the three phase double circuit with the conductors placed at the vertices of a regular hexagon which is shown in the Fig.



Conductor x, y, z are forming one circuit whereas conductors x', y' and z' are forming another circuit. Let us find out flux linkage of conductor x due to currents in other phases.

$$\Psi_x = 2 \times 10^{-7}\left(I_x\left(ln\frac{1}{r'} + ln\frac{1}{2D}\right) + I_y\left(ln\frac{1}{D} + ln\frac{1}{\sqrt{3}D}\right) + I_z\left(ln\frac{1}{\sqrt{3}D} + ln\frac{1}{D}\right)\right)$$

$$\Psi_x = 2 \times 10^{-7}\left(I_x\left(ln\frac{1}{r'} + ln\frac{1}{2D}\right) + (I_y + I_z)\left(ln\frac{1}{D} + ln\frac{1}{\sqrt{3}D}\right)\right)$$

But we have $I_x + I_y + I_z = 0$

$$\therefore \qquad I_y + I_z = -I_x$$

$$\Psi_x = 2 \times 10^{-7}\left(I_x\left(ln\frac{1}{r'} + ln\frac{1}{2D}\right) + (-I_x)\left(ln\frac{1}{D} + ln\frac{1}{\sqrt{3}D}\right)\right)$$

$$\Psi_x = 2 \times 10^{-7}\left(I_x\left(ln\frac{1}{2Dr'}\right) + (-I_x)\left(ln\frac{1}{\sqrt{3}D^2}\right)\right)$$

$$\Psi_x = 2 \times 10^{-7}\left(I_x\left(ln\frac{\sqrt{3}D^2}{2Dr'}\right)\right)$$

$$\Psi_x = 2 \times 10^{-7}\left(I_x\left(ln\frac{\sqrt{3}D}{2r'}\right)\right)$$

$$L_x = \frac{\Psi_x}{I_x} = 2 \times 10^{-7} I_x ln\frac{\sqrt{3}D}{2r'} H/m$$

As the conductor are in parallel,

Inductance of each conductor=2Lx = 4 x 10-17ln(√3D/2r')H/m

15. Obtain the expression for the Inductance of Three Phase Double Circuit with Unsymmetrical Spacing but Transposed:

Inductance of Three Phase Double Circuit with Unsymmetrical Spacing but Transposed:

Consider three phase double circuit having conductors which are unsymmetrically spaced. The line is transposed so that each conductor occupies the position of other conductor after certain interval length or distance of transmission line.

The transposition cycle is as shown in the Fig. 2.23

Flux linkage of conductor x in position 1

$$\Psi_{x1} = 2\times10^{-7}\left(I_x\left(ln\frac{1}{r'}+ln\frac{1}{n}\right)+I_y\left(ln\frac{1}{D}+ln\frac{1}{m}\right)+I_z\left(ln\frac{1}{2D}+ln\frac{1}{h}\right)\right)$$

$$\Psi_{x2} = 2\times10^{-7}\left(I_x\left(ln\frac{1}{r'}+ln\frac{1}{h}\right)+I_y\left(ln\frac{1}{D}+ln\frac{1}{m}\right)+I_z\left(ln\frac{1}{D}+ln\frac{1}{m}\right)\right)$$

$$\Psi_{x3} = 2\times10^{-7}\left(I_x\left(ln\frac{1}{r'}+ln\frac{1}{n}\right)+I_y\left(ln\frac{1}{2D}+ln\frac{1}{h}\right)+I_z\left(ln\frac{1}{D}+ln\frac{1}{m}\right)\right)$$

We have,

$$\Psi_x = \frac{1}{3}(\Psi_{x1}+\Psi_{x2}+\Psi_{x3})$$

$$\Psi_x = \frac{2\times10^{-7}}{3}\left(3I_x ln\frac{1}{r'}+I_x\ln\left(\frac{1}{n}.\frac{1}{h}.\frac{1}{n}\right)+I_y\ln\frac{1}{2D^3}+I_y\ln\left(\frac{1}{m}.\frac{1}{m}.\frac{1}{h}\right)+I_z\ln\frac{1}{2D^3}+I_z\ln\left(\frac{1}{h}.\frac{1}{m}.\frac{1}{m}\right)\right)$$

$$=\frac{2\times10^{-7}}{3}\left(3I_x ln\frac{1}{r'}+I_x\ln\left(\frac{1}{n^2h}\right)+(I_y+I_z)\ln\frac{1}{2D^3}+(I_y+I_z)\ln\left(\frac{1}{m^2h}\right)\right)$$

$$As\ I_x+I_y+I_z=0 \qquad \therefore -(I_y+I_z)=I_x$$

$$=\frac{2\times10^{-7}}{3}\left(3I_x ln\frac{1}{r'}+I_x\ln\left(\frac{1}{n^2h}\right)-I_x\ln\frac{1}{2D^3}-I_x\ln\left(\frac{1}{m^2h}\right)\right)$$

$$=\frac{2\times10^{-7}}{3}I_x\left\{\ln\left(\frac{2D^3m^2h}{3n^2h}\right)\right\}$$

$$=\frac{2\times10^{-7}}{3}I_x\left\{\ln\frac{2^{1/3}Dm^{2/3}h^{1/3}}{r'n^{2/3}h^{1/3}}\right\}$$

$$L_x=\frac{\Psi_x}{I_x}=2\times10^{-7}\ln\left[2^{1/3}\left(\frac{D}{r'}\right)\left(\frac{m}{n}\right)^{2/3}\right]H/m$$

Inductance of each phase = ½ inductance per conductor

$$=\frac{1}{2}L_x$$

$$L_x=2\times10^{-7}\ln\left[2^{1/6}\left(\frac{D}{r'}\right)^{1/2}\left(\frac{m}{n}\right)^{1/3}\right]H/m$$

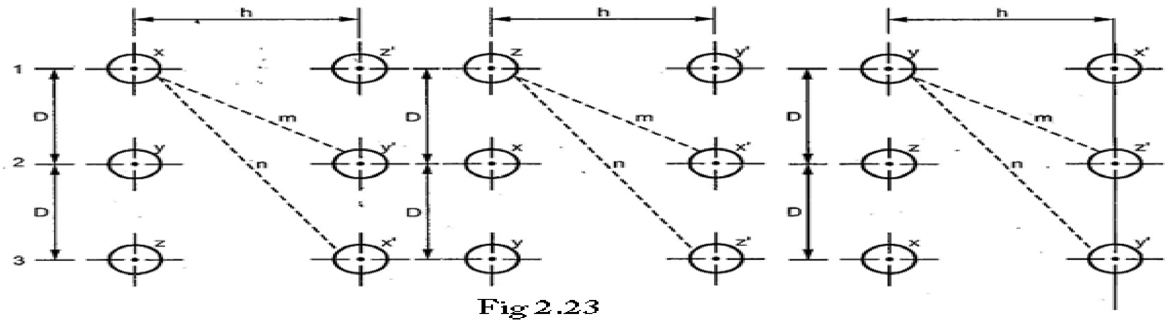


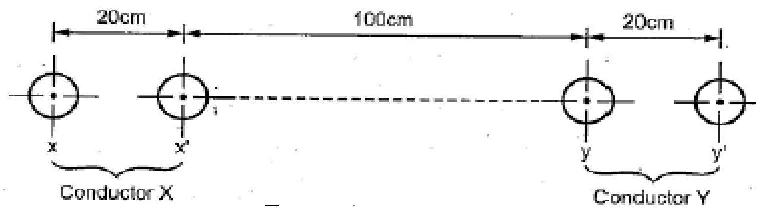
Fig 2.23

Problems related to Inductance of Three Phase Double Circuit

Problem 1: Calculate the loop inductance per km of a single phase transmission line consisting of two parallel conductor's 1.5 m apart and 1.5 cm in diameter. Calculate also the reactance of the transmission line if it is operating at a frequency of 50 Hz.

$$r' = GMR\ of\ the\ conductor$$
$$= 0.7788 \times \frac{diameter\ of\ conductor}{2}$$
$$= 0.7788 \times \frac{1.5 \times 10^{-2}}{2} = 5.841 \times 10^{-3} m$$
$$D = Distance\ between\ the\ conductors = 1.5\ m$$
$$L = 4 \times 10^{-7} \ln\frac{D}{r'} H/m\ of\ loop = 4 \times 10^{-4} \ln\frac{D}{r'} H/km\ of\ loop$$
$$L = 4 \times 10^{-7} \ln\left(\frac{1.5}{5.841 \times 10^{-3}}\right)$$
$$= 2.219327 \times 10^{-3}\ H/km$$
$$\therefore Inductance, L = 22.19327 \times 10^{-4}\ H/km$$
$$Inductive\ reactance, X_L = 2\pi f L = 2\pi \times 50 \times 22.19327 \times 10^{-4} = 0.69722\Omega$$

Problem 2: The Fig. 2.25 shows on arrangement of conductors for single phase supply, the current being equally divided between conductors. x and x' and between y and y'. If the diameter of each conductor is 8mm. Find the inductance per km of the line.



Solution: Distance between conductor x and x' = 20cm

Diameter of each conductor = 8mm

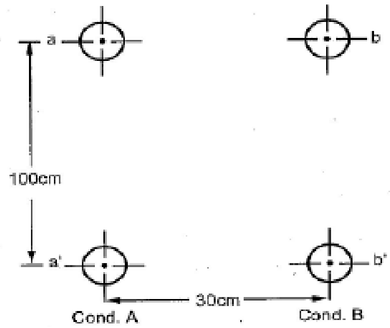
Radius of each conductor = 4mm

$$r' = 0.7788 \times 4 \times 10^{-3} = 3.1152 \times 10^{-3} m$$

$$\text{Loop inductance} = 4 \times 10^{-7} \ln\left[\frac{D_m}{D_s}\right] H/m\ of\ loop$$
$$D_m = \sqrt[4]{D_{xy'} D_{xy'} D_{yx'} D_{yx}}$$
$$= \sqrt[4]{(120)(140)(100)(120)}$$
$$= 119.15cm = 1.1915m$$
$$D_s = \sqrt[4]{D_{xx} D_{xx'} D_{x'x} D_{x'x'}}$$
$$= \sqrt[4]{(3.1152 \times 10^{-3})(20 \times 10^{-2})(20 \times 10^{-2})(3.1152 \times 10^{-3})}$$
$$= 0.02496m$$
$$\therefore \quad Loop\ inductance = 4 \times 10^{-4} \ln\left[\frac{1.1915}{0.02496}\right]$$
$$= 1.5462 \times 10^{-3}\ H/km = 1.5462\ mH/km$$

Problem 3:Two conductors of a single phase line, each of 1 cm diameter are arranged in a vertical plane with one conductor mounted 1m above the other. A second identical line is mounted at the same height as the first and spaced horizontally 30 cm apart from it. The upper and lower conductors are connected in parallel. Determine the inductance per km of the resulting double circuit.

Solution: The Fig. shows the arrangement of conductors. Diameter of each conductor = 1 cm. Radius of each conductor = 0.5 cm



$$r' = 0.7788 \times 0.5$$

$$= 0.3894\ cm = 3.894 \times 10^{-3} m$$

$$D_{ab} = 30cm = 0.3m$$

$$D_{aa'} = D_{a'a} = 100cm = 1m$$

$$D_{bb'} = D_{b'b} = 100cm = 1m$$

$$D_{ab} = D_{ba} = D_{a'b'} = D_{b'a'}$$

$$= 30cm = 0.03m$$

$$D_{ab'} = D_{ba'} = \sqrt{(100)^2 + (30)^2} = 104.40\ cm = 1.0440\ m$$

$$Loop\ inductance = 4 \times 10^{-7} \ln\left(\frac{D_m}{D_s}\right) H/m$$

$$Loop\ inductance = 4 \times 10^{-4} \ln\left(\frac{D_m}{D_s}\right) H/km$$

$$D_m = \sqrt[4]{D_{ab} D_{ab'} D_{ba'} D_{ba}} = \sqrt[4]{(0.3)(1.0440)(1.0440)(0.3)}$$

$$= 0.5596\ m$$

$$D_s = \sqrt[4]{D_{aa} D_{aa'} D_{a'a} D_{a'a'}} = \sqrt[4]{(3.894 \times 10^{-3})(1)(1)(3.894 \times 10^{-3})}$$

$$= 0.0624\ m$$

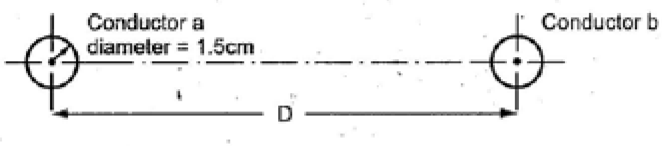
$$Loop\ inductance = 4 \times 10^{-4} \ln\left(\frac{0.5596}{0.0624}\right)$$

$$= 3.5871 \times 10^{-3}\ H/km$$

$$Loop\ inductance/km = 3.5871\ \text{mH}$$

Problem 4: A single phase overhead line 25 km long is to be constructed of conductor 1.5 cm diameter. Calculate the maximum spacing between the conductors in order that the loop inductance of conductor is .not mote than 0.08 H. Solution: Length of transmission Line = 25 km = 25000 m

$$Loop\ inductance\ per\ meter\ of\ transmission\ line = \frac{0.08}{25000} = 3.2 \times 10^{-6} H$$



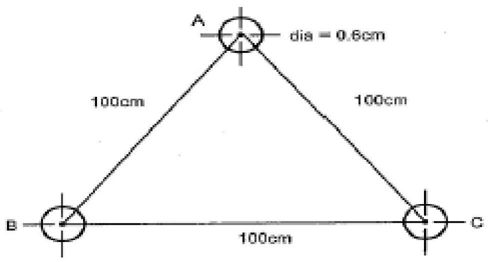
$$Diameter\ of\ conductor = 1.5cm$$
$$Radius\ of\ conductor = 0.75\ cm$$
$$r' = 0.7788 \times Radius\ of\ conductor$$
$$= 0.7788 \times 0.75 = 0.5841\ cm$$
$$= 5.841 \times 10^{-3} m$$
$$Loop\ inductance\ per\ meter\ of\ the\ line = 4\ \times 10^{-7} \left(\frac{D}{r'}\right)$$
$$3.2\ \times 10^{-6} = 4\ \times 10^{-7} \left(\frac{D}{r'}\right)$$
$$3.2\ \times 10^{-6} = 4\ \times 10^{-7} ln \left(\frac{D}{5.841 \times 10^{-3}}\right)$$
$$3.2\ \times 10^{-6} = 4\ \times 10^{-7}\ ln \left(\frac{D}{5.841 \times 10^{-3}}\right)$$
$$8 = \ ln \left(\frac{D}{5.841 \times 10^{-3}}\right)$$

$D = 17.41\ m$

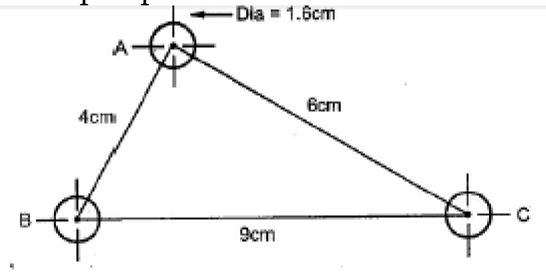
Problem 5: A three phase transmission line 100 km long has its conductors of 0.6 cm diameter spaced at the corners of an equilateral triangle of 100 cm side. The arrangement is as shown in the Fig. 2.28. Find the inductance per phase of the system.

Solution:

$$D = Distance\ between\ the\ conductors = 100\ cm = 1m$$
$$Radius\ of\ conductor = \frac{0.6}{2} = 0.3cm = \ 0.003m$$
$$r' = 0.7788r = 0.7788 \times 0.003 = 2.3364\ \times 10^{-3} m$$
$$Inductance\ per\ phase, L_A = 2 \times 10^{-4} \ln \left(\frac{D}{r'}\right) H/km$$
$$L_A = 2 \times 10^{-4} \ln \left(\frac{1}{2.3364 \times 10^{-3}}\right)$$
$$L_A = 1.2118 \times 10^{-3}\ H/km$$
$$For\ 100\ km\ long\ transmission\ line,$$
$$L_A = 1.2118 \times 10^{-3} \times 100 = 0.12118H$$



Problem 6: A three phase transmission line has conductor diameter of 1.6 cm each, the conductors being spaced as shown in the Fig. 2.29. The line is carrying balanced load and it is transposed. Find the inductance of the line per km per phase



$$Radius\ of\ conductor = \frac{1.6}{2} = 0.8cm = 0.008m$$

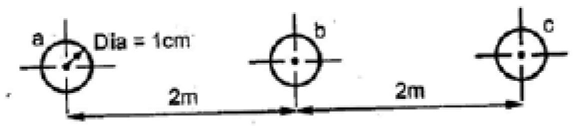
$$r' = 0.7788 \times 0.008 = 6.2304 \times 10^{-3}m$$

$$D_{AB} = 4cm = 0.04m$$
$$D_{BC} = 9cm = 0.09m$$
$$D_{CA} = 6cm = 0.06m$$

Inductance per phase,

$$L_A = 2 \times 10^{-7} \ln\left[\frac{D_{eq}}{r'}\right] H/m$$

Problem 7 :A 3 phase, 3 wire system consisting of lcm diameter conductors spaced 2m apart in a horizontal plane as shown in the Fig. supplies a balanced load. Calculate the inductance per km of each conductor.



Solution:

$$D_{ab} = 2m$$
$$D_{bc} = 2m$$
$$D_{ac} = 4m$$
$$Radius\ of\ conductor = 1cm/2 = 0.5cm = 0.005m$$
$$r' = 0.7788 \times 0.005 = 3.894 \times 10^{3}m$$
$$D_{eq} = \sqrt[3]{D_{ab}D_{bc}D_{ca}}$$
$$= \sqrt[3]{(2)(2)(4)}$$
$$= \sqrt[3]{16} = 2.5198\ m$$

Inductance,

$$L_a = 2 \times 10^{-7} \ln\left(\frac{D_{eq}}{r'}\right) H/m$$
$$= 2 \times 10^{-4} \ln\left(\frac{D_{eq}}{r'}\right)$$

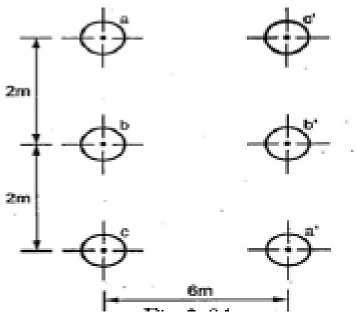
$$= 2 \times 10^{-4} \ln\left(\frac{2.5198}{3.894 \times 10^{-3}}\right)$$

$$L_a = 1.2944\ mH$$

Problem 8: The Fig. 2.31 shows the spacing of a double circuit 3 phase overhead line. The conductor radius is 1.5 cm and line is transposed. Find the inductance per phase per kilometer

Solution:

$r' = 0.7788 \times 1.5 = 1.1682\ cm = 0.011682\ m$



$$D_{ab'} = \sqrt{6^2 + 2^2} = 6.3245m = D_{ba'}$$

$$D_{aa'} = \sqrt{6^2 + 4^2} = 7.2111m$$

$D_s = \sqrt[3]{D_{s1}D_{s2}D_{s3}}$ D_{s1}, D_{s1}, D_{s1} *represent self* G.M.D in position 1,2 and 3 respectively

$$D_{s1} = \sqrt[4]{D_{aa}D_{aa'}D_{b'b}D_{bb'}} = \sqrt[4]{(0.011682)(7.2111)(7.2111)(0.011682)} = 0.2902m = D_{s3}$$

$$D_{s2} = \sqrt[4]{D_{bb}D_{bb'}D_{b'b}D_{bb'}} = \sqrt[4]{(0.011682)(6)(6)(0.011682)} = 0.2647m$$

$$D_s = \sqrt[3]{D_{s1}D_{s2}D_{s3}} = \sqrt[3]{(0.2902)(0.2647)(0.2902)} = 0.1493m$$

Equivalent mutual GMD,

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

$$D_{AB} = \sqrt[4]{D_{ab}D_{ab'}D_{ba}D_{ba'}} = \sqrt[4]{(2)(6.3245)(2)(6.3245)} = 3.5565\ m$$

$$D_{BC} = \sqrt[4]{D_{bc}D_{bc'}D_{cb}D_{cb'}} = \sqrt[4]{(2)(6.3245)(2)(6.3245)} = 3.5565\ m$$

$$D_{CA} = \sqrt[4]{D_{ca}D_{ca'}D_{ac}D_{ac'}} = \sqrt[4]{(4)(6)(4)(6)} = 4.8989\ m$$

$$D_m = \sqrt[3]{(3.5565)(3.5565)(4.8989)} = 3.9571\ m$$

$$Inductance\ per\ phase\ m = 2 \times 10^{-7} \ln\frac{D_m}{D_s}$$

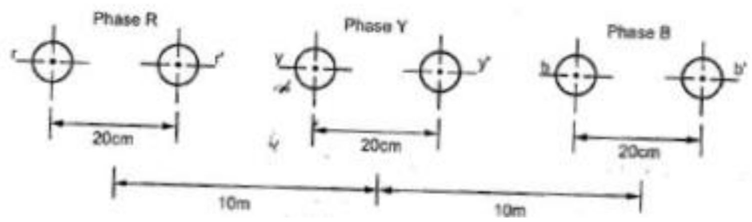
$$= 2 \times 10^{-4} \ln\frac{D_m}{D_s} H/km \ = 2 \times 10^{-4} \ln\frac{3.9571}{0.1493}$$

$$= 6.5546 \times 10^{-4}\ H/m$$

$\therefore\ Inductance\ per\ phase\ per\ km = 0.6554\ mH$

Problem.9 : Find the inductance per phase per km length of the system of conductors shown in the Fig. 2.32. Self GMD of conductors is a.80 cm. The line is transposed

. **Solution:** Self GMD = 0.80 cm = 0.008m



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

$$D_{s1}, D_{s2}, D_{s3} \text{ represent self} - GMD \text{ in postion 1,2 and 3 respectively}$$

$$D_{s1} = \sqrt[4]{D_{rr}D_{rr'}D_{r'r}D_{r'r'}} = \sqrt[4]{(0.008)(0.2)(0.2)(0.008)} = 0.04m = D_{s2} = D_{s3}$$

As the distance between rr' is the same in all the three positions

$$D_s = \sqrt[3]{(0.04)(0.04)(0.04)} = 0.04m$$

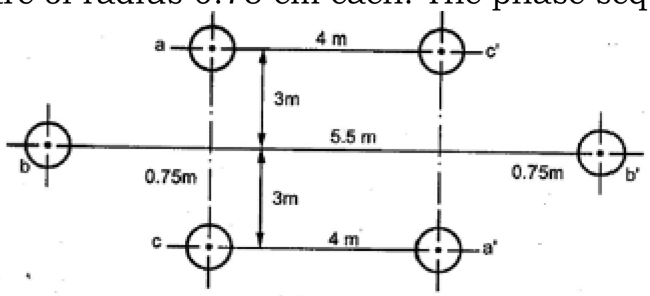
$$D_m = \sqrt[3]{D_{RY}D_{YB}D_{BR}}$$

$$D_{RY} = \sqrt[4]{D_{ry}D_{ry'}D_{yr}D_{yr'}} = \sqrt[4]{(10)(10.2)(10)(9.8)} = 9.9989m = D_{YB} = 10m$$

$$D_{BR} = \sqrt[4]{D_{rb}D_{rb'}D_{br}D_{br'}} = \sqrt[4]{(20)(20.2)(20)(19.8)} = 19.99m = 20m$$

$$D_m = \sqrt[3]{(10)(10)(20)}\ 12.59m$$

Problem 10 : Find the inductance per phase per km of double circuit 3 phase lint system shown in the Fig: 2.33. The conductors are transposed and are of radius 0.75 cm each. The phase sequence is ABC.



Solution:

$$GMR \text{ of each conductor} = 0.7788 \times 0.75 \times 10^{-2} = 5.841 \times 10^{-3} m$$

$$D_{ab} = \sqrt{3^2 + 0.75^2} = 3.0923\ m$$

$$D_{ab'} = \sqrt{3^2 + 4.75^2} = 5.618\ m = D_{ba'}$$

$$D_{aa'} = \sqrt{6^2 + 4^2} = 7.2111\ m = D_{cc'}$$

D_s is equivalent GMD of one phase which is given by

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

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

$$= \sqrt[4]{(5.841 \times 10^{-3})(7.2111)(7.2111)(5.841 \times 10^{-3})}$$

$$= 0.2052m$$

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

$$= \sqrt[4]{(5.841 \times 10^{-3})(5.5)(5.5)(5.841 \times 10^{-3})}$$

$$= 0.1972m$$

$$D_{s3} = \sqrt[4]{D_{cc}D_{cc'}D_{c'c}D_{c'c'}}$$

$$= \sqrt[4]{5.841 \times 10^{-3})(7.2111)(7.2111)(5.841 \times 10^{-3})}$$

$$= 0.2052m$$

$$D_S = \sqrt[3]{D_{s1}D_{s2}D_{s3}} = \sqrt[3]{(0.2052)(0.1792)(0.2052)} = 0.1961m$$

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

$$D_{AB} = \sqrt[4]{D_{ab}D_{ab'}D_{ba}D_{ba'}} = \sqrt[4]{(3.0923)(5.6180)(3.023)(5.6180)}$$

$$= 4.1680\ m = D_{BC}$$

$$D_{CA} = \sqrt[4]{D_{ac}D_{ac'}D_{ca}D_{ca'}} = \sqrt[4]{(6)(4)(6)(4)} = 4.8989m$$

$$D_m = \sqrt[4]{(4.1680)(4.1680)(4.8989)} = 4.3986$$

$$Inductance\ per\ phase\ per\ km = 2 \times 10^{-4} \ln\frac{D_m}{D_s} = 2 \times 10^{-4} \ln\frac{4.3986}{0.1961} = 6.43 \times 10^{-4}$$

$$= 0.6436\ mH$$

15. Obtain the expression for capacitance of transmission Line:

Capacitance of Transmission Line:

Due to the potential difference between the conductors we have to take into account the capacitance of transmission line. The capacitance causes the line to be charged similar to the plates of a capacitor when potential difference is applied to it.

The capacitance between the conductors is the charge per unit of potential difference. Between the parallel conductors, the capacitance is constant which depends on size and spacing of conductors. If the power transmission line is having the length of 80km, the effect of capacitance is assumed to be negligible and is not taken into consideration. But with increasing length of transmission line along with high voltage, the effect of capacitance becomes prominent and important in analysis. When an alternating voltage is impressed on a transmission line, it causes charge on the conductors at any point to increase and decrease with instantaneous change in value of voltage between the conductors.

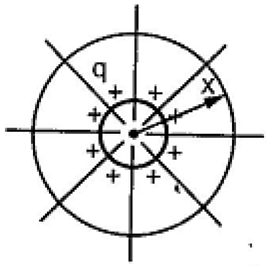
Due to alternate charging and discharging of line, current starts flowing in the line. This current is known as charging current. This current flows even when the line is open circuited. The voltage drop along the line is affected. It also affects the efficiency and power factor of the line. Stability of the system is also affected because of this.

2.22 Electric Field of a Long Straight Conductor:

Before we proceed for the concept of Electric field let us first see what do you mean by electrical potential. Electrical potential at a point due to a charge is the amount of work done in bringing a unit positive charge from infinity to that point. The concept of electrical potential is important for the evaluation of the capacitance.

While considering the inductance, magnetic field is important. Similarly while working with capacitance, electric field plays important role.

Lines of electric flux originate on the positive charges of one conductor and terminate on the negative charges of other conductor. The total electric flux emanating from a conductor is numerically equal to the number of coulombs of charge on the conductor. Electric flux density is the electric flux per square meter and is measured in coulombs per square meter. Consider a long, straight cylindrical conductor placed in uniform medium such as air as shown in the Fig. It has uniform charge along its entire length. It is isolated from other charges so that the charge is uniformly distributed around the periphery. The flux lines are radial. electric flux density at x meters from the conductor can be obtained by assuming a cylindrical surface concentric with the conductor and x meters in radius.



As all the parts of the surface are at the same distance from the conductor having uniformly distributed charge, the cylindrical surface is a surface of equipotential and the electric flux density on the surface is equal to the flux leaving the conductor per meter of length divided by the area of the surface in an axial length of 1 m Electric flux density,

$$D = \frac{q}{2\pi x} c/m^2$$

Here q is the charge on the conductor and x is the distance from the conductor to .the point where it is required to find field intensity. If the field density is divided by the permittivity of the medium then we get the field intensity.

$$Electric\ field\ intensity, E = \frac{D}{\varepsilon} = \frac{q}{2\pi\varepsilon x}$$

$$Permittivity, \varepsilon = \varepsilon_0\varepsilon_r \quad where$$

$$\varepsilon_0 = Permittivity\ of\ free\ space = 8.85 \times 10^{-12}\ F/m$$

$$\varepsilon_r = Relative\ permittivity$$

As x approaches infinity, the value of E approaches zero. Therefore the potential difference between conductor and neutral plane at infinity distance where .E and potential is zero, is given by,

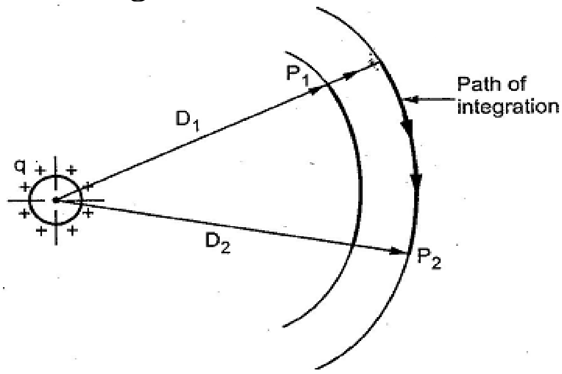
$$V_A = \int_r^{\infty} \frac{Q_A}{2\pi\varepsilon_0 x} dx = \frac{Q_A}{2\pi\varepsilon_0} \int_r^{\infty} \frac{dx}{x}$$

Potential Difference between Two Points due to a Charge:

The potential difference between any two points is nothing but the work done in joules per coulomb required to move a coulomb of charge between the two points.

The force on a charge in the field is measured by electric field intensity which is equal to the force in newtons per coulomb on a coulomb of charge at the point considered and is measured in volts per meter.

Consider a long straight wire carrying positive charge of q c/m as shown in the Fig.



Consider two points P1 and P2 located at a distances of D1 and D2 from center of wire. There is positive charge on wire which will repel when a positive charge is placed in the field. If we want to move charge from point P2 to P1 then work must be done on positive charge. Here P1 is at higher potential than P2 If the charge moves from P1 to P2 it expends energy which is nothing but voltage drop from P1 to P2The path followed does not affect the potential difference. In order to find the voltage drop from P1 to P2 is to obtain the voltage between equipotential surfaces passing through P1 and P2

The voltage drop between P_1 and P_2 is

$$V_{12} = \int_{D_1}^{D_2} E.dx = \int_{D_1}^{D_2} \frac{q}{2\pi\varepsilon x} dx = \frac{q}{2\pi\varepsilon} \int_{D_1}^{D_2} \frac{dx}{x} = \frac{q}{2\pi\varepsilon} \ln\left[\frac{D_2}{D_1}\right]$$

The voltage drop between two points may be either positive or negative depending upon the charge causing the potential difference is positive or negative. It also depends upon whether the voltage drop is computed from a point near the conductor to a point far away or vice versa.

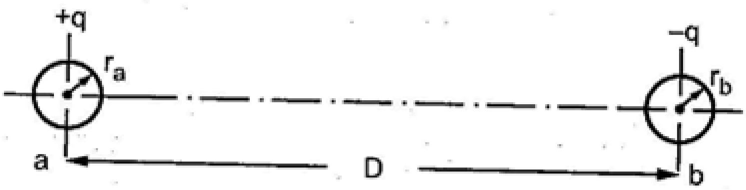
16. Obtain the expression for capacitance of single phase line:

Capacitance of Single Phase Line:

Capacitance between the two conductors of a two wire line is the charge on he conductors per unit of potential difference between them. Capacitance of the line per unit length is given by'

$$C = \frac{q}{v} F/m$$

The capacitance of single phase line is obtained by substituting in above equation v in terms of q. Consider a single phase overhead transmission line consisting of two conductors 'a' and 'b' which are separated by a distance of D in air as shown in the Fig. The charges on each conductors are respectively +q and -q coulombs per meter length .



The voltage Vab between the two conductors can be obtained by finding the potential difference between the two conductors of the line. Firstly let us find the voltage drop due to charge q on conductor a and then finding voltage drop due to charge -q on conductor b. Then by using principle of superposition the voltage drop between conductor a and b is obtained by adding the voltage drops caused by each charge alone.The voltage drop Vab is therefore given by

$$V_{ab} = V_{ab}\ due\ to + q + V_{ab}\ due\ to - q$$

$$V_{ab} = \left(\frac{q}{2\pi\varepsilon}\right)\ln\frac{D}{r_a} + \left(\frac{-q}{2\pi\varepsilon}\right)\ln\frac{r_b}{D}$$

$$= \left(\frac{q}{2\pi\varepsilon}\right)\left[\ln\frac{D}{r_a} - \ln\frac{r_b}{D}\right]$$

$$V_{ab} = \left(\frac{q}{2\pi\varepsilon}\right)\ln\left(\frac{D^2}{r_a r_b}\right)\ volts$$

The capacitance between the conductors is given by

$$C_{ab} = \frac{q}{V_{ab}} = \frac{2\pi\varepsilon}{\ln\left(\frac{D^2}{r_a r_b}\right)} F/m$$

We take

$$r_a = r_b = r$$

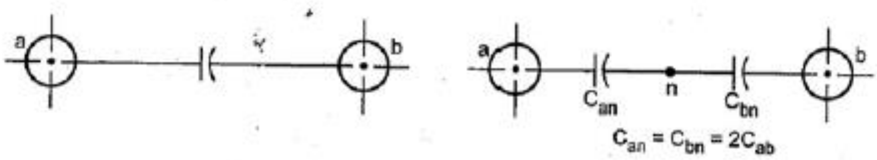
Then

$$C_{ab} = \frac{2\pi\varepsilon}{\ln(D^2/r^2)} = \frac{\pi\varepsilon}{\ln(D/r)} F/m$$

If it is required to find the capacitance between one of the conductors and the neutral point then it is given by,

$$C_n = C_{an} = C_{bn} = \frac{2\pi\varepsilon}{\ln(D/r)}$$

The idea of capacitance to neutral is shown in the Fig.



(a) Representation of line to line capacitance

(b) Representation of line to neutral capacitance

The equations derived so far related to the capacitance are based on the assumption of uniform charge distribution over the surface of the conductor. In presence of other charges, the distribution will not be uniform and the equations which. are derived will not give accurate results. However the non uniformity of charge distribution can be neglected in case of overhead lines as only 0.010% of error is caused for a close spacing of ratio of D/r = 50.

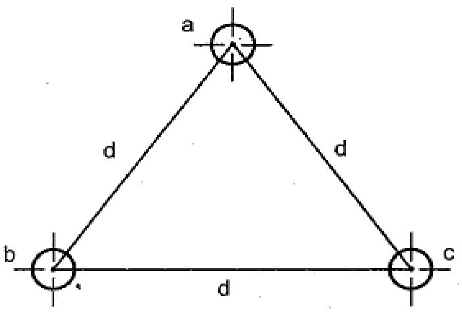
If instead of a solid round conductor, we have a stranded conductor then the' above equation will produce error slightly. The error will be small as only the field very close to the surface of the conductor is affected.' The electric flux at the surface of stranded conductor is not the same as the field at the surface of cylindrical conductor. The outside radius of conductor is used for evaluating capacitance.

If we are having the value of Can then capacitive reactance can be easily obtained. Permittivity of free air taken as unity.

$$Capacitiv\ reactance, X_c = \frac{1}{2\pi f C} = \frac{2.862}{f} \times 10^9 \ln\frac{D}{r} \Omega m$$

17. Obtain the expression for capacitance of a three phase line with equilateral spacing.

Capacitance of a Three Phase Line with Equilateral Spacing:



Consider the three conductors a, band c of 3 phase overhead transmission line having the charges qa, qb and qc respectively as shown in Fig. 2.38. Let the conductors be separated from each other by a distance of d from each other and placed on the vertices of equilateral triangle.

The radius of each conductor is say r. The voltage Vab of the three phase line due to only charges on conductors a and b is given by,

$$V_{ab} = \frac{1}{2\pi\varepsilon}\left(q_a \ln\frac{d}{r} + q_b \ln\frac{r}{d}\right)$$

Voltage Vab due to only charge qc is zero as uniform charge distribution over the surface of the conductor is equivalent to a concentrated charge at the center of conductor.

$$V_{ab} = \frac{q_c}{2\pi\varepsilon} \ln\frac{d}{d}$$

Considering all the three charges in writing the voltage equation we have,

$$V_{ab} = \frac{1}{2\pi\varepsilon}\left[q_a \ln\frac{d}{r} + q_b \ln\frac{r}{d} + Q_c \ln\frac{d}{d}\right]$$

Similarly

$$V_{ac} = \frac{1}{2\pi\varepsilon}\left[q_a \ln\frac{d}{r} + q_b \ln\frac{d}{d} + Q_c \ln\frac{r}{d}\right]$$

Adding above equations

$$V_{ab} + V_{ac} = \frac{1}{2\pi\varepsilon}\left[2q_a \ln\frac{d}{r} + (q_b + q_c) \ln\frac{r}{d}\right]$$

The voltages are sinusoidal and expressed as the phasors. In absence of other charges in the vicinity the sum of the charges is zero i.e.

$$q_a + q_b + q_c = 0$$

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

$$V_{ab} + V_{ac} = \frac{1}{2\pi\varepsilon}\left[2q_a \ln\frac{d}{r} - q_a \ln\frac{r}{d}\right] = \frac{1}{2\pi\varepsilon}\left[2q_a \ln\frac{d}{r} + q_a \ln\frac{d}{r}\right] = \frac{3q_a}{2\pi\varepsilon}\ln\frac{d}{r}$$

The fig 2.39 shows phasor diagram of balanced voltages of three phase line

$$V_{ab} = \sqrt{3}V_{an}\angle 30 = \sqrt{3}V_{an}[0.866 + j0.5]$$

$$V_{ac} = -V_{ca} = \sqrt{3}V_{an}\angle -30 = \sqrt{3}V_{an}[0.866 - j0.5]$$

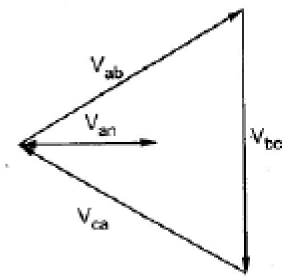
Adding above equations we get,

$$V_{ab} = V_{ac} = 3V_{an}$$

$$3V_{an} = \frac{3q_a}{2\pi\varepsilon}\ln\frac{d}{r}$$

$$\therefore\ V_{an} = \frac{q_a}{2\pi\varepsilon}\ln\frac{d}{r}$$

$$C_{an} = \frac{q_a}{V_{an}} = \frac{2\pi\varepsilon}{\ln\frac{d}{r}} F/m$$



It can be seen that capacitance to neutral for single phase and equilaterally spaced three phase lines is same. The current associated with capacitance of a transmission line is termed as charging current. In case of single phase circuits, the charging current is the product of line to line voltage and line to line susceptance.

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

In case of three phase circuits, the charging current is found by product of voltage to neutral and capacitive susceptance to neutral. The charging current obtained is for one phase. The current in any phase is given by,

$I_c = j\omega C_n V_{an}$

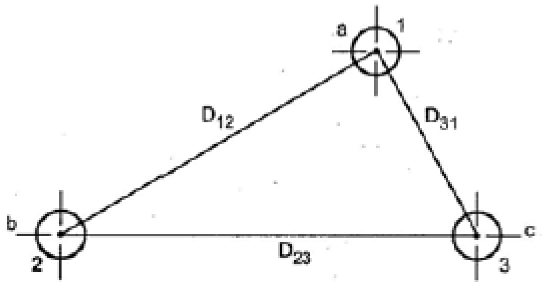
The charging current is not same everywhere as the rms voltage along line varies. For obtaining the charging current the value of voltage used is that for which the line is design which may not be actual voltage at either generating station or a load.

18. Obtain the expression for capacitance of a three phase line with unsymmetrical spacing. (APRIL/2012)

Capacitance of a Three Phase Line with Unsymmetrical Spacing:

The calculation of capacitance in case of conductors in three phase system which are not equally spaced is difficult. If the line is untransposed the capacitances of each phase to neutral is not same.

In case of transposed line the average capacitance of each line to neutral over a transposition cycle is same as the average capacitance to neutral of any other conductor occupies the same position of every other conductor after equal The effect of unsymmetry between the lines is small and calculations are It by considering transposition of lines. fig; shows three phase Iine with unsymmetrical spacing. The radius of each conductor is r.



When phase 'a' is in position 1, 'b' in position 2 and 'c' is in position 3.

$$V_{ab_1} = \frac{1}{2\pi\varepsilon}\left(q_a \ln\frac{D_{12}}{r} + q_b \ln\frac{r}{D_{12}} + q_c \ln\frac{D_{23}}{D_{31}}\right)$$

When phase 'a' is in position 2, 'b' in position 3 and 'c' is in position 1.

$$V_{ab_2} = \frac{1}{2\pi\varepsilon}\left(q_a \ln\frac{D_{23}}{r} + q_b \ln\frac{r}{D_{23}} + q_c \ln\frac{D_{31}}{D_{12}}\right)$$

Phase line with unsymmetrical spacing. The radius of each conductor is r.

When phase 'a' is in position 3, 'b' in position 1 and 'c' in position 2

$$V_{ab_3} = \frac{1}{2\pi\varepsilon}\left(q_a \ln\frac{D_{31}}{r} + q_b \ln\frac{r}{D_{31}} + q_c \ln\frac{D_{12}}{D_{23}}\right)$$

Average voltage between conductors 'a' and 'b' is given by

$$V_{ab} = \frac{V_{ab_1} + V_{ab_2} + V_{ab_3}}{3} = \frac{1}{6\pi\varepsilon}\left(q_a \ln\frac{D_{12}D_{23}D_{31}}{r^3} + q_b \ln\frac{r^3}{D_{12}D_{23}D_{31}} + q_c \ln\frac{D_{23}D_{31}D_{12}}{D_{31}D_{12}D_{23}}\right)$$

$$= \frac{1}{6\pi\varepsilon}\left(q_a \ln\frac{D_{12}D_{23}D_{31}}{r^3} + q_b \ln\frac{r^3}{D_{12}D_{23}D_{31}}\right)$$

Let

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

$$= \frac{1}{2\pi\varepsilon}\left(q_a \ln\frac{D_{eq}}{r} + q_b \ln\frac{r}{D_{eq}}\right)$$

Similarly average voltage drop between a and c is given by,

$$V_{ac} = \frac{1}{2\pi\varepsilon}\left(q_a \ln\frac{D_{eq}}{r} + q_c \ln\frac{r}{D_{eq}}\right)$$

We have, $V_{ab} + V_{ac} = 3V_{an}$

$$3V_{an} = \frac{1}{2\pi\varepsilon}\left(2q_a \ln\frac{D_{eq}}{r} + q_b \ln\frac{r}{D_{eq}} + q_c \ln\frac{r}{D_{eq}}\right)$$

For balanced circuit $(q_a + q_b + q_c) = 0$

$$3V_{an} = \frac{1}{2\pi\varepsilon}\left(3q_a \ln\frac{D_{eq}}{r}\right)$$

$$V_{an} = \frac{1}{2\pi\varepsilon}\left(q_a \ln\frac{D_{eq}}{r}\right)$$

$$C_{an} = \frac{q_{an}}{V_{an}} = \frac{2\pi\varepsilon}{\ln\frac{D_{eq}}{r}} F/m$$

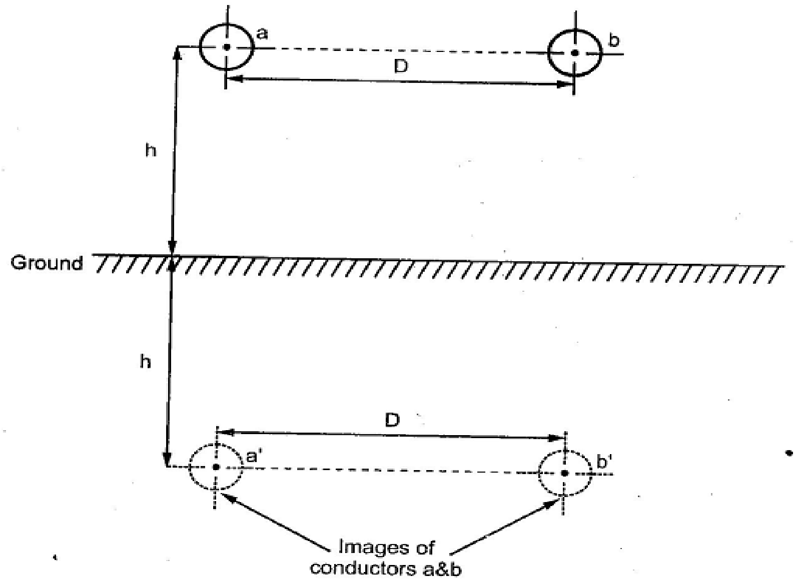
19. Write a note on the effect of earth on capacitance of transmission Line.

Effect of Earth on Capacitance of Transmission Line:

The capacitance of transmission line is affected by the presence of earth. Because of the earth Electrical field of a line is reduced. If we assume that the earth is a perfect r in the form of a horizontal plane of infinite extent, we realize that the field of charged conductors above the earth is not the same as it would be if potential surface of earth were not present.

The method of images is used while considering this type of problems. For this a single phase line having 2 conductors as shown in the Fig. A fictitious conductor is placed below each conductor of the same size and shape as overhead conductor lying directly below the original conductor at a distance equal to twice the distance of the conductor above the plane of ground.

If the earth is and a charge equal and opposite to that an over head conductor is assumed fictitious conductor, the plane midway between conductor and its image is an equipotential surface and occupies the same position as the equipotential surface earth this of s fictitious conductor is called image conductor having the charge opposite to overhead conductor.



The voltage V_{ab} is given as,

$$V_{ab} = \frac{1}{2\pi\varepsilon}\left(q_a \ln\frac{D}{r} + q_c \ln\frac{r}{D}\right) + \frac{1}{2\pi\varepsilon}\left(-q_a \ln\frac{\sqrt{D^2+4h^2}}{2h} - q_b \ln\frac{2h}{\sqrt{D^2+4h^2}}\right)$$

$$= \frac{1}{2\pi\varepsilon}\left(q_a \ln\frac{2hD}{r\sqrt{D^2+4h^2}} + q_b \ln\frac{r\sqrt{D^2+4h^2}}{2hD}\right)$$

$$q_b = -q_a$$

$$= \frac{1}{2\pi\varepsilon}\left(q_a \ln\frac{2hD}{r\sqrt{D^2+4h^2}} - q_a \ln\frac{r\sqrt{D^2+4h^2}}{2hD}\right)$$

$$= \frac{1}{2\pi\varepsilon} q_a \ln\left[\frac{4h^2D^2}{r^2(D^2+4h^2)}\right] = \frac{1}{2\pi\varepsilon} q_a \ln\left[\frac{D^2}{r^2\left(\frac{D^2}{4h^2}+1\right)}\right]$$

$$= \frac{1}{2\pi\varepsilon} 2q_a \ln\left[\frac{D}{r\sqrt{r^2\left(\frac{D^2}{4h^2}+1\right)}}\right]$$

$$= \frac{1}{\pi\varepsilon} q_a \ln\left[\frac{D}{r\sqrt{\left(1+\frac{D^2}{4h^2}\right)}}\right]$$

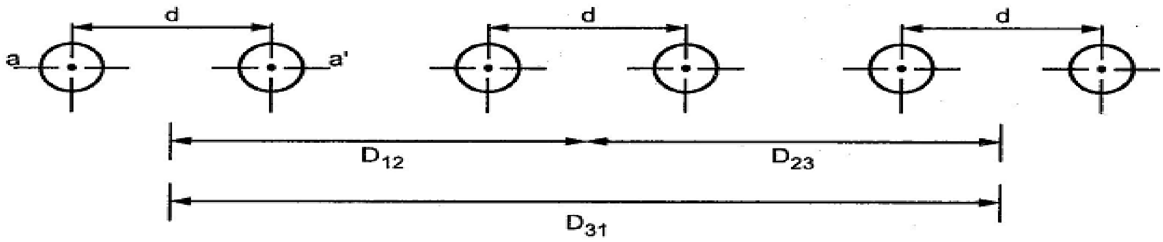
$$C_{ab} = \frac{q_a}{V_{ab}} = \frac{\pi\varepsilon}{\ln\left[\frac{D}{r\sqrt{\left(1-\frac{D^2}{4h^2}\right)}}\right]}$$

Comparing above equation with expression for capacitance of single phase line without considering the effect of earth, we can see that earth tries to increase the capacitance of line by small amount. But the effect is negligible if the conductors are high above ground compared to distances between them.

20. Write in detail about the bundled conductors & stranded conductors.

Bundled Conductors:

The Fig shows the arrangement if the conductors are bundled one



The conductors of anyone bundle are in parallel and charge per bundle is assumed to divide equally between the conductors of bundle. The composite or stranded conductors touch each other while the bundled conductors are away from each other. The typical distance is about 30 cm and more.

The conductors of each phase are connected by using connecting wires at particular length. Due to excessive corona loss, the round conductors are not feasible for use for voltage level more than 230 kV. It is preferable to use hollow conductor in substations while bundled conductors in transmission lines.

Following are advantages of bundled conductors.

1. Low radio interference and corona loss.
2. Reduced voltage gradient at conductor surface.
3. Increase in capacitance.
4. Low reactance due to increase in self GMD.
5. Increase in surge impedance loading.

If the charge on phase a isqa then charge on each of the conductors a and a' will be qa/2. Same is the case with remaining two phases.

$$V_{ab} = \frac{1}{2\pi\varepsilon}\left(\frac{q_a}{2}\left(\ln\frac{D_{12}}{r} + \ln\frac{D_{12}}{D}\right) + \frac{q_b}{2}\left(\ln\frac{r}{D_{12}} + \ln\frac{d}{D_{12}}\right) + \frac{q_c}{2}\left(\ln\frac{D_{23}}{D_{31}} + \ln\frac{D_{23}}{D_{31}}\right)\right)$$

$$V_{ab} = \frac{1}{2\pi\varepsilon}\left(q_a.\ln\left[\frac{D_{12}}{\sqrt{rd}}\right] + q_b.\ln\left[\frac{\sqrt{rd}}{D_{12}}\right] + q_c.\ln\left[\frac{D_{23}}{D_{31}}\right]\right)$$

This equation is similar to the expression we have written for 3 phase line with unsymmetrical spacing. Combining the terms we get

$$C_{an} = \frac{2\pi\varepsilon}{\ln[D_{eq}/\sqrt{rd}]} = \frac{2\pi\varepsilon}{\ln[D_{eq}/D_{sc}^b]}$$

Here,

$$D_{sc}^b = \sqrt{rd} = Modified\ GMR\ for\ capacitor$$

Thus, for a two strand bundle

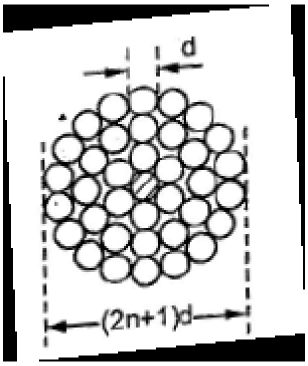
$$D_{sc}^b = \sqrt[4]{(r \times d)^2} = \sqrt{rd}$$

For a three strand bundle

$$D_{sc}^b = \sqrt[4]{(r \times d \times d)^3} = \sqrt[3]{rd^2}$$

2.28.1 Stranded Conductor:

The stranded conductor usually has a central wire which is surrounded by the layers of wires. These layers consist of 6, 12,18wires successively. Thus the total strands are 7,13, and 19. Such a stranded conductor with 37 strands is shown in the Fig.



Let d= diameter of each strand

Then the total diameter of a stranded conductor (cable) is given by,Dc = (2n+1)d

Where

n = number of layers in which the strands are arranged around central strand. The stranded conductor is specified as number of strands and diameter of strand.

For example 7/0.295 mm which indicates 7 strands with 0.295 mm diameter of each strand. If at all the number of layers are not specified then the number of layers can be calculated as number of strands and layers are related to each other by the equation,

x = 3n2 + 3n +1

where x = number of strands

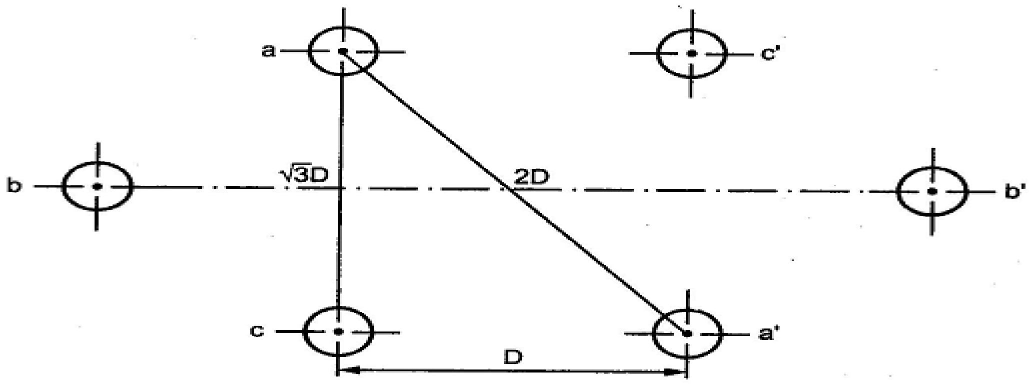
and n = number of layers

the standard number of strands in each successive layer from inner to outer is 6,12, 18, 24….

21. Obtain the expression for capacitance of three phase line with more than one circuit.

Capacitance of Three Phase Line with more than One Circuit:

Consider the arrangement of conductors shown in the Fig.



The voltage between phases a and b is given by,

$$V_{ab} = \frac{1}{2\pi\varepsilon}\left(q_a\left(\ln\frac{D}{r} + \ln\frac{\sqrt{3}D}{2D}\right) + q_b\left(\ln\frac{r}{D} + \ln\frac{2D}{\sqrt{3}D}\right) + q_c\left(\ln\frac{D}{\sqrt{3}D} + \ln\frac{\sqrt{3}D}{D}\right)\right)$$

$$V_{ab} = \frac{1}{2\pi\varepsilon}\left(q_a\left(\ln\frac{\sqrt{3}D}{2r}\right) + q_b\left(\ln\frac{2r}{\sqrt{3}D}\right) + q_c\left(\ln\frac{D}{\sqrt{3}D} + \ln\frac{\sqrt{3}D^2}{\sqrt{3}D^2}\right)\right)$$

$$V_{ab} = \frac{1}{2\pi\varepsilon}\left(q_a\left(\ln\frac{\sqrt{3}D}{2r}\right) + q_b\left(\ln\frac{2r}{\sqrt{3}D}\right)\right)$$

Similarly,

$$V_{ac} = \frac{1}{2\pi\varepsilon}\left(q_a\left(\ln\frac{\sqrt{3}D}{2r}\right) + q_c\left(\ln\frac{2r}{\sqrt{3}D}\right)\right)$$

We have, $V_{ab} + V_{ac} = 3V_{an}$

$$3V_{an} = \frac{1}{2\pi\varepsilon}\left(2q_a\left(\ln\frac{\sqrt{3}D}{2r}\right) + (q_b + q_c)\left(\ln\frac{2r}{\sqrt{3}D}\right)\right)$$

$$q_a + q_b + q_c = 0$$

$$q_b + q_c = -q_a$$

$$3V_{an} = \frac{1}{2\pi\varepsilon}\left(2q_a\left(\ln\frac{\sqrt{3}D}{2r}\right) - (-q_a)\left(\ln\frac{2r}{\sqrt{3}D}\right)\right)$$

$$3V_{an} = \frac{1}{2\pi\varepsilon}3q_a\ln\frac{\sqrt{3}D}{2r}$$

$$V_{an} = \frac{q_a}{2\pi\varepsilon}\ln\frac{\sqrt{3}D}{2r}$$

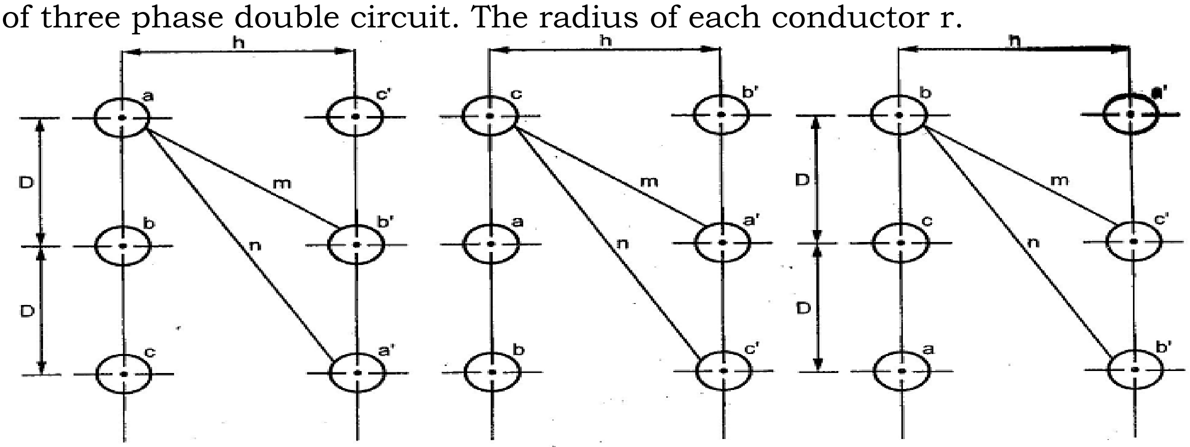
$$C_{an} = \frac{q_a}{V_{an}} = \frac{2\pi\varepsilon}{\ln\frac{\sqrt{3}D}{2r}}$$

Capacitance per phase will be nothing but 2 C_{an}.

22. Obtain the expression for capacitance of three phase double circuit Unsymmetrical spacing with transposed.

Capacitance of Three Phase Double Circuit with Unsymmetrical Spacing but Transposed:

Consider the arrangement of conductors shown in the Fig. 2.45. It consists of three phase double circuit. The radius of each conductor r.



The voltage between phases a and b can be calculated in order to calculate capacitance. One complete cycle of transposition is shown in the Fig.

$$V_{ab_1} = \frac{1}{2\pi\varepsilon}\left(q_a\left(\ln\frac{D}{r} + \ln\frac{m}{h}\right) + q_b\left(\ln\frac{r}{D} + \ln\frac{h}{m}\right) + q_c\left(\ln\frac{D}{2D} + \ln\frac{m}{h}\right)\right)$$

$$V_{ab_2} = \frac{1}{2\pi\varepsilon}\left(q_a\left(\ln\frac{D}{r} + \ln\frac{m}{h}\right) + q_b\left(\ln\frac{r}{D} + \ln\frac{h}{m}\right) + q_c\left(\ln\frac{2D}{D} + \ln\frac{h}{m}\right)\right)$$

$$V_{ab_3} = \frac{1}{2\pi\varepsilon}\left(q_a\left(\ln\frac{D}{r} + \ln\frac{h}{n}\right) + q_b\left(\ln\frac{r}{2D} + \ln\frac{n}{h}\right) + q_c\left(\ln\frac{D}{D} + \ln\frac{m}{m}\right)\right)$$

$$V_{ab} = \frac{1}{3}\left[V_{ab_1} + V_{ab_2} + V_{ab_3}\right]$$

$$= \frac{1}{6\pi\varepsilon}\left(q_a\left(\ln\frac{2D^3}{r^3} + \ln\frac{m^2h}{n^2h}\right) + q_b\left(\ln\frac{r^3}{2D^3} + \ln\frac{n^2h}{m^2h}\right) + q_c\left(\ln\frac{2D^3}{2D^3} + \ln\frac{m^2h}{m^2h}\right)\right)$$

$$3V_{an} = \frac{1}{6\pi\varepsilon}\left(2q_a\ln\frac{2D^3m^2}{r^3n^2} + (q_b + q_c)\ln\frac{r^3n^2}{2D^3m^2}\right)$$

$$Also\ q_a + q_b + q_c = 0$$

$$3V_{an} = \frac{1}{6\pi\varepsilon}\left(3q_a\ln\frac{2D^3m^2}{r^3n^2}\right)$$

$$V_{an} = \frac{1}{6\pi\varepsilon}\left(q_a\ln\frac{2D^3m^2}{r^3n^2}\right)$$

$$C_{an} = \frac{q_a}{V_{an}} = \frac{6\pi\varepsilon}{\ln\frac{2D^3m^2}{r^3n^2}}$$

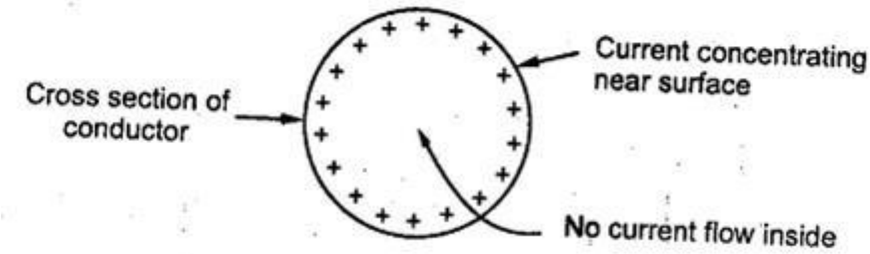
$$\therefore\ C_{an} = \frac{2\pi\varepsilon}{\ln\left\{2^{1/3}\left(\frac{D}{r}\right)\left(\frac{m}{n}\right)^{2/3}\right\}}$$

The capacitance per phase will be 2 C_{an}.

22. Write a short note on Skin effect and proximity effect. (NOV/2013)

Skin Effect:

When a conductor carries a steady or d.c. current, this current is uniformly distributed over the whole cross-section of the conductor. However the current distribution is non-uniform if conductor carries alternating current The current density is higher at the surface than at its center. Thus the Current is concentrated near the surface of the conductor as shown in the Fig. This effect becomes predominant with increase in frequency. This behavior of alternating current to concentrate near the surface of the conductor: is known as skin effect.



Because of skin effect, larger power loss is caused for a given rms value of AC than the loss when the same value of DC is flowing through the conductor. Alternatively the effective resistance of conductor is more for AC than for DC.

Due to this skin effect, the effective cross sectional area offered to the flow of current decreases which increases resistance. Consider a solid, round conductor consisting of large number of strands. Bach strand is carrying a small part of current. The strands near the centre are surrounded by a greater magnetic flux and hence have large inductance than that near the surface.

As we move towards the outer strands, the flux linking progressively reduces for the reason that the flux inside the strand does not link it. The reactance of inner strands is greater than outer strands which causes the alternating current to flow near the surface of the conductor. With increase in the frequency, the inductive reactance of the strands becomes more and more non-uniform which leads to non-uniform current distribution. The skin effect is quite significant for large, solid conductors even at a frequency of 50 Hz.

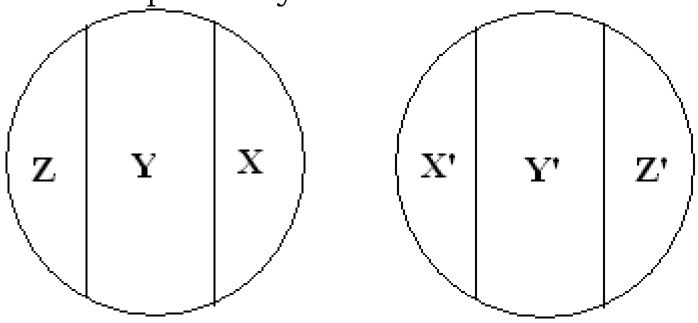
The skin effect depends on following factors

1. Nature of material
2. Diameter of wire
3. Frequency of supply
4. Shape of wire.

With increase in diameter of wire, the skin effect increases. Similarly as frequency increases, the skin effect increases. If we have stranded conductor rather than solid conductor then the skin effect is less. It can be seen that when supply frequency Is less than 50 Hz and conductor diameter is less than 1 cm then skin effect is negligible In large conductors at power frequencies the. Skin effect is a significant factor.

Proximity Effect:

The current distribution may be non-uniform because of another effect known as proximity effect. Consider a two wire line as shown in the Fig



Let each of the line conductor is assumed to be divided into 3 sections having' equal cross sectional area. Three parallel loops are formed by the pairs xx', yy' and zz'. The flux linking loop xx' is least and it increases for the remaining loops. Thus the inductance of inner loop is less. Thus the current density is highest at inner edges of the conductor. Due to this non uniform distribution of current, the effective conductor resistance increases. As the distance between the conductors goes on reducing, this distribution of current becomes more and more non-uniform. For normal spacing of overhead lines this proximity effect is negligible. For underground cables this effect is significant as the conductors are located close to each other. The proximity effect also depends on the same factors as that of skin effect.

2.33 Inductive Interference with Neighboring Circuits:

In practice it is observed that the power lines and the communication lines run along the same path. Sometimes it can also be seen that both these lines run on same supports along the same route.

The transmission lines transmit bulk power with relatively high voltage. Electromagnetic and electrostatic fields are produced by these lines having sufficient magnitude. Because of these fields, voltages and currents are induced in the neighboring communication lines. Thus it gives- rise to interference of power line with communication circuit.

Due to electromagnetic effect, currents are induced which is superimposed on speech current of the neighboring communication line which results into distortion. The potential of the communication circuit as a whole is raised because of electrostatic effect and the communication 'apparatus and the equipments may get damaged due' to 'extraneous 'voltages. In the worst situation, the faithful transmission of message becomes impossible due to effect of these fields. Also the potential of the apparatus is raised above the ground to such an extent that the handling of telephone. receiver becomes extremely dangerous .

The electromagnetic and the electrostatic effects mainly depend on what is the distance between power and communication circuits and the length of the route over which they are parallel. Thus it can be noted that if the distortion effect and potential rise effect are within 'permissible limits then the communication will be proper. The unacceptable disturbance which is produced in the telephone communication because of power lines is called Telephone interference. There are various factors influencing the telephone interference.

These factors are as follows

1) Because of harmonics in power Circuit, their frequency range and magnitudes.

2) Electromagnetic coupling between power and telephone conductor. The electric Coupling is in the form of capacitive coupling between power and telephone conductor whereas the magnetic coupling is through space and is generally expressed in terms. of mutual inductance at harmonic frequencies.

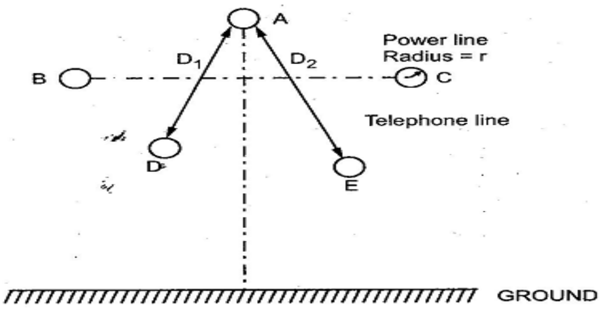
3) Due to unbalance in power circuits and in telephone circuits.

4) Type of return telephone circuit i.e. either metallic or ground return.

5) Screening effects.

2.33.1 Electromagnetic Effect:

Consider a line transmitting power with 3 conductors A, Band C. Consider a telephone line with two conductors D and E below the power line conductors. The two lines are running on the same supports. This is shown in the Fig



Consider the loop formed by the conductors A and D. Let the radius of each power line conductor be r. Let the distance between conductors A and D be D1 whereas the distance between conductors A and E be D2. Assuming that in loop AD, A is contributing to the emf induced in D. If we neglect the internal flux linkages then the inductance of this loop is given by,

$$L_{AD} = 2 \times 10^{-7} \ln\left(\frac{D_1}{r}\right) H/m$$

The inductance of the loop AE is given by

$$L_{AE} = 2 \times 10^{-7} \ln\left(\frac{D_2}{r}\right) H/m$$

The mutual inductance between conductor A and the loop DE is given by,

$$M_A = L_{AE} + L_{AD} = 2 \times 10^{-7} \left[\ln\left(\frac{D_2}{r}\right) - \ln\left(\frac{D_1}{r}\right)\right]$$

$$= 2 \times 10^{-7} \ln\left(\frac{D_2}{D_1}\right) \ H/m$$

Similarly the mutual inductance between conductors Band C and loop DE can be obtained. Let these mutual inductances be MB and Mc respectively. These mutual inductances ere due to fluxes which have a phase displacement of 120°. Hence the net effect of the magnetic field will be

$M = M_A + M_B + M_C$

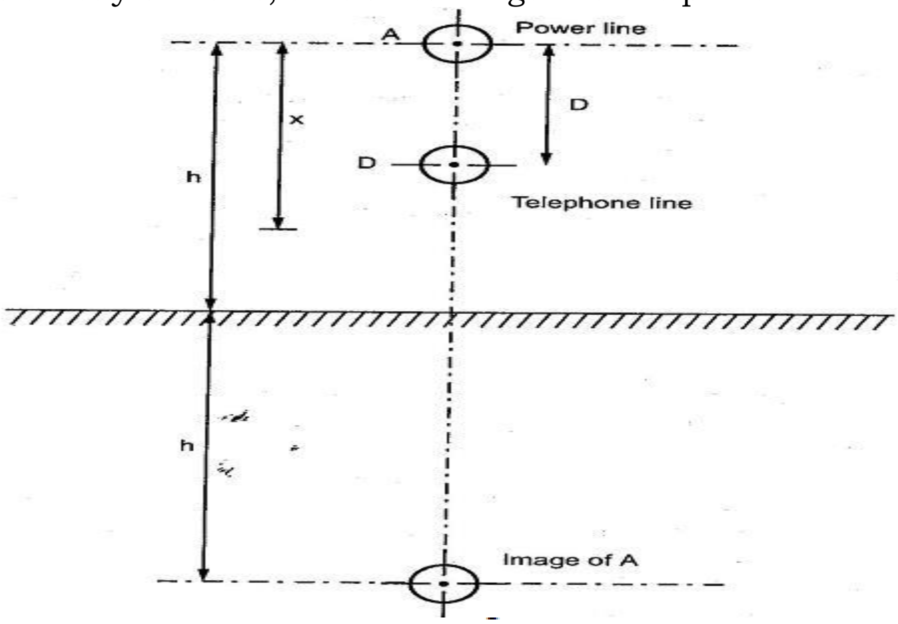
Here M is the net mutual inductance which is the phasor sum of the three inductances. If the current flowing through the power line conductors is I and the supply frequency is f then the voltage induced in the communication conductors D and E is given

by, v = 2πfIM volts/m From the above expression, it can be seen that with increase in distance between power and communication line, the values of MA ,MB and MC nearly becomes equal in magnitude and with the result that the, net inductance M becomes very very small.

As a consequence the voltage induced in telephone lines also diminishes. The voltage induced in the neighbouring telephone line is directly proportional to frequency. If third harmonic is present then voltage equal to 3 times the voltage due to fundamental frequency will be induced in telephone lines. Also as the higher frequencies may come within audible range they produce a distortion effect. The presence of harmonics and multiples of third harmonics will not cancel as they are in phase in all power .line conductors.

In balanced condition the total induced voltage due to harmonic currents in power line is additive. In unbalanced condition i.e. during fault the flux linkage and corresponding voltage induced is very high which may prove to be dangerous for telephone circuits. If the distance between power line and the telephone line is increased then the induced voltage in telephone line can be reduced. It can also be reduced by transposing the line

2.33.2 Electrostatic Effect : Consider the line conductor A running parallel to infinite plane (i.e. earth). Let D be the conductor from neighboring telephone line. Conductor A is the image of conductor A below ground as shown in the Fig. 2.49. The potential distribution between the conductor and earth is exactly same as, that of its image and the plane.



The potential of point A with respect to the earth is given by,

$$V_A = \frac{1}{2\pi\varepsilon}\int_r^h \left(\frac{q}{x} + \frac{q}{2h-x}\right) dx = \frac{q}{2\pi\varepsilon}\int_r^h \frac{dx}{x} + \int_r^h \frac{dx}{2h-x}$$

$$= \frac{q}{2\pi\varepsilon}\{(\ln x)_r^h + [-\ln(2h-x)]_r^h\}$$

$$= \frac{q}{2\pi\varepsilon}[\ln h - \ln r - \ln h + \ln(2h-r)]$$

$$= \frac{q}{2\pi\varepsilon}[\ln(2h-r) - \ln r]$$

$$V_A = \frac{q}{2\pi\varepsilon}\left[\ln\frac{(2h-r)}{r}\right] volts$$

The potential of point D due to conductor A is given by,

$$V_{DA} = \frac{1}{2\pi\varepsilon}\int_d^h \left(\frac{q}{x}+\frac{q}{2h-x}\right) dx$$

$$= \frac{q}{2\pi\varepsilon}\int_d^h \frac{dx}{x} + \int_d^h \frac{dx}{2h-x}$$

$$= \frac{q}{2\pi\varepsilon}\{(\ln x)_d^h + [-\ln(2h-x)]_d^h\}$$

$$= \frac{q}{2\pi\varepsilon}[\ln h - \ln d - \ln h + \ln(2h-d)]$$

$$= \frac{q}{2\pi\varepsilon}\ln\left(\frac{2h-d}{d}\right)$$

$$multiplying\ and\ dividing\ by \ln\left(\frac{2h-r}{r}\right)$$

$$= \frac{q}{2\pi\varepsilon}\ln\left(\frac{2h-r}{r}\right)\frac{\ln(2h-d/d)}{\ln(2h-r/r)}$$

$$V_{DA} = V_A\frac{\ln(2h-d/d)}{\ln(2h-r/r)} volts$$

In the similar fashion, the voltages VDB and VIX can be calculated. Finally the resultant potential of point D with respect to earth is given by, VD = VDA + VDB + VIX The above addition is the phasor addition. Similarly the resultant potential of point E, VE can be calculated using the same procedure.

24. Explain in detail about the Self GMD and Mutual GMD(APRIL/2014) (APRIL/2015)

Concept of Self-GMD and Mutual-GMD:

The use of self geometrical mean distance (abbreviated as self-GMD) and mutual geometrical mean distance (mutual-GMD) simplifies the inductance calculations, particularly relating to multi conductor arrangements. The symbols used for these are respectively Ds and Dm. We shall briefly discuss these terms.

(i) Self-GMD (Ds). In order to have concept of self-GMD (also sometimes called Geometrical mean radius : GMR), consider the expression for inductance per conductor per meter

$$Inductance/conductor/m = 2\times 10^{-7}\left(\frac{1}{4}+\log_e\frac{d}{r}\right)$$

10. $= 2\times 10^{-7}\times\frac{1}{4} + 2\times 10^{-7}\log_e\frac{d}{r}$ ……………. (i)

11.

In this expression, the term 2 × 10-7 × (1/4) is the inductance due to flux within the solid conductor. For many purposes, it is desirable to eliminate this term by the introduction of a concept called self-GMD or GMR. If we replace the original solid conductor by an equivalent hollow cylinder with extremely thin walls, the current is confined to the conductor surface and internal conductor flux linkage would be almost zero. Consequently, inductance due to internal flux would be zero and the term 2 × 10-7 × (1/4) shall be eliminated. The radius of this equivalent hollow cylinder must be sufficiently smaller than the physical radius of the conductor to allow room for enough additional flux to compensate for the absence of internal

flux linkage. It can be proved mathematically that for a solid round conductor of radius *r,* the self-GMD or GMR = 0·7788 *r*. Using self- GMD, the eq. (*i*)
Becomes:

$$Inductance/conductor/m = 2 \times 10^{-7} \log_e \frac{d}{D_S}$$

$$Where \quad D_S = GMR\ or\ self\ GMD = 0.7788\ r$$

It may be noted that self-GMD of a conductor depends upon the size and shape of the conductor and is independent of the spacing between the conductors.

(*ii*) Mutual-GMD. The mutual-GMD is the geometrical mean of the distances form one conductor to the other and, therefore, must be between the largest and smallest such distance. In fact, mutual-GMD simply represents the equivalent geometrical spacing. ***(a)*** The mutual-GMD between two conductors (assuming that spacing between conductors is large compared to the diameter of each conductor) is equal to the distance between their centers *i.e.*

1. Dm= spacing between conductors = d

(b) For a single circuit 3-Ø line, the mutual-GMD is equal to the equivalent equilateral spacing *i.e.,* $(d1\ d2\ d3)^{1/3}$

1. $Dm = (d1\ d2\ d3)^{1/3}$

(c) The principle of geometrical mean distances can be most profitably employed to 3- Φ doublecircuit lines. Consider the conductor arrangement of the double circuit shown in Fig.2.50. Suppose the radius of each conductor is *r.*

Self-GMD of conductor = 0·7788 *r*

Self-GMD of combination *aa´ is*

$Ds1 = (^{*}{}^{*}Daa \times Daa' \times Da'a' \times Da'a)^{1/4}$

Self-GMD of combination *bb´ is*

$Ds^2 = (Dbb \times Dbb' \times Db'b' \times Db'b)^{1/4}$

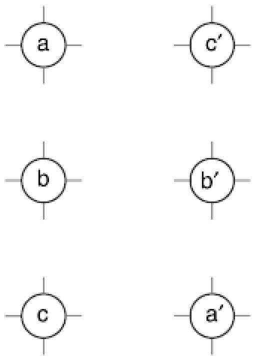
Self-GMD of combination *cc' is*

$Ds^3 = (Dcc \times Dcc' \times Dc'c' \times Dc'c)^{1/4}$

Equivalent self-GMD of one phase

$Ds = (Ds1 \times Ds2 \times Ds3)^{1/3}$

The value of Ds is the same for all the phases as each conductor has the same radius.



Mutual-GMD between phases *A* and *B* is

$D_{AB} = (Dab \times Dab' \times Da'b \times Da'b')^{1/4}$

Mutual-GMD between phases *B* and *C* is

$D_{BC} = (Dbc \times Dbc' \times Db'c \times Db'c')^{1/4}$

Mutual-GMD between phases *C* and *A* is

$D_{CA} = (Dca \times Dca' \times Dc'a \times Dc'a')^{1/4}$

Equivalent mutual-GMD, $D_m = (D_{AB} \times D_{BC} \times D_{CA})^{1/3}$

It is worth while to note that mutual GMD depends only upon the spacing and is substantially independent of the exact size, shape and orientation of the conductor.

Inductance Formulas in Terms of GMD:

The inductance formulas developed in the previous articles can be conveniently expressed in terms of geometrical mean distances.

(i) Single phase line

$$Inductance/conductor/m = 2 \times 10^{-7} \log_e \frac{D_m}{D_S}$$

Where $D_S = GMR \text{ or self } GMD = 0.7788\,r$ and $D_m = \text{spacing between conductors} = d$

(ii) Single circuit 3Ø line

$$Inductance/conductor/m = 2 \times 10^{-7} \log_e \frac{D_m}{D_S}$$

Where $D_S = 0.7788\,r$ and $D_m = (d1\,d2\,d3)^{\frac{1}{3}}$

(iii) Double circuit 3Ø line

15.

$$Inductance/conductor/m = 2 \times 10^{-7} \log_e \frac{D_m}{D_S}$$

Where $D_S = (Ds1 \times Ds2 \times Ds3)^{\frac{1}{3}}$ and $D_m = (D_{AB} \times D_{BC} \times D_{CA})^{\frac{1}{3}}$

Problem 1: A single phase line has two parallel conductors 2 meters apart. The diameter of each conductor is 1·2 cm. Calculate the loop inductance per km of the line.

Solution:

Spacing of conductors, d = 2 m = 200 cm

Radius of conductor, r = 1·2/2 = 0·6 cm

Loop inductance per meter length of the line =

= 10^{-7} (1 + 4 loge d/r)H

= 10^{-7} (1 + 4 loge 200/0·6) H

= 24·23x10^{-7} H

Loop inductance per km of the line

=24·23x10^{-7} x 1000 = 24·23x10^{-4} H = 2·423 mH

Problem 2: A single phase transmission line has two parallel conductors 3 m apart, the radius of each conductor being 1 cm. Calculate the loop inductance per km length of the line if the material of the conductor is (i) copper (ii) steel with relative permeability of 100.

Solution: Spacing of conductors, *d* = 300 cm

Radius of conductor, *r* = 1 cm

Loop inductance = 10^{-7} (μ_r + 4 loge *d/r*) H/m

(i) With copper conductors, μ_r = 1

Loop inductance/m = 10^{-7} (1 + 4 log*e d/r*) H = 10^{-7} (1 + 4 log*e* 300/1) H

= 23·8 × 10^{-7} H

Loop inductance/km = 23·8 × 10^{-7} × 1000 = 2·38 × 10^{-3} H = 2·38 mH

(ii) With steel conductors, μ_r = 100

Loop inductance/m = 10^{-7} (100 + 4 log*e* 300/1) H = 122·8 × 10^{-7} H

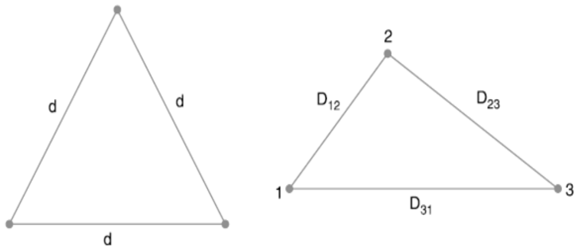
Loop inductance/km = 122·8 × 10^{-7} × 1000 = 12·28 × 10^{-3} H = 12·28 mH

Problem 3. Find the inductance per km of a 3-phase transmission line using 1·24 cm diameter conductors when these are placed at the corners of an equilateral triangle of each side 2 m.

Solution. Fig.2.58 shows the three conductors of the three phase line placed at the corners of an equilateral triangle of each side 2 m. Here conductor spacing d = 2 m and conductor radius r = 1·24/2 = 0·62 cm.

Inductance/phase/m = 10^{-7} (0·5 + 2 $\log_e d/r$) H
= 10^{-7} (0·5 + 2 $\log_e$ 200/0·62) H
= 12 × 10^{-7} H

Inductance/phase/km = 12 × 10^{-7} × 1000
= 1·2 × 10^{-3} H = 1·2 mH



Problem 4: The three conductors of a 3-phase line are arranged at the corners of a triangle of sides 2 m, 2·5 m and 4·5 m. Calculate the inductance per km of the line when the conductors are regularly transposed. The diameter of each conductor is 1·24 cm.

Solution: Fig.2.58 shows three conductors of a 3-phase line placed at the corners of a triangle of sides D_{12} = 2 m, D_{23} = 2·5 m and D_{31} = 4·5 m. The conductor radius r = 1·24/2 = 0·62 cm.

$$\text{Equivalent equilateral spacing, } D_{eq} = \sqrt[3]{D_{12} \times D_{23} \times D_{31}} = \sqrt[3]{2 \times 2.5 \times 4.5} = 2.82m = 282cm$$

Inductance/phase/m = 10^{-7} (0·5 + 2 $\log_e D_{eq}/r$) H = 10^{-7}(0·5 + 2 $\log_e$ 282/0·62) H
= 12·74 × 10^{-7} H

Inductance/phase/km = 12·74 × 10^{-7} × 1000 = 1·274 × 10^{-3} H = 1·274 mH

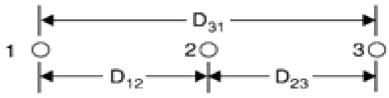
Problem 5: Calculate the inductance of each conductor in a 3-phase, 3-wire system when the conductors are arranged in a horizontal plane with spacing such that D_{31} = 4 m ; D_{12} = D_{23} = 2m.The conductors are transposed and have a diameter of 2·5 cm.

Solution: Fig.2.59 shows the arrangement of the conductors of the 3phase line. The conductor radius r = 2·5/2 = 1·25 cm.

$$\text{Equivalent equilateral spacing, } D_{eq} = \sqrt[3]{D_{12} \times D_{23} \times D_{31}} = \sqrt[3]{2 \times 2 \times 4} = 2.52m = 252cm$$

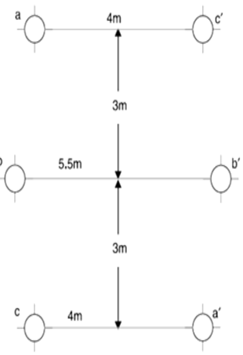
Inductance/phase/m = 10^{-7} (0·5 + 2 $\log_e D_{eq}/r$) H
= 10^{-7} (0·5 + 2 $\log_e$ 252/1·25) H
= 11·1 × 10^{-7}H

Inductance/phase/km = 11·1 × 10^{-7} × 1000 = 1·11 × 10^{-3} H = 1·11 mH



Problem 6: Find the inductance per phase per km of double circuit 3-phase line shown in Fig.2.62. The conductors are transposed and are of radius 0·75 cm each. The phase sequence is ABC.

Solution:



$G.M.R\ of\ conductor = 0.75 \times 0.7788 = 0.584\ cm$

$Distance\ a\ to\ b = \sqrt{3^2 + (0.75)^2} = 3.2\ m$

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

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

Equivalent self GMD of one phase is

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

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

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

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

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

$$= \sqrt[4]{(0.584 \times 10^{-2}) \times (5.5) \times (0.584 \times 10^{-2}) \times (5.5)} = 0.18\ m$$

$$D_s = \sqrt[3]{0.205 \times 0.18 \times 0.205} = 0.195\ m$$

Equivalent mutual GMD is

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

$$D_{AB} = \sqrt[4]{D_{ab} \times D_{ab'} \times D_{a'b'} \times D_{a'b'}} = \sqrt[4]{3.1 \times 5.62 \times 5.62 \times 3.1} = 4.17\ m = D_{BC}$$

$$D_{CA} = \sqrt[4]{D_{ca} \times D_{ca'} \times D_{c'a} \times D_{c'a'}} = \sqrt[4]{6 \times 4 \times 4 \times 6} = 4.9\ m$$

$$D_m = \sqrt[3]{4.17 \times 4.17 \times 4.9} = 4.4\ m$$

Inductance/phase/m = $10^{-7} \times 2 \log_e Dm/Ds = 10^{-7} \times 2 \log_e 4{\cdot}4/0{\cdot}195$ H
= $6{\cdot}23 \times 10^{-7}$ H = $0{\cdot}623 \times 10^{-3}$ mH

Inductance/phase/km = $0{\cdot}623 \times 10^{-3} \times 1000 = 0{\cdot}623$ mH

25. Explain: Corona effect and factors effecting corona. (APRIL/2014) (NOV/2013)

Corona Effect:

It can be noticed that near the overhead lines there exists a hissing noise and sometimes a faint violet glow. The effect due to which such phenomenon exists surrounding the overhead lines, is called corona effect.

When a normal alternating voltage is applied across two conductors with enough spacing in between, then there is no change in the atmospheric conditions surrounding the conductors. But if the voltage" applied exceeds a particular limiting value then the air surrounding the conductor & gets ionized due to which hissing noise or a faint violet glow appears.

Thus the phenomenon of hissing noise, faint violet glow and production of ozone gas surrounding the overhead lines, due to ionization of air is called corona.

The corona effect takes place when applied voltage exceeds a particular value which is called critical disruptive voltage. As this voltage increases, the glow and hissing noise also increases.

If the voltage increases upto breakdown value then the flash over Occurs between the conductors, due to breakdown of air between the' conductors. Similarly if the ratio of spacing between the conductors to the radius of the conductor is less than 15 then the flash over occurs before corona. In practice this ratio is very high and there is no possibility of a flash over. When a more voltage than the critical disruptive voltage is applied, the faint violet glow is even between the two parallel polished conductors and can be seen all along the length of the conductors. At the rough points, it appears little bit brighter.

In case of voltage more reddish beads are formed near negative conductor while smoother bluish white uniform glow is formed near positive conductor. The hissing noise can be easily heard while the formation of ozone gas can be detected from its odor.

Basic Principle of Corona:

In the free space surrounding the conductors, some ionization is always present due to radioactivity, cosmic rays and ultraviolet rays. Thus the air near the conductors consists of some free electrons, ionized particles along with the neutral molecules. When the potential is applied to the conductors, a potential gradient is developed in the air. This potential gradient is maximum around the surface of the conductors. Due to the potential gradient, the free electrons will start moving with certain velocity which depends on the field strength. The greater is the applied voltage, higher is the potential gradient and the velocity acquired by the. free electrons. These electrons moving with high speed collide with the neutral molecules in the air. If the potential gradient is about 30 kV / cm (maximum) then striking free electron dislodge the electrons from the neutral molecules. This increases the number of free electrons which also=acquire high velocities and start colliding with other neutral molecules. The process of ionization is cumulative which finally results into an electron avalanche. This ionization of air surrounding the conductors gives rise to corona effect.

2.36.2 Critical Disruptive Voltage:

The critical disruptive voltage is defined as the minimum phase to neutral voltage at which corona occurs. It is denoted as Vd.

For a given transmission conductor, the gradient is maximum at the surface i.e. at a distance of radius r from the Centre . So if there are two conductors each of radius r and distance between them is d then the potential gradient at the surface of the conductor is given by,

$$g_{max} = \frac{V_d}{r\, ln\frac{d}{r}}$$

$$i.e. \qquad V_d = r\, g_{max}\, ln\frac{d}{r}$$

At the critical disruptive voltage, the complete disruption of dielectric occurs. At this voltage, the potential gradient developed is equal to breakdown strength of the air which is denoted as go. At a normal temperature of 25CC and pressure of 76 cm of H8 the value of g , is 30 kV /cm. Hence V d can be expressed as,

$$V_d = r\, g_0\, ln\frac{d}{r}$$

But for any other temperature and pressure the value of go is different. It is given by,

$$g_0{}' = \delta\, g_0$$

Where, δ = air density correction factor The air density correction factor which depends on the pressure and temperature is given by,

$$\delta = \frac{3.92b}{273 + t}$$

Where,

b= barometric pressure in cm of H_g

t= temperature in ¤C

Hence V_d can be further expressed as,

$$V_d = r\,\delta\,g_0\,ln\frac{d}{r}$$

The equation V_d is valid if the conductors are solid and having uniform smooth surface. But the surface conditions are different for large cables and stranded conductors. Hence another correction factor must be introduced in V_d. Such a factor is called irregularity factor denoted as mo. This factor is the average value of the ratio of breakdown voltage for irregular conductor to the smooth conductor. Hence the final expression for the critical disruptive voltage becomes, V_d

$$V_d = r\,\delta\,g_0\,m_0\,ln\frac{d}{r}\ KV/phase$$

Critical Visual Disruptive Voltage: When the voltage applied is equal to critical disruptive voltage, the corona start but it can not be visible. To have it visible, the charged ions in air require further ionization and hence surface gradient must increase and reach a value gv. The voltage required to cause a gradient of gv at the surface is called critical visual disruptive voltage denoted as V The critical Visual disruptive voltage is the minimum phase to neutral voltage at which corona glow appears and visible all along the conductors. The distance between gv and go is called the energy distance

Which is equal to (r + 0.301 √r) for two parallel conductors and (r + 0.30s√r) for co-axial conductors. Thus gv is not constant and depends on the size of the conductors. It is given by,

$$g_V = \delta\,g_o\left(1 + \frac{0.3}{\sqrt{r\delta}}\right)\ KV/cm$$

This is for parallel conductors. The irregularity factor is slightly different denoted as mv , Its value is 1.0 for polished conductors, 0.98 to 0.93 for rough conductors and 0.72 for the local corona-on stranded conductors. For the general corona its value is 0.S2. The conductor surface is not regular and hence corona does not start simultaneously all along the surface. It starts at the portions which are pointed. This is called local corona. Considering all these factors the critical visual disruptive voltage can be expressed

$$V_V = m_V\,\delta\,g_O\,r\left(1 + \frac{0.3}{\sqrt{r\delta}}\right) ln\frac{d}{r}\ KV/phase$$

If V_d and $V_{R.M.S.}$ values are to be calculated then R.M.S. value of go must be used

$$g_O(r.m.s) = \frac{30\ KV/cm\ (peak)}{\sqrt{2}} = 21.21\ KV/cm$$

Factors Affecting Corona and Corona Loss :

The various factors affecting corona and corona Joss are,

1. **Electrical factors**:- From the equation of corona loss it can be observed that it depends on the supply frequency. Higher the supply frequency, higher is the corona loss. Thus d.c. corona loss is less compared to a.c. corona loss. Due to corona effect third harmonic components are generated hence actually corona loss is higher.

2. Line voltage:- The line voltage directly affects the corona and the corona loss. For lower line voltage corona may be absent. But for voltages higher than disruptive voltage, corona starts. Higher the line voltage, higher is the corona loss.

3. Atmospheric conditions:- The most important atmospheric factors are pressure and temperature. The pressure and temperature together decide the value of 8 which affects the disruptive voltage and the corona loss. Lower the value of 0, higher is the corona loss hence it is very important factor regarding corona. For lower pressures and higher temperatures, value of is small and corona effect and loss is dominant. Hence in mountain areas the corona loss is high. Similarly in the stormy conditions, dusty and rainy conditions, number of free electrons is more hence disruptive voltage is lower. This increases the corona loss considerably.

4. Size of the conductor: - The corona loss is directly proportional to square root of radius of conductor. So it appears that loss is more if size of conductor is more. But for large size conductors, V d is more and hence the term (V ph - V d) is less. Thus loss is less. The effect of V d is more dominating than the factor. If hence higher the size of the conductor, lower is the corona loss.

5. Surface conditions:-The corona depends on the surface conditions. For rough and uneven surfaces, the value of disruptive voltage is less and corona effect is dominant. Similarly corona loss is also more for rough and dirty surfaces.

6 Number of conductors per phase: - For higher voltages a single conductor per phase produces large corona loss. Hence bundled conductors are used due to which self GMD of the conductor 8 increases, which increases the disruptive voltage, reducing corona loss.

7. Spacing between conductors: - If the spacing is made very large, coronas can beabsent. Practically the spacing is selected so that corona is tolerable.

8. Shape of conductors: - The shape of the conductors like flat, oval, cylindrical etc.
Affects the corona loss. For uniform cylindrical shape, corona loss is less compared to any other shape.

9. Clearance from ground: - The height of the conductors from the ground also affects the corona loss. The smaller the clearance of the conductors from the ground, higher is the corona loss.

10. Effect of load current: - As the load current increases, the temperature of the conductor's increases. This does not allow snow, dew and dirt to deposit on the surface. This reduces the corona loss. Due to all these factors for the long transmission lines the corona loss per km of line at various points is obtained. And net corona loss is obtained by taking average of all the values.

Advantages of Corona: The various advantages of corona effect are,

1. Due to corona, the air surrounding the conductor is ionised and becomes conducting.
   This increases the virtual diameter of the corona
2. Corona reduces the effects produced by the surges and conductor is saved from possibility of lightning. It acts as a safety device.

Disadvantages of Corona:

The various disadvantages of corona are,

1. The corona power loss is the biggest disadvantage which reduces the transmission efficiency.
2. The third harmonic components' produced due to corona makes the current non sinusoidal. This increases the corona loss.
3. The ozone gas formed due to corona chemically reacts with the conductor and can cause corrosion.

University Question Papers:

2 marks

1) What are the various factors affecting skin effect (APRIL/2015)
2) What are the classifications of OH transmission lines (APRIL/2015)
3) What is meant by skin effect? (NOV/2014)
4) Define self GMD. (NOV/2014)
5) Give the expression for the inductance per phase of three phase overhead line in which conductor are symmetrically placed. (APRIL/2014)
6) Distinguish between stranded and bundled conductors (APRIL/2014)
7) What is meant by transposition of the power conductors (NOV/2013)
8) What are bundled conductors (NOV/2013)
9) What is meant by corona? (APRIL/2013)
10) Define mutual GMD. (APRIL/2013)
11) Why is transmission lines transposed? (NOV/2012)
12) On what factors does the skin effect depend? (NOV/2012)
13) What is corona discharge? (NOV/2012)
14) Write about bundled conductor. (NOV/2012)
15) What is the need for different transmission line models? (APRIL/2012)
16) What is a guard ring? (APRIL/2012)
17) What is the necessity for double circuit line (APRIL/2012)
18) Distinguish between GMD and GMR? Explain the influence of power factor on the regulation of a transmission line (APRIL/2012)

11 marks:

1) Derive an expression for the capacitance of a single phase overhead transmission line. (APRIL/2013)
2) a) A single phase line has two parallel conductor 2 meters apart. The diameter of each conductor id 1.2 cm. Calculate the loop inductance per km of the line. (APRIL/2013) b) A three phase overhead transmission line has its conductors arranged at corners of an equivalent triangle of 2m side. Calculate the capacitance of each line conductor per km. Give that diameter of each conductor is 1.25cm. (APRIL/2013)
3) Derive the expression for capacitance of unsymmetrically spaced transposition three phase lines. (APRIL/2014)
4) a)Discuss the concept of self GMD and mutual GMD in the calculation of transmission line inductance. (APRIL/2014) b) Write a note on corona power loss and discuss the methods of reducing corona loss. (APRIL/2014)
5) Derive the expression for the inductance of three phase line with conductors untransposed and write the significance of imaginary term in the expression of inductance. (NOV/2012)
6) a) A three phase stranded conductor consists of seven identical strands each having a diameter of 2.3546 cm and arranged in the corners of equilateral triangle with spacing between conductors is 10M. Find the capacitance per phase. (NOV/2012) b) State the factor affecting the corona. (NOV/2012)
7) What are corona discharge and its characteristics? (NOV/2012)
8) From the fundamentals derive an expression for inductance of a single phase transmission system. (NOV/2012)
9) Derive an expression for the loop inductance of single phase line. (NOV/2014)
10) a) A single phase transmission line has two parallel conductors 3 m apart, the radius of each conductor being 1cm. Calculate the loop inductance per km length of the line if material of the conductor is (NOV/2014) i) Copper
    ii) Steel with relative permeability of 100.

b) A single phase transmission line has two parallel conductors 3 meters apart, radius of each conductor being 1 cm. Calculate the capacitance of the line per km. Given ϵ_0 =8.854 x 10^{-12} f/m. (NOV/2014)

11) A single phase transmission line has two parallel conductors 3 metre apart, the radius of each conductors 3 metre apart, the radius of each conductor being 1 cm. Calculate the loop inductance per Km length of the line if the material of the conductor is (APRIL/2012)

a) Copper

b) Steel with relative permeability 100

12) a) Derive an expression for the capacitance of a single phase transmission line. (APRIL/2012)

b) Explain proximity effect (APRIL/2012)

13) a) What is corona? What are the factors affecting it? List the advantages of corona. (8) (APRIL/2015) b) A single phase line has two parallel conductors 2 meters apart. The diameter of each conductor is 1.2 cm. calculate the loop inductance per km of the line. (3) (APRIL/2015)

14) a)Derive the expression for the line to neutral capacitance of a three phase OH line when the conductors are symmetrically placed. (5) (APRIL/2015)

UNIT III

2 marks:

1. **Define voltage regulation of transmission line** (APRIL/2015) (or) **Define voltage regulation**. (NOV/2014) (or) **Define regulation of transmission line** (NOV/2012)

"The difference in voltage at the receiving end of a transmission line between conditions of no load and full load is called voltage regulation "

This is expressed as a percentage of the receiving end voltage.

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

2. List out the draw backs of end condenser method. (NOV/2014)

- There is a considerable error (about 10%) in calculations because the distributed capacitance has been assumed to be lumped or concentrated.
- This method overestimates the effects of line capacitance

3. Define surge impedance voltage. (APRIL/2014) (or) **Define the term Surge Impedance Loading (SIL)** (NOV/2013) (or) **what is surge impedance**? (NOV/2012) (APRIL/2012)

The surge impedance loading (SIL) is defined as the load, at unity power factor, power can be delivered by the line having No resistance

4. What are the main objectives of compensation? (APRIL/2014)

- To improve the system stability
- To produce substantially flat voltage profile
- To meet the economical way for reactive power requirement
- To increase power transfer capability

5. How the lines are classified based on their length of transmission (NOV/2013)

Based on their length of transmission line; the overhead transmission lines are classified as:

- Short transmission lines
- Medium transmission lines
- Long transmission lines

6. Define transmission efficiency (APRIL/2013)

"The ratio of receiving end power to the sending end power of a transmission line is known as the transmission efficiency of the line"

$$\% \, Transmission \ efficiency, \eta_T = \frac{Receiving \ end \ power}{Sending \ end \ power} \times 100$$

7. What are receiving end power circle diagram? (NOV/2012)

The locus of all points obtained by plotting Qr(3-φ) versus Pr(3-φ) for fixed line voltages and varying load angle is a circle with radius $V_{SL} * V_{RL} / B$ and center. This is known as receiving end power circle diagram

8. Write in short about shunt compensation. (NOV/2012)

The provision of shunt capacitor involves insertion of shunt capacitor across the line in order to improve the power factor & voltage as well as to reduce lossless

9. Explain "Ferranti effect" in transmission line. (APRIL/2012)

In long transmission lines and cables, receiving end voltage is greater than sending end voltage during light load or no load operation. Under no load or light load the capacitance associated with the line generate more reactive power than the reactive power which absorbed hence Vr >Vs this effect is known as Ferranti effect

11 marks:

1) Explain the classification of Overhead transmission lines:

CLASSIFICATION OF OVERHEAD TRANSMISSION LINES:

A transmission line has three constants R, L and C distributed uniformly along the whole length of the line. The resistance and inductance form the series impedance. The capacitance existing between conductors for single-phase line or from a conductor to neutral for a three-phase line forms a shunt path throughout the length of the line. Therefore, capacitance effects introduce complications in transmission line calculations.

Depending upon the manner in which capacitance is taken into account; the overhead transmission lines are classified as:

- Short transmission lines
- Medium transmission lines
- Long transmission lines

SHORT TRANSMISSION LINES:

"When the length of an overhead transmission line is upto about 50km and the line voltage is comparatively low (< 20 kV), it is usually considered as a short transmission line".

Due to smaller length and lower voltage, the capacitance effects are small and hence can be neglected. Therefore, while studying the performance of a short transmission line, only resistance and inductance of the line are taken into account.

MEDIUM TRANSMISSION LINES:-

"When the length of an overhead transmission line is about 50-150 km and the line voltage is moderately high (>20 kV < 100 kV), it is considered as a medium transmission line".

Due to sufficient length and voltage of the line, the capacitance effects are taken into account. For purposes of calculations, the distributed capacitance of the line is divided and lumped in the form of condensers shunted across the line at one or more points.

LONG TRANSMISSION LINES: -

"When the length of an overhead transmission line is more than 150km and line voltage is very high (> 100 kV), it is considered as a long transmission line. "

For the treatment of such a line, the line constants are considered uniformly distributed over the whole length of the line and rigorous methods are employed for solution. It may be emphasized here that exact solution of any transmission line must consider the fact that the constants of the line are not lumped but are distributed uniformly throughout the length of the line.

IMPORTANT TERMS:

VOLTAGE REGULATION:

When a transmission line is carrying current, there is a voltage drop in the line due to resistance and inductance of the line. The result is that receiving end voltage (V_R) of the line is generally less than the sending end voltage (V_S). This voltage drop ($V_S - V_R$) in the line is expressed as a percentage of receiving end voltage V_R and is called voltage regulation.

"The difference in voltage at the receiving end of a transmission line between conditions of no load and full load is called voltage regulation "

This is expressed as a percentage of the receiving end voltage.

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

Obviously, it is desirable that the voltage regulation of a transmission line should be low i.e., the increase in load current should make very little difference in the receiving end voltage.

TRANSMISSION EFFICIENCY:

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

"The ratio of receiving end power to the sending end power of a transmission line is known as the transmission efficiency of the line"

$$\%\, Transmission\ efficiency, \eta_T = \frac{Receiving\ end\ power}{Sending\ end\ power} \times 100$$

$$\%\, Transmission\ efficiency, \eta_T = \frac{V_R I_R \cos \Phi_R}{V_S I_S \cos \Phi_S} \times 100$$

where,

V_R ------- Receiving end Voltage

I_R ------- Receiving end Current

Cos Φ_R ---- Receiving end Power factor

V_S ------- Sending end Voltage

I_S ------- Sending end Current

Cos Φ_S ------- Sending end Power factor

1. **Explain the equivalent circuit of single phase short transmission line. Also deduce an expression for voltage regulation and sending end voltage.** (APRIL/2013)

PERFORMANCE OF SINGLE PHASE SHORT TRANSMISSION LINES

The effects of line capacitance are neglected for a short transmission line. Therefore, while studying the performance of such a line, only resistance and inductance of the line are taken into account. The equivalent circuit of a single phase short transmission line is shown in below figure (i). Here, the total line resistance and inductance are shown as concentrated or lumped instead of being distributed.

Let, I = load current ($I_S = I_R = I$)

R = loop resistance (i.e., resistance of both conductors)

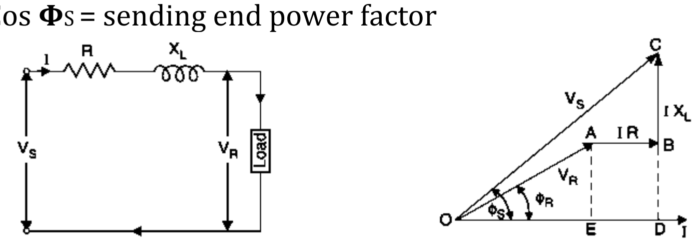
X_L = loop reactance (i.e., reactance of both conductors)

V_R = receiving end voltage

Cos Φ_R = receiving end power factor (lagging)

V_S = sending end voltage

Cos Φ_S = sending end power factor



(i) (ii)

The phasor diagram of the line for lagging load power factor is shown in above figure (ii).

From the right angled triangle ODC, we get,

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

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

$$= (V_R cos\,\Phi_R + IR)^2 + (V_R cos\,\Phi_R + IX_L)^2$$

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

(i) $\%\,Voltage\ regulation = \frac{V_s - V_R}{V_R} \times 100$

(ii) $Sending\ end\ p.f\ cos\Phi_s = \frac{OD}{OC} = \frac{V_R cos\,\Phi_R + IR}{V_S}$

(iii) $Power\ delivered = V_R\, I_R\ cos\,\Phi_R$

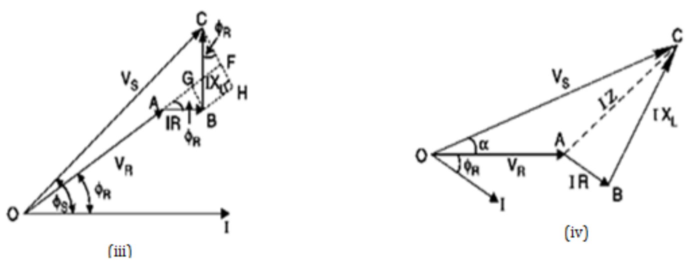
Line losses = I^2R

Power sent out = $V_R\, I_R\ cos\,\Phi_R + I^2R$

$$\%\,transmission\ efficiency = \frac{power\ delivered\ (Receiving\ end\ Power)}{power\ sent\ out\ (Sending\ end\ Power)} \times 100$$

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

An approximate expression for the sending end voltage Vs can be obtained as follows. Draw perpendicular from B and C on OA produced as shown in below figure. Then OC is nearly equal to OF



OC=OF=OA+AF=OA+AG+GF

=OA+AG+BH

$$V_S = V_R\, I_R\ cos\,\Phi_R + IX_L sin\Phi_R$$

Taking $\vec{V_R}$ as the reference phasor, draw the phasor diagram as shown in Fig.3.3. it is clear that $\vec{V_S}$ is the phasor sum of and $\vec{I}\,\vec{Z}$.

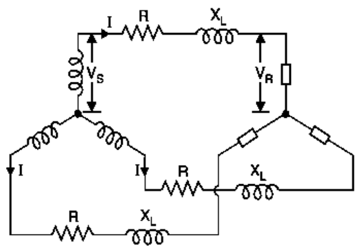
$$\vec{V_R} = V_R + j\,0$$
$$\vec{I} = \vec{I} - \Phi_R = I\,(cos\,\Phi_R - j\,sin\Phi_R)$$
$$\vec{Z} = R + jX_L$$
$$\vec{V_S} = \vec{V_R} + \vec{I}\,\vec{Z}$$
$$= (V_R + j\,0) + I\,(cos\,\Phi_R - j\,sin\Phi_R)\,R + jX_L$$
$$= (V_R + I_R\ cos\,\Phi_R + IX_L sin\Phi_R) + j\,(IX_L cos\,\Phi_R - IR\ sin\Phi_R)$$
$$V_S = \sqrt{(V_R + I_R\ cos\,\Phi_R + IX_L sin\Phi_R)^2 + (IX_L cos\,\Phi_R - IR\ sin\Phi_R)^2}$$

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

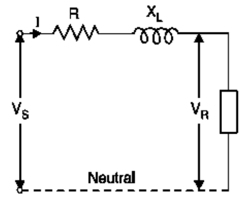
$$V_S = V_R + I_R\ cos\,\Phi_R + IX_L sin\Phi_R$$

Three-Phase Short Transmission Lines:

For reasons associated with economy, transmission of electric power is done by 3-phase system. This system may be regarded as consisting of three single phase units, each wire transmitting one-third of the total power. As a matter of convenience, we generally analyze 3-phase system by considering one phase only.



(i)



(ii)

Therefore, expression for regulation, efficiency etc. derived for a single phase line can also be applied to a 3-phase system. Since only one phase is considered, phase values of 3-phase system should be taken. Thus, V_S and V_R are the phase voltages, whereas R and X_L are the resistance and inductive reactance per phase respectively.

Above figure (i) shows a Y-connected generator supplying a balanced Y-connected load through a transmission line. Each conductor has a resistance of R Ω and inductive reactance of X_L Ω. Figure (ii) shows one phase separately. The calculations can now be made in the same way as for a single phase line.

Effect on Regulation:

The expression for voltage regulation of a short transmission line is given by :

$$\%\,Voltage\ regulation = \frac{I_R\ cos\ \Phi_R + IX_L sin\Phi_R}{V_R} \times 100 \qquad (for\ lagging\ p.f)$$

$$\%\,Voltage\ regulation = \frac{I_R\ cos\ \Phi_R - IX_L sin\Phi_R}{V_R} \times 100 \qquad (for\ leading\ p.f)$$

Effect on Transmission Efficiency:

The power delivered to the load depends upon the power factor.

$$P = V_R\, I_R\ cos\ \Phi_R \qquad (For\ 1 - Phase\ line)$$

$$P = 3V_R\, I_R\ cos\ \Phi_R \qquad (For\ 3 - Phase\ line)$$

<u>*Problem 1:*</u> **A single phase overhead transmission line delivers 1100 kW at 33 kV at 0·8 p.f. lagging. The total resistance and inductive reactance of the line are 10 Ω and 15 Ω respectively. Determine: (i) sending end voltage (ii) sending end power factor and (iii) transmission efficiency.**

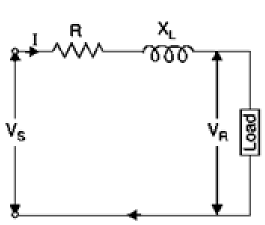
Solution: Load power factor, cos Φ_R = 0·8 lagging

$$Total\ line\ impedence, \vec{Z} = R + jX_L = 10 + j\,15$$

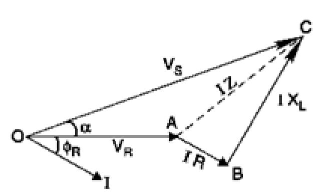
Receiving end voltage, V_R = 33 KV=33,000 V

$$\therefore\ Line\ current, I = \frac{KW \times 10^3}{V_R\ cos\ \Phi_R} = \frac{1100 \times 10^3}{33000 \times 0.8} = 41.67\ A$$

$$As \quad cos\ \Phi_R = 0.8 \qquad \therefore\ sin\Phi_R = 0.6$$



(i)



(ii)

The equivalent circuit and phasor diagram of the line are shown in figure (i) and (ii) respectively.

$$\vec{V_R} = V_R + j\,0 = 33000\ V$$

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

$$= 41.67\,(0.8 - j\,0.6) = 33.33 - j\,25$$

(i) Sending end voltage, $\vec{V_S} = \vec{V_R} + \vec{I}\,\vec{Z}$

$$= 33{,}000 + (33.33 - j\,25.0)(10 + j\,15)$$
$$= 33000 + 333.3 - j\,250 + j\,500 + 375$$

$$= 33{,}708.3 + j\,250$$
$$\therefore Magnitude\ of\ V_S = \sqrt{(33708.3)^2 + (250)^2} = 33709\ V$$

(ii) Angle between $\vec{V_R}$ and $\vec{V_S}$ is

$$\alpha = tan^{-1}\frac{250}{33708.3} = tan^{-1}\,0.0074 = 0.42°$$

$\therefore$ *the sending end power factor angle is*

$$\Phi_S = \Phi_R + \alpha = 36.87° + 0.42° = 37.29°$$

Sending end p.f is $\cos\Phi_S = \cos 37.29° = 0.7956\ lagging$

(iii) Line losses $= I^2R = (41.67)^2 \times 10 = 17364\ W = 17.364\ KW$

Output delivered = 1100 KW

Power sent=1100+17.364=1117.364 KW

$$\therefore\ Transmission\ efficiency = \frac{power\ delivered}{power\ sent} \times 100 = \frac{1100}{1117.364} \times 100 = 98.44\%$$

Problem 2: **What is the maximum length in km for a 1-phase transmission line having copper conductor of 0·775 cm2 cross-section over which 200 kW at unity power factor and at 3300V are to be delivered? The efficiency of transmission is 90%. Take specific resistance as 1.725 µ Ω cm.**

Solution:

Receiving end power = 200 kW = 2, 00,000 W

Transmission efficiency = 0·9

$$\therefore sending\ end\ power = \frac{200000}{0.9} = 222222\ W$$

$$\therefore\ Line\ losses = 222222 - 200000 = 22222\ W$$

$$Line\ current, I = \frac{200 \times 10^3}{3300 \times 1} = 60.6\ A$$

$$Line\ losses = 2I^2R$$

$$22222 = 2(60.6)^2 \times R$$

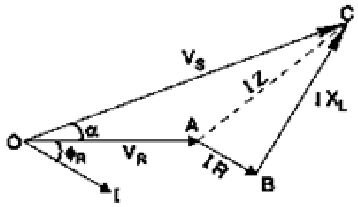
$$R = \frac{22222}{2(60.6)^2} = 3.025\Omega$$

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

$$\therefore\ l = \frac{Ra}{\rho} = \frac{3.025 \times 0.775}{1.725 \times 10^{-6}} = 1.36 \times 10^6 cm = 13.6km$$

Problem 3: **An overhead 3-phase transmission line delivers 5000 kW at 22 kV at 0·8 P.F. lagging. The resistance and reactance of each conductor is 4 Ω and 6 Ω respectively. Determine: (i) sending end voltage (ii) percentage regulation (iii) transmission efficiency**.

Solution:



Load power factor, $\cos\Phi_R = 0.8\ lagging$

Receiving end voltage/ phase $V_R = 22000/\sqrt{3} = 12{,}700$ V

Impedance/phase $\vec{Z} = 4 + j\,6$

Line current, $I = \frac{5000\times10^3}{3\times12700\times0.8} = 164\ A$

As $\cos\Phi_R == 0.8$ $\therefore\ \sin\Phi_R = 0.6$

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

$$\overrightarrow{V_R} = V_R + j\,0 = 12700\ V$$

$$\vec{I} = I\,(\cos\Phi_R - j\,\sin\Phi_R) = 164(0.8 - j\,0.6) = 131.2 - j\,98.4$$

(i) Sending end voltage per phase is

$$\overrightarrow{V_S} = \overrightarrow{V_R} + \vec{I}\vec{Z} = 12700 + (131.2 - j\,98.4)(4 + j\,6)$$

$$= 12700 + 524.8 + j\,787.2 - j\,393.6 + 590.4$$

$$= 13815.2 + j\,393.6$$

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

$$Line\ value\ of\ V_S = \sqrt{3}\times 13820.8 = 23938\ V = 23.938\ KV$$

(ii) $\%\ voltage\ regulation = \frac{V_S - V_R}{V_R}\times 100 = \frac{13820.8 - 12700}{12700}\times 100 = 8.825\%$

(iii) $Line\ losses = 3I^2R = 3\times(164)^2\times 4 = 322752\ W = 322.752\ KW$

Transmission efficiency $= \frac{5000}{5000+322.752}\times 100 = 93.94\%$

Problem 4: **Estimate the distance over which a load of 15000 kW at a P.F. 0·8 lagging can be delivered by a 3-phase transmission line having conductors each of resistance 1 Ω per kilometer. The voltage at the receiving end is to be 132 kV and the loss in the transmission is to be 5%.**

Solution:

$$Line\ current,\quad I = \frac{Power\ dewlivered}{\sqrt{3} \times Linevoltage \times Power\ factor} = \frac{15000 \times 10^3}{\sqrt{3} \times 132 \times 10^3 \times 0.8} = 82\ A$$

Line losses = 5% of power delivered=0.05*15000=750 KW

Let R be the resistance of one conductor,

$$\text{Line losses} = 3I^3 R$$

$$750 \times 10^3 = 3 \times (82)^2 \times R$$

$$R = \frac{750 \times 10^3}{3 \times (82)^2} = 37.18\Omega$$

Resistance of each conductor per km is Ω (given)

Length of line=37.18 km

Problem 5: **A 3-phase load of 2000 kVA, 0·8 p.f. is supplied at 6·6 kV, 50 Hz by means of a 33 kV transmission line 20 km long and 33/6·6 kV step-down transformer. The resistance and reactance of each conductor are 0·4 Ω and 0·5 Ω per km respectively. The resistance and reactance of transformer primary are 7.5 Ω and 13.2 Ω, while those of secondary are 0.35 Ω and 0.65 Ω respectively. Find the voltage necessary at the sending end of transmission line when 6.6 kV is maintained at the receiving end. Determine also the sending end power factor and transmission efficiency.**

Solution:

Figure shows the single diagram of the transmission system. Here, the voltage drop will be due to the impedance of transmission line and also due to the impedance of transformer.

Resistance of each conductor =20*0.4= 8Ω

Reactance of each conductor =20*0.5= 10Ω

Let us transfer the impedance of transformer secondary to high tension side i.e., 33KV side.

Equivalent resistance of transformer referred to 33KV side

$$= primary\ resistance + 0.35\,(33/6.6)^2$$

$$= 7.5 + 8.75 = 16.25\Omega$$

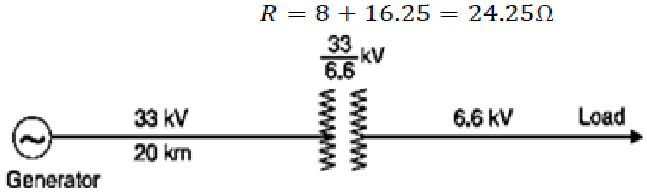
Equivalent reactance of transformer referred to 33KV side

$$= primary\ rectance + 0.65\,(33/6.6)^2$$

$$= 13.2 + 16.25 = 29.45\Omega$$

Total resistance of line and transformer is

$$R = 8 + 16.25 = 24.25\Omega$$



Total reactance of line and transformer is

$$X_L = 10 + 29.45 = 39.45\Omega$$

Receiving end voltage per phase is

$$V_R = \frac{33000}{\sqrt{3}} = 19052\ V$$

$$Line\ current\ ,\quad I = \frac{200 \times 10^3}{\sqrt{3} \times 33000} = 35\ A$$

Using the approximate expression for sending end voltage V_S per phase

$$V_S = V_R + I_R\ cos\ \Phi_R + IX_L sin\Phi_R$$

$$= 19052 + 35 \times 24.25 \times 0.8 + 35 \times 39.45 \times 0.6$$

$$= 19052 + 679 + 828 = 20559\ V = 20.559\ KV$$

Sending end line voltage $= \sqrt{3} \times 20.559\ KV = 35.6\ KV$

Sending end p.f

$$\cos \Phi_S = \frac{V_R cos\ \Phi_R + I_R}{V_S} = \frac{19052 \times 0.8 + 35 \times 24.25}{20559} = 0.7826\ lag$$

Line losses $= \frac{3I^2R}{1000} KW = \frac{3 \times (35)^2 \times 24.25}{1000} = 89.12KW$

Output power, =2000KVA * 0.8=1600 KW

$$\text{Transmission efficiency} = \frac{1600}{1600+89.12} \times 100 = 94.72\%$$

MEDIUM TRANSMISSION LINES:

Medium transmission lines have sufficient length (50-150 km) and usually operate at voltages greater than 20 kV, the effects of capacitance cannot be neglected. Therefore, in order to obtain reasonable accuracy in medium transmission line calculations, the line capacitance must be taken into consideration. The capacitance is uniformly distributed over the entire length of the line. However, in order to make the calculations simple, the line capacitance is assumed to be lumped or concentrated in the form of capacitors shunted across the line at one or more points. Such a treatment of localizing the line capacitance gives reasonably accurate results.

The most commonly used methods (known as localized capacitance methods) for the solution of medium transmissions lines are:

- End condenser method
- Nominal T method
- Nominal π method

2. **Explain end condenser method of medium transmission lines.** (NOV/2014)

END CONDENSER METHOD:

In this method, the capacitance of the line is lumped or concentrated at the receiving or load end as shown in below figure. This method of localizing the line capacitance at the load end overestimates the effects of capacitance. In figure one phase of the three phase transmission line is shown as it is more convenient to work in phase instead of line-to-line values.

Let, I_R= load current per phase

R = resistance per phase

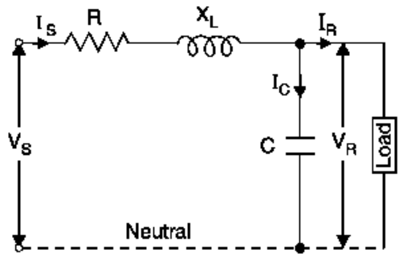
X_L= inductive reactance per phase

C =capacitance per phase

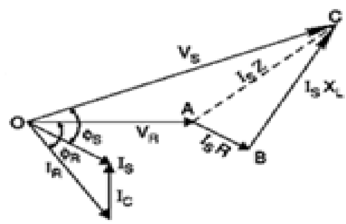
Cos Φ_R= receiving end power factor (*lagging*)

V_S= sending end voltage per phase

V_R = receving end voltage per phase



The phase diagram for the circuit is shown in below figure taking the receiving end voltage $\overrightarrow{V_R}$ as the reference phasor we have, $\overrightarrow{V_R} = V_R + j\,0$



Load current, $\overrightarrow{I_R} = I_R\,(\cos\Phi_R - j\sin\Phi_R)$

Capacitive current, $\overrightarrow{I_C} = j\,\overrightarrow{V_R}\,\omega C = j\,2\pi f C\overrightarrow{V_R}$

The sending end current $\overrightarrow{I_S}$ is the phasor sum of load current $\overrightarrow{I_R}$ and capacitive current $\overrightarrow{I_C}$ i.e.,

$$\overrightarrow{I_S} = \overrightarrow{I_R} + \overrightarrow{I_C}$$

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

$$= I_R\cos\Phi_R + j(-\sin\Phi_R + \;2\pi f C\,V_R$$

$$\frac{Voltagedrop}{phase} = \overrightarrow{I_S}\overrightarrow{Z} = \;\overrightarrow{I_S}\,(R + j\,X_L\,)$$

Sending end voltage, $\overrightarrow{V_S} = \overrightarrow{V_R} + \overrightarrow{I_S}\overrightarrow{Z} = \overrightarrow{V_R}\,\overrightarrow{I_S}\,(R + j\,X_L\,)$

Thus the magnitude of sending end voltage V_S can be calculated

$$\%\,voltage\;regulation = \frac{V_s - V_R}{V_R} \times 100$$

$$\%\,Voltage\;transmission\;efficiency = \frac{Power\;delivered/phase}{Power\;delivered/phase + losses/phase} \times 100$$

$$= \frac{V_R I_R\;\cos\Phi_R}{V_R I_R\;\cos\Phi_R + I_s^2 R} \times 100$$

Limitations:

Although end condenser method for the solution of medium lines is simple to work out calculations, yet it has the following drawbacks:

- There is a considerable error (about 10%) in calculations because the distributed capacitance has been assumed to be lumped or concentrated.
- This method overestimates the effects of line capacitance.

Problem 1: **A (medium) single phase transmission line 100 km long has the following constants Resistance/km = 0·25 Ω; Reactance/km = 0·8 Ω Susceptance/km = 14 × 10−6 siemen ; Receiving end line voltage = 66,000 V Assuming that the total capacitance of the line is localized at the receiving end alone, determine(i) the sending end current (ii) the sending end voltage (iii) regulation and (iv) supply power factor. The line is delivering 15,000 kW at 0.8 power factor lagging. Draw the phasor diagram to illustrate your calculations.**

Solution:

Figure (i) and (ii) show the circuit diagram and phasor diagram of the line respectively.

Solution:

Figure (i) and (ii) show the circuit diagram and phasor diagram of the line respectively.

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

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

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

$$Receiving\ end\ voltage, V_R = 66{,}000\ V$$

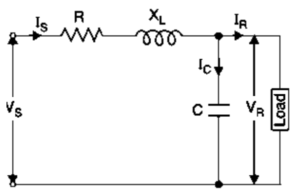
$$\therefore Load\ current, I_R = \frac{15000 \times 10^3}{66000 \times 0.8} = 284A$$

$$\cos \Phi_R = 0.8; \qquad \sin \Phi_R = 0.6$$

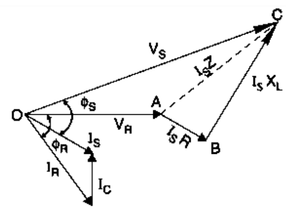
Taking receiving end voltage as the reference phasor [see figure(ii)], we have,

$$\overline{V_R} = V_R + j0 = 66{,}000V$$

$$Load\ current, \overline{I_R} = I_R(\cos \Phi_R - j \sin \Phi_R) = 284(0.8 - j\,0.6) = 227 - j170$$



(i)



(ii)

$$Capacitive\ current, \overline{I_C} = jY \times V_R = j14 \times 10^{-4} \times 66000 = j92$$

$$i)\ Sending\ end\ current, \overline{I_S} = \overline{I_R} + \overline{I_C} = (227 - j78) + j92$$

$$= 227 - j78$$

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

$$ii)\ Voltae\ drop = \overline{I_S Z} = \overline{I_S}(R + jX_L) = (227 - j78)(25 + j80)$$

$$= 5675 + j18160 - j1950 + 6240$$

$$= 11915 + j16210$$

$$Sending\ end\ voltage, \overline{V_S} = \overline{V_R} + \overline{I_S Z} = 66000 + 11915 + j16210$$

$$= 77915 + j16210$$

$$Magnitude\ of\ V_S = \sqrt{(77915)^2 + (16210)^2} = 79583V$$

$$iii)\ \%\ Voltage\ regulation = \frac{V_S - V_R}{V_R} \times 100 = \frac{79583 - 66000}{66000} \times 100 = 20.58\%$$

$$iv)\ Referring\ to\ exp.(i), phase\ angle\ between\ \overline{V_R}\ and\ \overline{I_R}\ is$$

$$\theta_1 = tan^{-1}\left(-\frac{77}{227}\right) = tan^{-1}(-0.3436) = -18.96°$$

$$Referring\ to\ exp.(ii), phase\ angle\ between\ \overline{V_R}\ and\ \overline{V_S}\ is$$

$$\theta_1 = tan^{-1}\left(\frac{16210}{77915}\right) = tan^{-1}(0.2036) = 11.50°$$

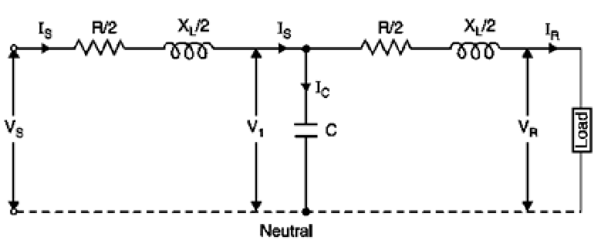
$$\therefore Supply\ power\ factor\ angle, \Phi_S = 18.96° + 11.50° = 30.46°$$

$$\therefore Supply\ p.f. = \cos \Phi_S = \cos 30.46° = 0.86\ lag$$

3. **Derive the expression for sending end voltage of medium transmission line by using nominal T method.** (7) (APRIL/2015) (NOV/2013)

NOMINAL T METHOD:

The whole line capacitance is assumed to be concentrated at the middle point of the line and half the line resistance and reactance are lumped on its either side as shown in below figure. Therefore, in this arrangement, full charging current flows over half the line. In figure, one phase of 3- phase transmission line is shown as it is advantageous to work in phase instead of line-to-line values.



Let, I_R = load current per phase　　R = resistance per phase

X_L=inductive reactance per phase　　C = capacitance per phase

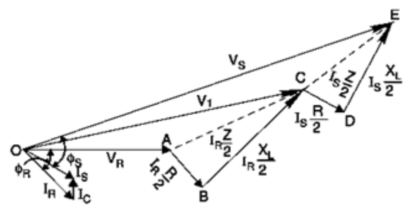
Cos Φ_R = receiving end power factor (lagging)　　V_S = sending end voltage/ phase

V_1 = voltage across capacitor C

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

$$Receiving\ end\ voltage, \overline{V_R} = V_R + j0$$

$$Load\ current,\quad \overline{I_R} = I_R(\cos\Phi_R - j\sin\Phi_R)$$



$$Voltage\ across\ C, \qquad \overline{V_1} = \overline{V_R} + \frac{\overline{I_R}\bar{Z}}{2}$$

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

$$Capacitive\ current, \overline{I_C} = j\omega C\overline{V_1} = j2\pi fC\overline{V_1}$$

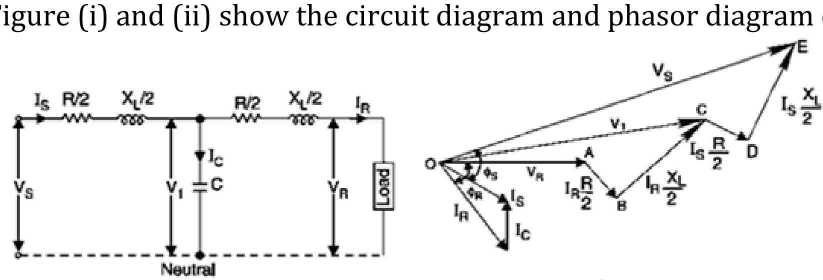
$$Sending\ end\ current, \overline{I_S} = \overline{I_R} + \overline{I_C}$$

$$Send\ end\ voltage, \quad \overline{V_S} = \overline{V_1} + \overline{I_S}\frac{\bar{Z}}{2} = \overline{V_1} + \overline{I_S}\left(\frac{R}{2} + j\frac{X_L}{2}\right)$$

Problem 1: **A 3- phase, 50-Hz overhead transmission line 100 km long has the following constants:**
Resistance/km/phase = 0.1Ω
Inductive reactance/km/phase = 0.2Ω
Capacitive susceptance/km/phase =0.04*10-4 Siemen
Determine (i) the sending end current (ii) sending end voltage (iii) sending end power factor and (iv) transmission efficiency when supplying a balanced load of 10000 kW at 66kV, p.f. 0.8 lagging. Use nominal T method.

Solution:

Figure (i) and (ii) show the circuit diagram and phasor diagram of the line respectively



(i)　　(ii)

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

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

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

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

$$Load\ current, I_R = \frac{10000 \times 10^3}{\sqrt{3} \times 66 \times 10^3 \times 0.8} = 109A$$

$$\cos\Phi = 0.8; \sin\Phi_R = 0.6$$

Impedance per phase, $\bar{Z} = R + jX_L = 10 + j20$

i) Taking receiving end voltage as the reference phasor [see figure (ii)], we have

$$Receiving\ end\ voltage, \overline{V_R} = V_R + j0 = 38.105V$$

$$Load\ current, \overline{I_R} = I_R(\cos\Phi_R - j\sin\Phi_R) = 109(0.8 - j0.6) = 87.2 - j65.4$$

$$Voltage\ across\ C, \overline{V_1} = \overline{V_R} + \frac{\overline{I_R}\bar{Z}}{2} = 38105 + (87.2 - j65.4)(5 + j10)$$

$$= 38105 + 436 + j872 - j327 + 654 = 39195 + j545$$

$$Charging\ current, \overline{I_C} = jY\overline{V_1} = j4 \times 39.195 + j545) = -0.218 + j15.6$$

$$Sending\ end\ current, \overline{I_S} = \overline{I_R} + \overline{I_C} = (87.2 - j65.4) + (-0.218 + j15.6)$$

$$= 87.0 - j49.8 = 100\angle - 29°47'A$$

$$\therefore Sending\ end\ current = 100\ A$$

$$ii)\ Sending\ end\ voltage, \overline{V_S} = \overline{V_1} + \overline{I_S}\bar{Z}/2 = (39195 + j545) + (87.0 - j49.8)(5 + j10)$$

$$= 39195 + j545 + 434.9 + j870 - j249 + 498$$

$$= 40128 + j1170 = 40145\ \ 1°40'V$$

$$\therefore Line\ value\ of\ sending\ end\ voltage$$

$$= 40145 \times \sqrt{3} = 69533V = 69.533kV$$

iii) Referring to phasor diagram in figure

$$\theta_1 = angle\ between\ \overline{V_R}\ and\ \overline{V_S} = 1°40'$$

$$\theta_2 = angle\ between\ \overline{V_R}\ and\ \overline{I_S} = 29°47'$$

$$\theta_1 = angle\ between\ \overline{V_R}\ and\ \overline{I_S} = \theta_1 + \theta_2 = 1°40' + 29°47' = 31°27'$$

$$\therefore Sending\ end\ power\ factor, \cos\Phi = \cos 31°27' = 0.853\ lag$$

$$iv)\ Sending\ end\ power = 3V_SI_S\cos\Phi_S = 3 \times 40.145 \times 100 \times 0.853$$

$$= 10273105W = 10273.105kW$$

$$Power\ delivered = 10000kW$$

$$\therefore Transmission\ efficiency = \frac{10000}{10273.105} \times 100 = 97.34\%$$

Problem 2: **A 3-phase, 50 Hz transmission line 100 km long delivers 20 MW at 0·9 p.f. lagging and at 110 kV. The resistance and reactance of the line per phase per km are 0·2 Ω and 0·4Ω respectively, while capacitance admittance is 2·5 × 10− 6 siemen/km/phase. Calculate: (i) the current and voltage at the sending end (ii) efficiency of transmission. Use nominal T method.**

Solution.

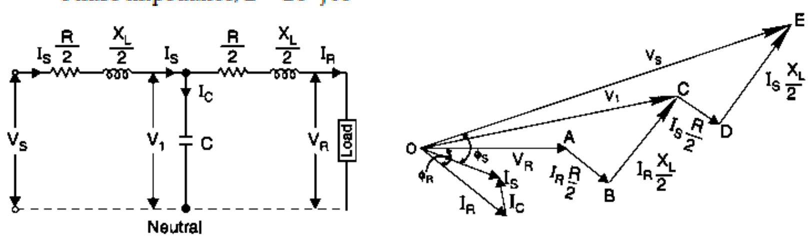
Figure (i) and (ii) show the circuit diagram and phasor diagram respectively.

Total resistance/phase, R = 0.2*100 = 20Ω

Total reactance/phase, X_L = 0.4*100=40Ω

Total capacitance admittance/phase, Y = 2.5*10^{-6}*100=2.5*10^{-4}S

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



(i) (ii)

$$Receiving\ end\ voltage/phase\ , V_R = 110 \times 10^3/\sqrt{3}$$
$$= 63508V$$
$$Load\ current, I_R = \frac{20 \times 10^6}{\sqrt{3} \times 110 \times 10^3 \times 0.9} = 116.6A$$
$$\cos \Phi_R = 0.9; \sin \Phi_R = 0.435$$

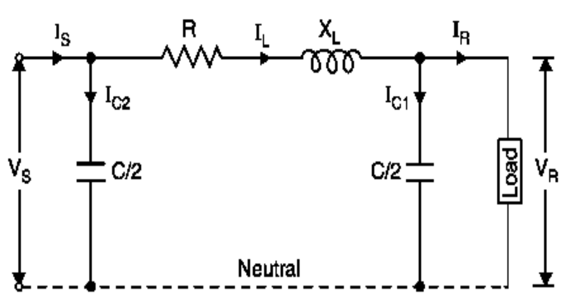
i) Taking receiving end voltage as the reference phasor [see phasor diagram (ii). we have

$$\overline{V_R} = V_R + j0 = 63508V$$
$$Load\ current, \overline{I_R} = I_R(\cos \Phi - j\sin\ \Phi_R) = 116.6\ (0.9 - j0.435) = 105 - j50.7$$
$$Voltage\ across\ C, \overline{V_1} = \overline{V_R}$$

4. **Derive a nominal T and nominal pi model using medium transmission lines.** (NOV/2012)

NOMINAL Π METHOD:

In this method, capacitance of each conductor (*i.e.,* line to neutral) is divided into two halves; one half being lumped at the sending end and the other half at the receiving end as shown in below figure. It is obvious that capacitance at the sending end has no effect on the line drop. However, it's charging current must be added to line current in order to obtain the total sending end current.



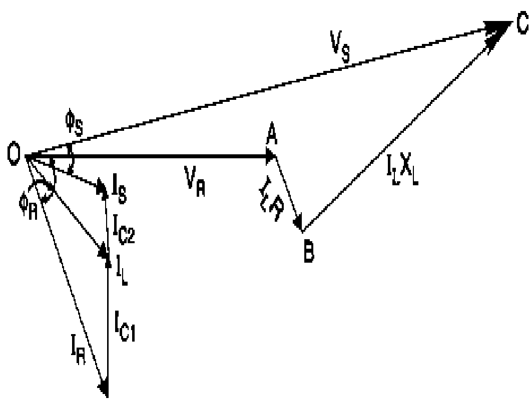
Let, V_S= Sending end voltage
V_R= Receiving end voltage
I_R= Load current or receiving end current
R= Resistance per phase
X_L= Inductive reactance per phase
C= Capacitance per phase
Cos Φ_R= p.f at receiving end

We have, $\overrightarrow{V_R} = V_R + j\,0$

Load current, $\overrightarrow{I_R} = I_R(\cos\Phi_R - j\,\sin\Phi_R)$

Charging current at load end,

$$\overrightarrow{I_{C1}} = j\,\omega(C/2)\,\overrightarrow{V_R} = j\,\pi\,f\,C\,\overrightarrow{V_R}$$



Line current, $\overrightarrow{I_L} = \overrightarrow{I_R} + \overrightarrow{I_{C1}}$

Sending end voltage, $\overrightarrow{V_S} = \overrightarrow{V_R} + \overrightarrow{I_L}\,\overrightarrow{Z} = \overrightarrow{V_R} + \overrightarrow{I_L}\,(R + j\,X_L)$

Charging current at the sending end is,

$$\overrightarrow{I_{C2}} = j\,\omega(C/2)\,\overrightarrow{V_S} = j\,\pi\,f\,C\,\overrightarrow{V_S}$$

Sending end current, $\overrightarrow{I_S} = \overrightarrow{I_L} + \overrightarrow{I_{C2}}$

Problem 1: **A 3-phase, 50 Hz, 150km line has a resistance, inductive resistance and capacitive shunt admittance of 0.1Ω, 0.5 Ω and $3*10^{-6}$ S per km per phase. If the line delivers 50 MW at 110KV and 0.8 p.f lagging, determine the sending end voltage and current. Assume a nominal π circuit for the line.**

Solution:

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

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

Capacitive admittance / phase, $Y = 3 \times 10^{-6} \times 150 = 45 \times 10^{-5} S$

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

Load current,

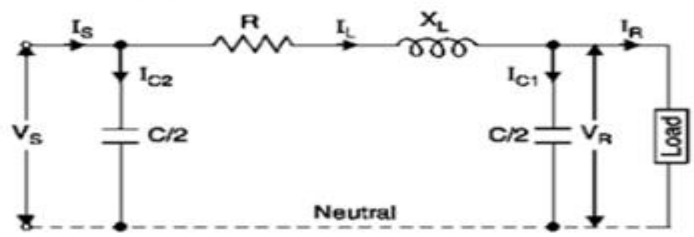
$$I_R = \frac{50 \times 10^6}{\sqrt{3} \times 110 \times 10^3 \times 0.8} = 328\ A$$

$$\cos\Phi_R = 0.8\ ; \qquad \sin\Phi_R = 0.6$$

Taking receiving end voltage as the reference phasor, we have,

$$\overrightarrow{V_R} = V_R + j\,0 = 63508\ V$$

Load current, $\overrightarrow{I_R} = I_R(\cos\Phi_R - j\ \sin\Phi_R) = 328(0.8 - j\,0.6) = 262.4 - j\,196.8$



Charging current at load end,

$$\overrightarrow{I_{C1}} = \overrightarrow{V_R}\, j\, \frac{Y}{2} = 63508 \times j\frac{45 \times 10^{-5}}{2} = j\,14.3$$

Line current, $\overrightarrow{I_L} = \overrightarrow{I_R} + \overrightarrow{I_{C1}} = (262.4 - j\,196.8) + j\,14.3 = 262.4 - j\,182.5$

Sending end voltage, $\overrightarrow{V_S} = \overrightarrow{V_R} + \overrightarrow{I_L}\,\vec{Z} = \overrightarrow{V_R} + \overrightarrow{I_L}\,(R + j\,X_L)$

$$= 63508 + (262.4 - j\,182.5)(15 + j\,75)$$

$$= 63508 + 3936 + j\,19680 - j\,2737.5 + 13687$$

$$= 81131 + j\,16942.5 = 82881 \quad 11.47°V$$

$\therefore$ *Line to line sending end voltage* $= 82881 \times \sqrt{3} = 143550\ V = 143.55\ KV$

Charging current at sending end,

$$\overrightarrow{I_{C2}} = \overrightarrow{V_S}\, j\, \frac{Y}{2} = (81131 + j\,16942.5) \times j\frac{45 \times 10^{-5}}{2} = -3.81 + j\,18.25$$

Sending end current, $\overrightarrow{I_S} = \overrightarrow{I_L} + \overrightarrow{I_{C2}} = (262.4 - j\,182.5) + (-3.81 + j\,18.25)$

$$= 258.6 - j\,164.25 = 306.4 \ \angle -32.4°\,A = 306.4\ A$$

LONG TRANSMISSION LINES:

Line constants of the transmission line are uniformly distributed over the entire length of the line. However, reasonable accuracy can be obtained in line calculations for short and medium lines by considering these constants as lumped.

If such an assumption of lumped constants is applied to long transmission lines (having length excess of about 150 km), it is found that serious errors are introduced in the performance calculations. Therefore, in order to obtain fair degree of accuracy in the performance calculations of long lines, the line constants are considered as uniformly distributed throughout the length of the line.

Rigorous mathematical treatment is required for the solution of such lines.

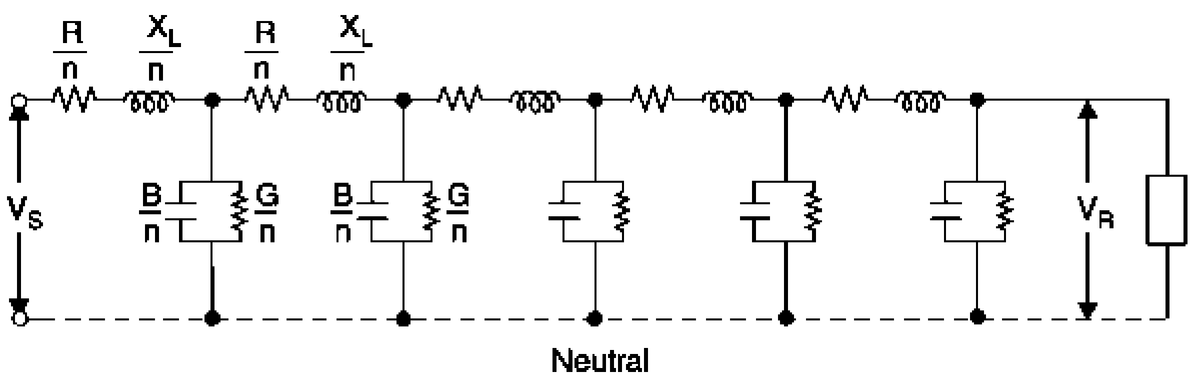


Figure shows the equivalent circuit of a 3-phase long transmission line on a phase-neutral basis. The whole line length is divided into *n* sections, each section having line constants 1/nth of those for the whole line. The following points may by noted:

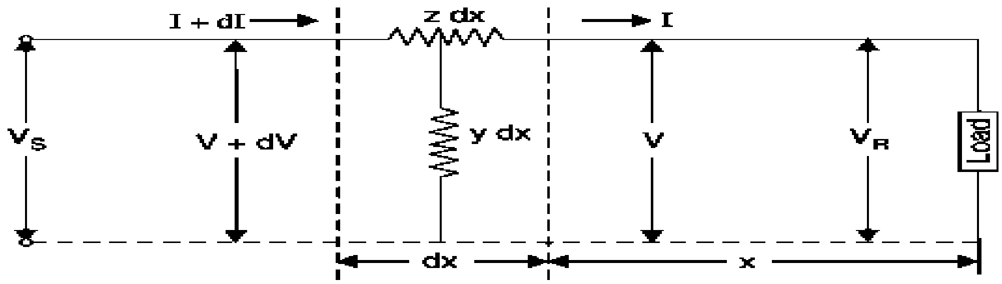
- The line constants are uniformly distributed over the entire length of line as is actually the case.
- The resistance and inductive reactance are the series elements.
- The leakage susceptance (*B*) and leakage conductance (*G*) are shunt elements. The leakage susceptance is due to the fact that capacitance exists between line and neutral. The leakage conductance takes into account the energy losses occurring through leakage over the insulators or due to corona effect between conductors

$$Admittane = \sqrt{G^2 + B^2}$$

- The leakage current through shunt admittance is maximum at the sending end of the line and decreases continuously as the receiving end of the circuit is approached at which point its value is zero.

ANALYSIS OF LONG TRANSMISSION LINE (RIGOROUS METHOD) :

Below figure shows one phase and neutral connection of a 3-phase line with impedance and shunt admittance of the line uniformly distributed



Consider a small element in the line of length dx situated at a distance x from the receiving end,
Let, z= series impedance of the line per unit length

y= shunt admittance of the line per unit length

V= voltage at the end of element towards receiving end

V+ dV= voltage at the end of element towards sending end

I+ dI= current entering the element dx

I= current leaving the element dx

Then for the small element dx,

zdx= series impedance

ydx= shunt admittance

obviously, dV= l z dx

dV/dx = l z ………… (i)

Now the current entering the element is I+dI whereas the current leaving the element is I. the difference in the current flows through shunt admittance of the element i.e.,

dI= current through shunt admittance of element = V y dx

dI/dx = V y ……………. (ii)

Differentiating eq. (i) w.r.t x, we get,

$$\frac{d^2V}{dx^2} = z\,\frac{dI}{dx} = z\,(Vy) \qquad \textit{from the eqn (ii)}$$

$$\frac{d^2V}{dx^2} = y\,z\,V \qquad \ldots\ldots\ldots\ldots\ldots..(iii)$$

The solution of this differential equation is

$$V = K_1 \cos h\,(x\sqrt{yz}) + K_2 \sin h\,(x\sqrt{yz}) \quad \ldots\ldots\ldots\ldots\ldots.(iv)$$

Differentiate eq. (iv) w.r.t x, we get,

$$\frac{dV}{dx} = K_1\,\sqrt{yz}\sin h\,(x\sqrt{yz}) + K_2\,\sqrt{yz}\cos h\,(x\sqrt{yz})$$

But

$$\frac{dV}{dx} = I\,z \qquad \textit{from the eqn (i)}$$

$$I\,z = K_1\,\sqrt{yz}\sin h\,(x\sqrt{yz}) + K_2\,\sqrt{yz}\cos h\,(x\sqrt{yz})$$

$$I = \sqrt{\frac{y}{z}}[K_1\ \sin h\,(x\sqrt{yz}) + K_2\ \cos h\,(x\sqrt{yz})] \quad \ldots\ldots\ldots\ldots\ldots.(v)$$

Equating the (iv) and (v) gives expression for V and I in the form of unknown constant K_1 and K_2. The values of K_1 and K_2 can be found by applying end condition as under:

At x = 0, $V = V_R$ and $I = I_R$

Putting these values in eq (iv), we have,

$$V_R = K_1 \cos h\ 0 + K_2 \sin h\ 0 = K_1 + 0$$

$$V_R = K_1$$

Similarly, putting x = 0, V = V_R and I = I_R in eq (v), we get,

$$I_R = \sqrt{\frac{y}{z}}[K_1 \ \sin h\ 0 + K_2 \ \cos h\ 0] = \sqrt{\frac{y}{z}}[0 + K_2]$$

$$K_2 = \sqrt{\frac{y}{z}} I_R$$

Substituting the values of K_1 and K_2 in eq (iv) and (v), we get

$$V = V_R \cos h \left(x\sqrt{yz}\right) + \sqrt{\frac{y}{z}} I_R \ \sin h \left(x\sqrt{yz}\right)$$

$$I = \sqrt{\frac{y}{z}} V_R \ \sin h \left(x\sqrt{yz}\right) + I_R \cos h \left(x\sqrt{yz}\right)$$

The sending end voltage V_S and sending end current I_S are obtained by putting x=l in the above equation i.e..,

$$V_S = V_R \cos h \left(l\sqrt{yz}\right) + \sqrt{\frac{z}{y}} I_R \ \sin h \left(l\sqrt{yz}\right)$$

$$I_S = \sqrt{\frac{y}{z}} V_R \ \sin h \left(l\sqrt{yz}\right) + I_R \cos h \left(l\sqrt{yz}\right)$$

$$l\sqrt{yz} = \sqrt{l\,y.l\,z} = \sqrt{YZ}$$

$$\sqrt{\frac{y}{z}} = \sqrt{\frac{y\,l}{z\,l}} = \sqrt{\frac{Y}{Z}}$$

Where Y = total shunt admittance of the line

Z= total series impedance of the line

Therefore expression for V_S and I_S become:

$$\boldsymbol{V_S = V_R \cos h \left(\sqrt{YZ}\right) + \sqrt{\frac{Z}{Y}} I_R \ \sin h \left(\sqrt{YZ}\right)}$$

$$\boldsymbol{I_S = \sqrt{\frac{y}{z}} V_R \ \sin h \left(\sqrt{YZ}\right) + I_R \cos h \left(\sqrt{YZ}\right)}$$

It is helpful to expand hyperbolic sine and cosine in terms of their power series

$$\cosh\sqrt{YZ} = [1 + \frac{ZY}{2} + \frac{Z^2+Y^2}{24} + \cdots \ldots]$$

$$\sinh\sqrt{YZ} = [\sqrt{YZ} + \frac{[YZ]^{\frac{3}{2}}}{6} \ldots \ldots]$$

Problem 1: **A 3-phase transmission line 200km long has the following constants Resistance /phase/km=0.16Ω ,Reactance/phase/km=0.25Ω Shunt admittance/phase/km= 1.5*10-6 S**

Calculate by rigorous method the sending end voltage and current when the line is delivering a load of 20 MW at 0.8 p.f lagging

Total resistance / phase, $R = 0.16 \times 200 = 32\Omega$

Total reactance / phase, $X_L = 0.25 \times 200 = 50\Omega$

Total shunt admittance / phase, $Y = j\,1.5 \times 10^{-6} \times 200 = 0.0003 \angle 90°$

Series impedance/ phase, $Z = R + j\,X_L = 32 + j\,50 = 59.4 \angle 58°$

The sending end voltage V_S is given by:

$$V_S = V_R \cosh\sqrt{YZ} + I_R\sqrt{\frac{Z}{Y}}\sinh\sqrt{ZY} \quad \dots\dots\dots(i)$$

Now $$\sqrt{ZY} = \sqrt{59.4 \angle 58° \times 0.0003 \angle 90°} = 0.133 \angle 74°$$

$$ZY = 0.0178 \angle 148°$$

$$Z^2Y^2 = 0.00032 \angle 296°$$

$$\sqrt{\frac{Z}{Y}} = \sqrt{\frac{59.4 \angle 58°}{0.0003 \angle 90°}} = 445 \angle -16°$$

$$\sqrt{\frac{Y}{Z}} = \sqrt{\frac{0.0003 \angle 90°}{59.4 \angle 58°}} = 0.00224 \angle 16°$$

$$\cosh\sqrt{YZ} = 1 + \frac{ZY}{2} + \frac{Z^2 + Y^2}{24} \quad approximately$$

$$= 1 + \frac{0.0178}{2}\angle 148° + \frac{0.00032}{24}\angle 296°$$

$$= 1 + 0.0089 \angle 148° + 0.0000133\angle 296°$$

$$= 1 + 0.0089(-0.848 + j\,0.529) + 0.0000133\,(0.438 - j\,0.9)$$

$$= 0.992 + j\,0.00469 = 0.992 \angle 0.26°$$

$$\sinh\sqrt{YZ} = [\sqrt{YZ} + \frac{[YZ]^{\frac{3}{2}}}{6}\dots\dots] \quad approximately$$

$$= 0.133\angle 74° + \frac{0.00224 \angle 16°}{6}$$

$$= 0.133\angle 74° + 0.0004\angle 222°$$

$$= 0.133(0.275 + j\,0.961) + 0.0004(-0.743 - j\,0.67)$$

$$= 0.0362 + j\,0.1275 = 0.1325\angle 74.6°$$

Receiving end voltage per phase is

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

Receiving end current,

$$I_R = \frac{20 \times 10^6}{\sqrt{3} \times 110 \times 10^3 \times 0.8} = 131\ A$$

Putting various values in exp (i) we get,

$$V_S = 63508 \times 0.992\angle 0.26° + 131 \times 445\angle -16° \times 0.1325\angle 74.6°$$

$$= 63000\ \angle 0.26° + 7724\ \angle 58.6°$$

$$= 63000\ (0.999 + j\ 0.0045) + 7724\ (0.5284 + j\ 0.8489)$$

$$= 67018 + j\ 6840 = 67366\ \angle 5.50°$$

Sending end line to line voltage,

$$= 67366 \times \sqrt{3} = 116.67 \times 10^3 V = 116.67KV$$

The sending end current I_S is given by,

$$I_S = \sqrt{\frac{y}{z}} V_R\ \sin h\left(\sqrt{YZ}\right) + I_R \cos h\left(\sqrt{YZ}\right)$$

Putting various values, we get,

$$I_S = 63508 \times 0.00224\ \angle 16° \times 0.1325\angle 74.6° + 131 \times 0.992\angle 0.26°$$

$$= 18.85\ \angle 90.6° + 130\angle 0.26°$$

$$= 18.85(-0.0017 + j\ 0.999) + 130(0.999 + j\ 0.0045)$$

$$= 129.83 + j\ 19.42 = 131.1\angle 8°\ A = 131.1\ A$$

GENERALIZED CIRCUIT CONSTANTS OF A TRANSMISSION LINE:

In any four terminal networks, the input voltage and input current can be expressed in terms of output voltage and output current. Incidentally, a transmission line is four-terminal network: two input terminal where power enters the network and two output terminals where power leaves the network.

Therefore the input voltage ($\overrightarrow{V_S}$) and input current ($\overrightarrow{I_S}$) of a 3-phase transmission line can be expressed as:

$$\overrightarrow{V_S} = \vec{A}\,\overrightarrow{V_R} + \vec{B}\,\overrightarrow{I_R}$$

$$\overrightarrow{I_S} = \vec{C}\,\overrightarrow{V_R} + \vec{D}\,\overrightarrow{I_R}$$

Where, $\overrightarrow{V_S}$ = sending end voltage per phase

$\overrightarrow{I_S}$ = sending end current

$\overrightarrow{V_R}$ = receiving end voltage per phase

$\overrightarrow{I_R}$ = receiving end current

And $\vec{A}$, $\vec{B}$, $\vec{C}$ and $\vec{D}$ are constants known as generalised circuit constant of the transmission line. The values of these constants depend upon the particular method adopted for solving a transmission line. Once the values of these constants are known, performance calculation of the line can be easily worked out.

The following points should be kept in mind.

- The constants $\vec{A}$, $\vec{B}$, $\vec{C}$ and $\vec{D}$ are generally complex number
- The constants $\vec{A}$ $\vec{D}$ are dimensionless whereas the dimensions of $\vec{B}$, $\vec{C}$ are ohms and siemen respectively
- For a given transmission line $\vec{A} = \vec{D}$
- For a given transmission line

$$\vec{A}\,\vec{D} - \vec{B}\,\vec{C} = 1$$

DETERMINATION OF GENERALIZED CONSTANTS FOR TRANSMISSION LINES:

The sending end voltage ($\vec{V_S}$) and sending end current ($\vec{I_S}$) of transmission line can be expressed as:

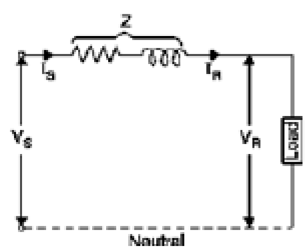
$$\vec{V_S} = \vec{A}\,\vec{V_R} + \vec{B}\,\vec{I_R} \quad \ldots\ldots\ldots\ldots (i)$$

$$\vec{I_S} = \vec{C}\,\vec{V_R} + \vec{D}\,\vec{I_R} \quad \ldots\ldots\ldots\ldots (ii)$$

Now determine the values of these constants for different types of transmission line

SHORT LINES:

In short transmission line capacitance is neglected. Therefore the line is considered to have series impedance. Figure shows the circuit of a 3-phase transmission line on single phase basis



Here, $$\vec{I_S} = \vec{I_R} \quad \ldots\ldots\ldots\ldots\ldots (iii)$$

$$\vec{V_S} = \vec{V_R} + \vec{I_R}\,\vec{Z} \quad \ldots\ldots\ldots\ldots\ldots (iv)$$

Comparing these with equation (i) and (ii), we have

$$\vec{A} = 1; \qquad \vec{B} = \vec{Z}; \qquad \vec{C} = 0; \qquad \vec{D} = 1$$

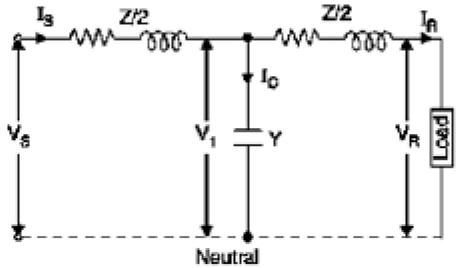
Incidentally,

$$\vec{A} = \vec{D}$$

$$\vec{A}\,\vec{D} - \vec{B}\,\vec{C} = 1 \times 1 - \vec{Z} \times 0 = 1$$

MEDIUM LINES- NOMINAL T METHOD:

The whole line to neutral capacitance is assumed to be concentrated at the middle point of the line and half the line resistance and reactance are lumped on either side as shown in below figure



Here, $\vec{V_S} = \vec{V_1} + \vec{I_R}\,\vec{Z}/2 \quad \ldots\ldots\ldots\ldots\ldots(v)$

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

Now, $\vec{I_{c1}} = \vec{I_S} - \vec{I_R}$

$= \vec{V_1}\,\vec{Y}$ *where* $\vec{Y}$ *= shunt admittance*

$$\vec{I_S} = \vec{I_R} + \vec{Y}\,\vec{V_R} + \vec{Y}\,[\vec{V_R} + \frac{\vec{I_R}\,\vec{Z}}{2}]$$

$$= \vec{Y}\,\vec{V_R} + \vec{I_R}[1 + \frac{\vec{Y}\,\vec{Z}}{2}] \quad \ldots\ldots\ldots\ldots\ldots(vi)$$

Substituting the values of V_1 in eq (v), we get,

$$\vec{V_S} = \vec{V_R} + \frac{\vec{I_R}\,\vec{Z}}{2} + \frac{\vec{I_S}\,\vec{Z}}{2}$$

Substituting the values of I_S, we get

$$\vec{V_S} = 1 + \frac{\vec{Y}\,\vec{Z}}{2}\,\vec{V_R} + [\vec{Z} + \frac{\vec{Y}\,\vec{Z}^2}{4}]\vec{I_R}$$

Comparing equation (vii) and (vi) with those of (i) and (ii), we have

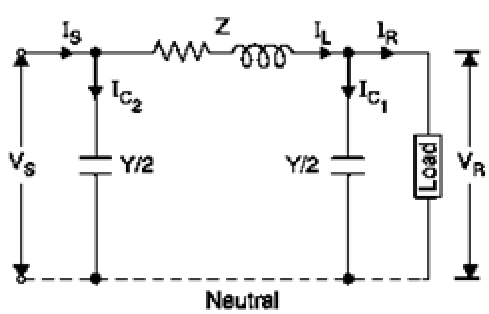
$$\vec{A} = \vec{D} = 1 + \frac{\vec{Y}\,\vec{Z}}{2}; \qquad \vec{B} = \vec{Z}\left[1 + \frac{\vec{Y}\,\vec{Z}}{4}\right]; \qquad \vec{C} = \vec{Y}$$

Incidentally:

$$\vec{A}\,\vec{D} - \vec{B}\,\vec{C} = [1 + \frac{YZ}{2}]^2 - Z\left[1 + \frac{YZ}{2}\right]Y$$
$$= 1 + \frac{Y^2Z^2}{4} + YZ - ZY - \frac{Z^2Y^2}{4} = 1$$

MEDIUM LINES-NOMINAL Π METHOD:

In this method, line to neutral capacitance is divided into two halves one half being concentrated at the load end and the other half at the sending end as shown in below figure.



Here, $\vec{Z} = R + jX_L$

$$\vec{Y} = j\,\omega\,C = shunt\ admittance$$

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

$$\vec{I_S} = \vec{I_L} + \frac{\vec{V_S}\,\vec{Y}}{2} \quad \dots\dots\dots\dots\dots (viii)$$

$$\vec{I_L} = \vec{I_R} + \overrightarrow{I_{C1}} = \vec{I_R} + \frac{\vec{V_R}\,\vec{Y}}{2} \dots\dots\dots.(ix)$$

$$\vec{V_S} = \vec{V_R} + \vec{I_L}\,\vec{Z} = \vec{V_R} + [\vec{I_R} + \frac{\vec{V_R}\vec{Y}}{2}]\,\vec{Z}$$

$$\vec{V_S} = \vec{V_R}\left[1 + \frac{\vec{Y}\,\vec{Z}}{2}\right] + \vec{I_R}\,\vec{Z} \quad \dots\dots\dots\dots.(x)$$

$$\vec{I_S} = \vec{I_L} + \frac{\vec{V_S}\,\vec{Y}}{2} = \vec{I_R} + \frac{\vec{V_R}\vec{Y}}{2} + \frac{\vec{V_S}\vec{Y}}{2}$$

Putting the values of $\vec{V_S}$ from eqn (x), we get.

$$\vec{I_S} = \vec{I_R} + \frac{\overrightarrow{V_R}\vec{Y}}{2} + \frac{\vec{Y}}{2}\,\{\vec{V_R}\left[1 + \frac{\vec{Y}\,\vec{Z}}{2}\right] + \vec{I_R}\,\vec{Z}\}$$

$$= \vec{I_R} + \frac{\overrightarrow{V_R}\vec{Y}}{2} + \frac{\overrightarrow{V_R}\vec{Y}}{2} + \frac{\overrightarrow{V_R}\vec{Y}^2\vec{Z}}{4} + \frac{\vec{Y}\,\overrightarrow{I_R}\vec{Z}}{2}$$

$$= \vec{I_R}\left[1 + \frac{\vec{Y}\,\vec{Z}}{2}\right] + \overrightarrow{V_R}\vec{Y}\left[1 + \frac{\vec{Y}\,\vec{Z}}{4}\right] \dots\dots\dots\dots.(xi)$$

Comparing equation (x) and (xi) with those of (i) and (ii), we get,

$$\vec{A} = \vec{D} = 1 + \frac{\vec{Y}\,\vec{Z}}{2}; \qquad \vec{B} = \vec{Z}; \quad \vec{C} = \vec{Y}\left[1 + \frac{\vec{Y}\,\vec{Z}}{4}\right]$$

$$\vec{A}\,\vec{D} - \overrightarrow{B}\,\vec{C} = [1 + \frac{YZ}{2}]^2 - ZY\left[1 + \frac{YZ}{4}\right]$$

$$= 1 + \frac{Y^2Z^2}{4} + YZ - ZY - \frac{Z^2Y^2}{4} = 1$$

(i) Long lines-Rigorous method: By rigorous method, the sending end voltage and current of a long transmission line are given by:

$$\vec{V_S} = \vec{V_R}\cosh\sqrt{YZ} + \vec{I_R}\sqrt{\frac{Z}{Y}}\,\sinh\sqrt{YZ}$$

$$I_S = \sqrt{\frac{Y}{Z}}V_R\ \sin h\,(\sqrt{YZ})\ + I_R \cos h\,(\sqrt{YZ})$$

Comparing these equations with those of (i) and (ii), we get

$$\vec{A} = \vec{D} = \cosh\sqrt{YZ}\,; \quad \vec{B} = \sqrt{\frac{Z}{Y}}\,\sinh\sqrt{YZ}\,; \quad \vec{C} = \sqrt{\frac{Y}{Z}}V_R\ \sin h\,(\sqrt{YZ})$$

Incidentally

$$\vec{A}\,\vec{D} - \vec{B}\,\vec{C} = \cosh\sqrt{YZ}\ \times \cosh\sqrt{YZ} - \sin h\,(\sqrt{YZ})\ \times \sin h\,(\sqrt{YZ})$$

$$= cosh^2\sqrt{YZ} - sinh^2\sqrt{YZ} = 1$$

Problem 1: **A balanced 3-phase load of 30MW is supplied at 132kV, 50Hz and 0.85 p.f laging by means of a transmission line. The series impedance of a single conductor is (20+j52) ohms and the total phase neutral admittance is 315*10-6 siemen. Using nomila T method, determine: i) the A, B, C and D constants of the line ii) sending end voltage iii) regulation of the line**

Solution:

Figure shows the representation of 3 phase line on the single phase basis

Series line impedance/phase, $\bar{Z} = (20 + j52)\Omega$

Shunt admittance/phase, $\bar{Y} = j315 \times 10^{-6} S$

i) *Generalized constants of line. For nominal T method, various constants have the values as under*

$$\bar{A} = \bar{D} = 1 + \frac{\bar{Z}\bar{Y}}{2} = 1 + \frac{20 + j52}{2} \times j315 \times 10^{-6}$$

$$0.992 + j0.00315 = 0.992\angle 0.18°$$

$$\bar{B} = \bar{Z}\left[1 + \frac{\bar{Z}\bar{Y}}{4}\right] = (20 + j52)\left[1 + \frac{(20 + j52)j315 \times 10^{-6}}{4}\right]$$

$$19.84 + j51.82 = 55.5\angle 69°$$

$$\bar{C} = \bar{Y} = 0.000315\angle 90°$$

$$\bar{I_L} = \bar{I_R} + \bar{I_{C1}} = \bar{I_R} + \bar{V_R}\bar{Y}/2$$

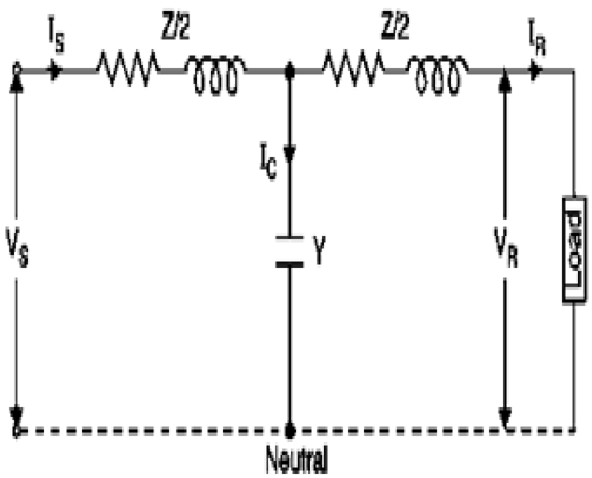
$$\bar{V_S} = \bar{V_R} + \bar{I_L}\bar{Z} = \bar{V_R} + (\bar{I_R} + \bar{V_R}\bar{Y}/2)\bar{Z} \ \ (\text{putting the value of } \bar{I_L})$$

$$\bar{V_S} = \bar{V_R}\left(1 + \frac{\bar{Y}\bar{Z}}{2}\right) + \bar{I_R}\bar{Z}$$

$$\bar{I_S} = \bar{I_L} + \bar{V_S}\bar{Y}/2 = (\bar{I_R} + \bar{V_R}\bar{Y}/2) + \bar{V_S}\bar{Y}/2 \ \ (\text{putting the value of } \bar{I_L})$$

Putting the value of $\bar{V_S}$, we get

$$\bar{I_S} = \left(\bar{I_R} + \frac{\bar{V_R}\bar{Y}}{2}\right) + \frac{\bar{Y}}{2}\left\{\bar{V_R}\left(1 + \frac{\bar{Y}\bar{Z}}{2}\right) + \bar{I_R}\bar{Z}\right\}$$



ii) *Sending end voltage*

Receiving end voltage/phase, $V_R = 132 \times \frac{10^3}{\sqrt{3}} = 76210\ V$

Receiving end current, $I_R = \frac{30\times10^6}{\sqrt{3}\times132\times10^3\times0.85} = 154A$

$$\cos\Phi_R = 0.85;\ \sin\Phi_R = 0.53$$

Taking receiving end voltage as the reference phasor, we have

$$\overline{V_R} = V_R + j0 = 76210V$$

$$\overline{I_R} = I_R(\cos\Phi_R - j\sin\Phi_R) = 154(0.85 - j0.53) = 131 - j81.62$$

Sending end voltage per phase is

$$\overline{V_S} = \overline{A}\overline{V_R} + \overline{B}\overline{I_R}$$

$$= (0.992 + j0.0032)76210 + (19.84 + j51.82)(131 - j81.62)$$

$$= 82.428 + j5413$$

∴Magnitude of sending end voltage is

$$V_S = \sqrt{(82.428)^2 + (5413)^2} = 82.6\times10^3V = 82.6kV$$

∴ sending end line to line voltage is

$$= 82.6\times\sqrt{3} = 143kV$$

iii) *Regulation:*

Regulation is defined as the change in voltage at the receiving end when full load is thrown off.

Now,

$$\overline{V_S} = \overline{A}\overline{V_R} + \overline{B}\overline{I_R}$$

At no load,

$$\overline{I_R} = 0$$

$$\therefore \overline{V_S} = \overline{A}\overline{V_{R0}}$$

$$where$$

$$\overline{V_{R0}} = voltage\ at\ receiving\ end\ at\ no\ load$$

$$\overline{V_{R0}} = \overline{V_S}/\overline{A}$$

$$V_{R0} = V_A/A\ \ (in\ magnitude)$$

$$\%\ regulation = \frac{(V_S/A - V_R)}{V_R}\times100 = \frac{(82.6/0.992 - 76.21)}{76.21}\times100 = 9.25\%$$

Problem 2: **A 132 kV, 50Hz, 3-phase transmission line delivers a load of 50MW at 0.8 pf lagging at the receiving end. The generalized constants of the transmission line are:**

$$\boldsymbol{A = D = 0.95\angle1.4°;\ B = 96\angle78°;\ C = 0.015\angle90°;}$$

Find the regulation of the line and charging current. Use nominal T method

Solution:

$$Receiving\ end\ voltage\ /phase.\ \ V_R = 132\times10^3/\sqrt{3} = 76210V$$

$$Receiving\ end\ current = I_R = \frac{50\times10^6}{\sqrt{3}\times132\times10^3\times0.8} = 273A$$

$$\cos\Phi_R = 0.8; \quad \sin\Phi_R = 0.6$$

Taking receiving end voltage as the reference phasor, we have

$$\overline{V_R} = V_R + j0 = 76210\angle 0°$$

$$\overline{I_R} = I_R\angle -\Phi_R = 273\angle -36.9°$$

Sending end voltage per phase is

$$\overline{V_S} = \overline{A}\overline{V_R} + \overline{B}\overline{I_R}$$
$$= 0.95\angle 1.4° \times 76210\angle 0° + 96\angle 78° \times 273\angle -36.9°$$
$$= 72400\angle 1.4° + 26208\angle 41.1°$$
$$= 72400(\cos 1.4° + j\sin 1.4°) + 26208(\cos 1.4° + j\sin 1.4°)$$
$$= 72400(0.9997 + j0.0244) + 26208(0.7536 + j0.6574)$$
$$= (72738 + j1767) + (19750 + j17229)$$
$$= 92128 + j18996 = 94066\angle 11.65°$$

Sending end current,

$$\overline{I_S} = \overline{C}\overline{V_R} + \overline{D}\overline{I_R}$$

$$= 0.0015\angle 90° \times 76210\angle 0° + 0.95\angle 1.4° \times 273\angle -36.9°$$

$$= 114\angle 90° + 260\angle -35.5°$$

$$= 114(\cos 90° + j\sin 90°) + 260(\cos 35.5° - j\sin 35.5°)$$

$$= 114(0 + j) + 260(0.814 - j0.58)$$

$$= j114 + 211 - j150 = 211 - j36$$

Charging current,

$$\overline{I_C} = \overline{I_S} - \overline{I_R} = (211 - j36) - 273\angle -36.9°$$

$$= (211 - j36) - (218 - j164) = -7 + j128 = 128.2\angle 93.1° A$$

$$\%\,Regulation = \frac{(V_S/A) - V_R}{V_R} \times 100 = \frac{(94066/0.95) - 76210}{76210} \times 100 = 30\%$$

SURGE IMPEDANCE:

The characteristic impedance is sometimes referred as surge impedance. It is also termed as natural loading

"It is defined as square root of the ratio of total series impedance to the total shunt admittance"

$$Z_o = \sqrt{\frac{Z}{Y}}$$

Z = series impedance of line = R + j X

Y = shunt admittance of line = G + j B

The term surge impedance is normally reserved for the special case of a lossless line. For lossless line, its resistance and conductance are zero. (ie., R=0 and G=0)

Thus the characteristic impedance reduces to

$$Z_o = \sqrt{\frac{L}{C}}$$

which is nothing but a pure resistance in terms of dimensions.

SURGE IMPEDANCE VALUE

Overhead transmission line -------- Normally 400 to 600 .

Underground cable ------------ Between 40 to 60 .

The phase value of Zc for transmission line is usually between0 °and -15°

SURGE IMPEDANCE LOADING (SIL):

"The surge impedance loading (SIL) is defined as the load, at unity power factor, power can be delivered by the line having No resistance".
The line is assumed to have no resistance. With such loading, the current will be

$$|I_R| = \frac{|V_R|}{\sqrt{3}\sqrt{L/C}}$$

Where , V_R is the line to line voltage at the load.

As the load is purely resistive we have,

$$SIL = \sqrt{3}|V_R|\frac{|V_R|}{\sqrt{3}\sqrt{L/C}} = \frac{|V_R|^2}{\sqrt{L/C}}$$

$$\therefore \qquad SIL = \frac{V_R^2}{Z_C}$$

SIL is also called natural power of the line. Sometimes it is convenient to express the power transmitted by a line in terms of per unit of SIL which is the ratio of the power transmitted to the surge impedance loading. The permissible loading of a transmission line may be expressed as a fraction of its SIL and SIL provides a comparison of load carrying capabilities of lines. If surge impedance,

$$Z_C = 400\Omega$$

$$SIL = \frac{V_R^2}{400} = 2.5|V_R|^2 \quad kW$$

The above equation puts on the maximum power that can be delivered which is helpful in designing the transmission lines. By increasing the value of receiving end voltage, the power transmitted through long transmission line can be increased. It can also be increased by using more than one transmission lines in parallel. But the method is costly. Hence for increasing SI-V R is increased or Zc is decreased.

Problem 1: **A 3 phase transmission line 100 km long has the following constants Resistance / phase / km = 0.15 n Reactance / phase / km = 0.200 Shunt admittance / phase / km = 1.5 x 10- 6 mho Calculate by rigorous method the sending end voltage and current when the line is delivering a load of 30 MW at 0.8 pf lagging. The receiving end voltage is kept constant at 110 kV.**
Solution:

$$Total\ \ ressitance/phase\ ,R = 0.15 \times 100 = 15\Omega$$

$$Total\ \ reactance/phase\ ,X_L = 0.20 \times 100 = 20\Omega$$

$$Total\ \ shunt\ admitance/phase\ ,Y = 1.5 \times 10^{-6} \times 100 = 1.5 \times 10^{-4} mho$$

$$Series\ impendance, Z = R + jX_L = 15 + j20 = 25\angle 53.13°\Omega$$

$$Shunt\ admittance, Y = +j1.5 \times 10^{-4} = 1.5 \times 10^{-4}\angle 90°\, mho$$

The sending end voltage Vs per phase is given by,

$$V_S = V_R \cosh\sqrt{YZ} + I_R\sqrt{\frac{Y}{Z}}\sinh\sqrt{ZY}$$

$$\sqrt{ZY} = \sqrt{(25\angle 53.13°)(1.5 \times 10^{-4}\angle 90°)} = 0.0612\angle 71.565$$

$$ZY = 3.745 \times 10^{-3}\angle 143.13$$

$$Z^2Y^2 = 1.4025 \times 10^{-5}\angle 286.26$$

$$\sqrt{\frac{Z}{Y}} = \sqrt{\frac{25\angle 53.13°}{1.5 \times 10^{-4}\angle 90°}} = 408.24\angle -18.43°$$

$$\sqrt{\frac{Y}{Z}} = \sqrt{\frac{1.5 \times 10^{-4}\angle 90°}{25\angle 53.13°}} = 2.44 \times 10^{-3}\angle -18.43°$$

$$\cosh\sqrt{YZ} = 1 + \frac{YZ}{2} + \frac{Y^2Z^2}{24}$$

$$= 1 + \frac{3.745 \times 10^{-3}}{2}\angle 143.13° + \frac{1.4025 \times 10^{-25}}{24}\angle 286.26°$$

$$= 1 + 1.8725 \times 10^{-3}\angle 143.13° + 5.8437 \times 10^{-7}\angle 286.26°$$

$$= 1 + (-1.49 \times 10^{-3} + j1.12 \times 10^{-3}) + (1.63 \times 10^{-7} + j5.61 \times 10^{-7})$$

$$= 0.9985 + j1.11 \times 10^{-3} = 0.9985\angle 0.0642°$$

$$\sinh(\sqrt{YZ}) = \sqrt{YZ} + \frac{(YZ)^{3/2}}{6}$$

$$= [0.0612\angle 71.56°] + \frac{[3.745 \times 10^{-3}\angle 143.13°]^{3/2}}{6}$$

$$= [0.0612\angle 71.56°] + \frac{2.29180 \times 10^{-4}\angle 143.13°}{6}$$

$$= [0.019 + j0.058] + [-3.055 \times 10^{-5} j2.291 \times 10^{-5}]$$

$$= 0.018 + j0.058$$

$$= 0.060\angle 72.76°$$

$$V_{R\,phase} = \frac{V_{R\,line}}{\sqrt{3}} = \frac{110 \times 10^3}{\sqrt{3}} = 63508V$$

$$I_R = \frac{Power\ delivered}{\sqrt{3} \times V_R \times \cos\emptyset_R} = \frac{30 \times 10^6}{\sqrt{3} \times 100 \times 10^3 \times 0.8} = 196.82A$$

Putting the above values in equation (1)

$$V_S = (63508)(0.9985\angle 0.0642°) + (196.82)(408.24\angle -18.43°)(0.060\angle 72.76°)$$

$$= [63412.73\angle 0.0642°] + [4820\angle 54.33°]$$

$$= [63412.9 + j71.05] + [2810.61 + l3915.71]$$

$$= 66223 + j3986.76$$

$$= 66343.197\angle 3.44°\ volts$$

$$V_S = 66.343 volts$$

$$Line\ voltage\ at\ sending\ end = \sqrt{3} \times 66.343 = 114.90kV$$

$$\overline{I_S} = V_R\sqrt{\frac{Y}{Z}}\sinh\sqrt{YZ} + I_R\cosh\sqrt{YZ}$$

$$= (63508)(2.44 \times 10^{-3})\angle 18.43°(0.06\angle 72.76°) + (196.82)(0.09985\angle 0.0642°)$$

$$= (9.29\angle 91.29°) + (196.52\angle 0.0642°)$$

$$= (-0.1929 + j9.2879) + (196.51 + j0.2202)$$

$$= 196.31 + j9.5081$$

$$196.54\angle 2.77° A$$

$$I_S = 196.54A$$

CIRCLE DIAGRAM:

To represent characteristics of transmission line graphically. By taking Vs, VR Is or IR as a reference these characteristics can be plotted. These characteristics are nothing but representing circles. Hence such diagrams are called circle diagram. A circle diagram is drawn with real power P on X-axis and Q on Y axis on complex plane.

The circle diagram can be drawn at the sending end as well as at the receiving end.

These diagrams are helpful for determination of active power P, reactive power Q, power angle **δ**, power factor for given load conditions, voltage conditions and impedance Z of the line.

5. **Explain the receiving end power circle diagram**. (APRIL/2012) (or) **Explain the various steps involved to draw the receiving end power circle diagram with neat sketches. Write its significance** (APRIL/2014)(or) **Write in detail about power circle diagram for receiving ends.** (NOV/2012)

RECEIVING END CIRCLE DIAGRAM:

The complex power at the receiving end is given by,

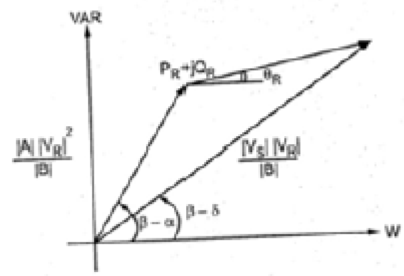
$$S_R = P_R + jQ_R$$

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

$$P_R = \frac{|V_S||V_R|}{|B|}\cos(\beta - \delta) - \frac{|A||V_R|^2}{|B|}\cos(\beta - \alpha)$$

$$Q_R = \frac{|V_S||V_R|}{|B|}\sin(\beta - \delta) - \frac{|A||V_R|^2}{|B|}\sin(\beta - \alpha)$$

This complex power can be plotted in the complex plane with horizontal and vertical components having the units of powers. This is shown in below figure



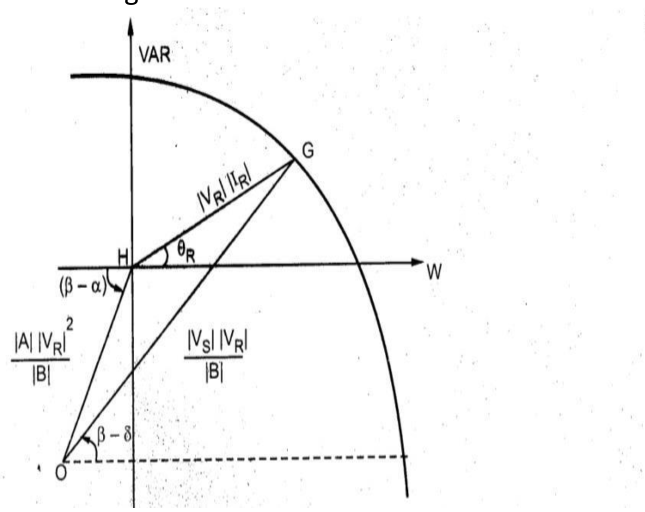
The real component is (P_R+ j Q_R) is, $P_R = |V_{SR}||I_R|\cos\theta_R$

Where, θ_R is p.f. at the receiving end

The imaginary component of (P_R+ j Q_R) is, $Q_R = |V_R||I_R|\sin\theta_R$

Here Θ_R is the phase angle by which I_R lags behind V_R. By convention we will consider that inductive load draws positive reactive power

Now if the same phasor diagram is redrawn with the origin of the co-ordinates axes shifted, then the resultant figure is shown in below figure



Now we will show that the locus of operating point is circles with centre at O. For this consider the phasor diagram shown in below figure.

It can be shown that for constant values of V_R and V_S and for variable values of I_R, the point G moves on a circle with centre O.

In $\nabla\, OGH$

$$V_S = |A||V_R|[-\cos(\beta-\alpha) + \ jsin(\beta-\alpha)\,] + |B||I_R|[\cos\theta_R - \ jsin\theta_R\,]$$

$$= |A||V_R|[-\cos(\beta-\alpha)] + |B||I_R|\cos\theta_R + j[|A||V_R|\sin(\beta-\alpha) - |B||I_R|sin\theta_R]$$

Let $|A||V_R|[\cos(\beta-\alpha)] = -X_1$

$$|B||I_R|\cos\theta_R = X_2$$

$$|A||V_R|[\sin(\beta-\alpha)] = Y_1$$

$$|B||I_R|\sin\theta_R = -Y_2$$

The above equations are now reduced as

$$V_S = (x_1 + x_2) + j(y_1 + y_2) \ldots\ldots(1)$$

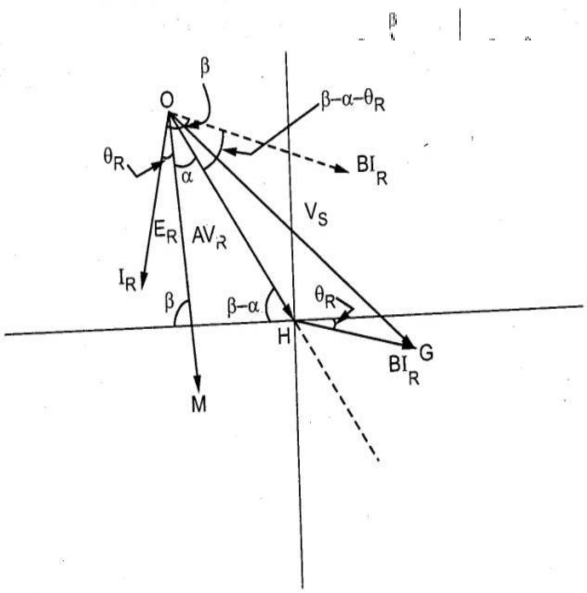
The conjugate of V_S can be written as,

$$V_S^* = (x_1 + x_2) - j(y_1 + y_2) \ldots\ldots(2)$$

Multiplying equation (1) and (2) we get,

$$V_S^2 = (x_1+x_2)^2 + (y_1+y_2)^2$$

The above equation represents a circle with its centre at O and having co-ordinates



All the phasor shown in above figure represent voltage. In order to represent them as volt amperes, multiply each phasor by constant V_R /B which represents a current phasor because B has dimensions of impedance.

The co-ordinates of the centre of the receiving end circle are given as

$$x_1 = -\frac{|A||V_R|^2}{|B|}\cos(\beta-\alpha)$$

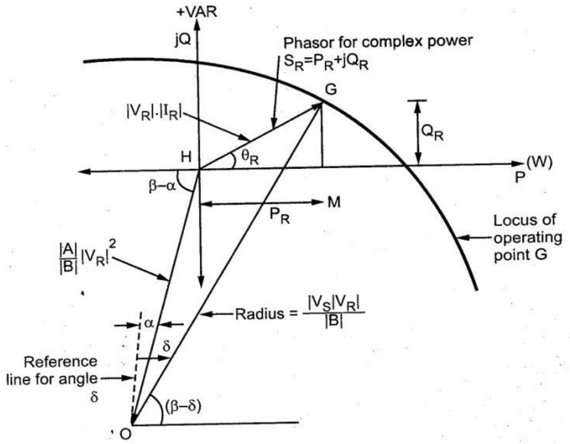
$$y_1 = -\frac{|A||V_R|^2}{|B|}\sin(\beta-\alpha)$$

The radius OG of the circle is given by,

$$Radius = \frac{|V_S||V_R|}{|B|}$$

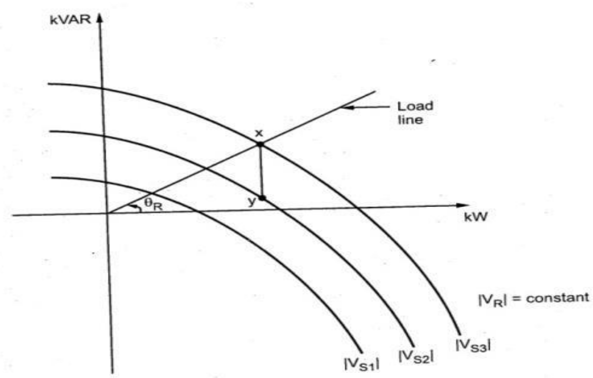
The Θ_R is the phase angle by which V_R leads I_R. The position of point 0 is independent of load current I_R and will not change as long as $|V_R|$ is constant. Luther more if values of V_s and V_R are constant then distance OG remains constant. Low with change in load, the distance between points H and G goes on changing. As the values of V_S and VR are fixed, distance between points O and G remains same which constrain point G to move on a circle with centre at O and radius as OG. In order to keep point G on the circle it is required that with change in P_R, Q_R should also change.

If values of sending end voltage are changed then for same values $|V_R|$ then position of point O is unchanged but a new circle with different radius is obtained.



With constant receiving end voltage different circles can be obtained for different values of sending end voltages. The circles so obtained are concentric circles as the location of centre of receiving end power circle is independent of sending end voltage. Number of concentric circles can be obtained for a constant receiving end voltage. This is shown in above figure
From the above figure, it can be seen that there is limit to the power that can be transmitted to the receiving end of the line for the various magnitude of sending and receiving end voltages. An increase in power delivered means that point G will move along the circle until the angle β-δ is zero. Thus so long as δ= β, maximum power is delivered. With further increase in δ, results in less power at receiving end. The equation for maximum power is given by,

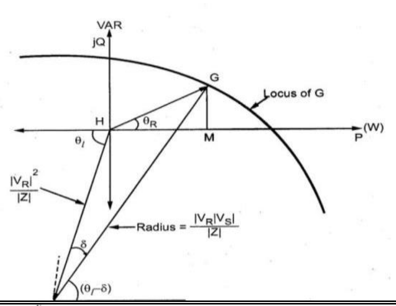
$$P_{R\,max} = \frac{|V_S||V_R|}{|B|} - \frac{|A||V_R|^2}{|B|}\cos(\beta-\alpha)$$



As shown in the below figure if a vertical line is drawn from x on circle with sending end voltage $|V_{S3}|$ to the point y on circle with sending end voltage $|V_{S2}|$ then distance xy represents the amount of negative reactive power that must be drawn by capacitors added in parallel with the load to maintain constant $|V_R|$ when sending end voltage is reduced from $|V_{S3}|$ to $|V_{S2}|$.
Thus circle diagram helps us to study various aspects of power transmission at sending end and receiving end. From the receiving end power circle diagram, P_R, Q_R and angle 6 for any point on the circle can be determined.
For a short transmission line with series impedance per phase as Z <Θ l
For a short line

$$\bar{A} = \bar{D} = 1\angle 0^\circ, \quad \bar{B} = |Z|\angle\theta_l;\ \beta = \theta_l$$

The circle diagram is as shown in Figure



SENDING END POWER CIRCLE DIAGRAM:

With the help of circle diagram at sending end we get P_S, Q_S and power factor on complex plane.

The complex power at sending end is given by,

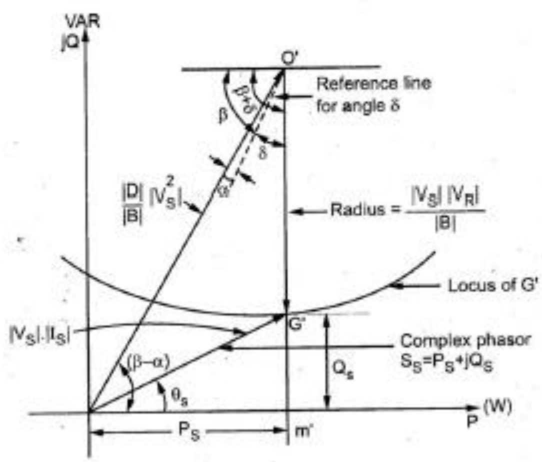
$$S_S = P_S + jQ_S$$

$$= \frac{|D|}{|B|}|V_S|^2\angle\beta-\alpha - \frac{|V_S||V_R|}{|B|}\angle\beta+\delta$$

$$P_S = \frac{|D|}{|B|}|V_S|^2\cos(\beta-\alpha) - \frac{|V_S||V_R|}{|B|}\cos(\beta+\delta)$$

$$Q_S = \frac{|D|}{|B|}|V_S|^2\sin(\beta-\alpha) - \frac{|V_S||V_R|}{|B|}\sin(\beta+\delta)$$

The sending end power circle diagram is shown in below figure



By the same method as for the receiving end circle diagram if V_R and V_S are kept constant then it can be proved that the point G' moves with the centre O'. The co-ordinates of the centre are given as,

$$x_1 = \frac{|D|}{|B|}|V_S|^2\cos(\beta-\alpha)$$

$$y_1 = \frac{|D|}{|B|}|V_S|^2\sin(\beta-\alpha)$$

The radius of the sending end circle is given as,

$$Radius = \frac{|V_S||V_R|}{|B|}$$

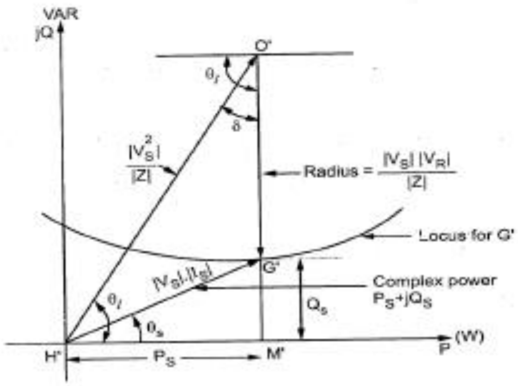
The radius is same as that obtained in case of receiving end circle diagram.

When sending end voltage is fixed, the position of centre 0' is fixed and concentric circles are obtained with radii corresponding to different values of V_R. However if $|V_R|$ is fixed and. it is required to draw sending end power circles for various values of $|V_S|$ then centre 0' of sending end circle changes and lies along O'H'.

This distance O'H' varies as $|V_S|^2$ and radii of the circles will also change as $|V_S|$ keeps on changing. If voltages $|V_S|$ and $|V_R|$ are fixed then Ps will be maximum when δ=180-β

$$P_{S\,max} = \frac{|V_S||V_R|}{|B|} + \frac{|D||V_S|^2}{|B|}\cos(\beta-\alpha)$$

The sending end power circle diagram for a short transmission line is as shown in below figure



It is obtained by using the ABCD parameters for short line which are as follows.

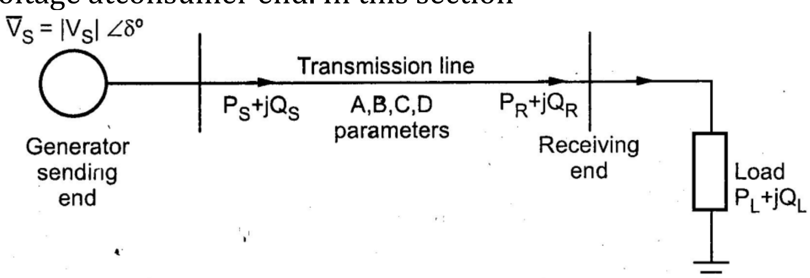
$$\bar{A} = \bar{D} = 1\angle 0°$$

$$\bar{B} = \bar{Z} = |Z|\angle\theta_l$$

METHODS OF VOLTAGE CONTROL:

The electrical energy generated in the generating station is supplied to the consumers through the network of transmission and distribution. For satisfactory operation of various loads at the consumer end, it must be supplied with fairly constant voltage. In order to avoid erratic operation or malfunctioning of appliances at the consumer end, the voltage at the consumer end must be controlled and kept within permissible limits.

Because of change in load on the power system, the voltage at user end goes on changing. With increase in load, the voltage drop in alternator synchronous impedance, transmission line, transformer impedance, feeders and distributors increases. With decrease in load, these drops increase. These variations in voltages are undesirable andmust be kept within proper limits. This limit is generally ± 6% of declared voltage atconsumer end. In this section



Consider the two bus system shown in above figure. Let the line is having negligible resistance and consists of series reactance. For fixed sending end voltage and at the given receiving end voltage, the real and reactive powers are given by,

$$P_R = \frac{|V_R^s||V_S|}{X_L}\sin\delta$$

$$Q_R^s = \frac{|V_R^s|}{X_L}[|V_S| - |V_R^s|]$$

$$Q_R^s X_L = |V_R^s||V_S| - |V_R^s|^2$$

$$|V_R^s|^2 - |V_R^s||V_S| + Q_R^s X_L = 0$$

$$|V_R^s| = \frac{1}{2}|V_S| + \frac{1}{2}|V_S|\left[1 - \frac{4X_L Q_R^S}{|V_S|^2}\right]^{1/2}$$

As the real power demanded by the load must be delivered by line

$P_R = P_L$.

The varying real power demanded by load is met by consequent changes in torque angle δ.

The reactive power of the line should remain fixed at Q_{SR} when |Vs| fixed for the specified $|V_{SR}|$ · the line will hence operate with specified receiving end voltage for only one value of Q_L given by

$$Q_L = Q_R^S$$

But the loads in actual practice are normally lagging in nature such that VAR demand Q_L may exceed Q_{SR} from above equation for Q_{SR} it can be seen that for $Q_L > Q_{SR}$ the receiving end voltage must change from the specified value I V_RI to some value $|V_{SR}|$ I to meet demanded VAR. Hence

$$Q_L = Q_R = \frac{|V_R|}{X}(|V_S| - |V_R|)\ for\ Q_L > Q_R^S$$

The modified I V_RI is given by,

$$|V_R| = \frac{1}{2}|V_S| + \frac{1}{2}|V_S|\left[1 - \frac{4X_L Q_R}{|V_S|^2}\right]^{1/2}$$

The above value I V_RI is less than $|V^S_R|$ for $Q_L > Q^S_R$ similarly I V_R I is greater than $|V^S_R|$ · for $Q_L < Q^S_R$.

It can be seen that under light load condition the line capacitance causes VAR demand to become negative which results in receiving end voltage exceeding the sending end voltage The various methods employed for voltage control include

- Use of series capacitors
- Use of shunt capacitors
- Use of static V AR sources
- Use of shunt reactors
- Tap changing of transformers.

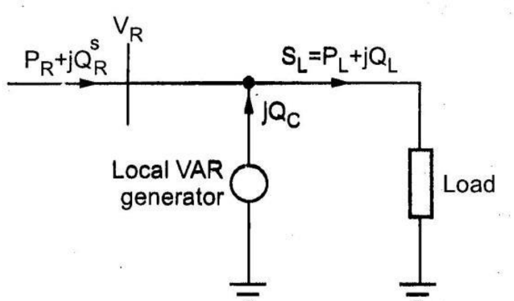
REACTIVE POWER INJECTION:

It can be seen from the previous section that to maintain the receiving end voltage at its specified value, a fixed amount of VARs (Q^S_R) must be drawn from the line. A local VAR generator must be used for conditions of varying VAR demand QL. The VAR balance equation at the receiving end is given as,

$Q^S_R + Q_C = Q_L$

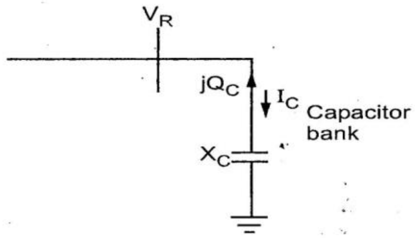
The fluctuations in Q_L are absorbed by local VAR generator in such a way that total VAR drawn by the line remain fixed at Q^S_R. The receiving end voltage is therefore maintained at fixed value of I V^S_R I. This is shown in below figure.

This is nothing but compensation of V AR which can be made automatic by taking signal from V AR meter installed at receiving end. Normally two types of V AR generators are used in practice via static type and rotating type.



STATIC VAR COMPENSATOR:

It consists of bank of 3 phase static capacitors and/or inductors. From the Fig. 3.42. We can see that Xc is reactance per phase of the capacitor bank.



We have, $I_C = \frac{|V_R|}{\sqrt{3}[-jX_c]} = j\frac{|V_R|}{\sqrt{3}X_c}$

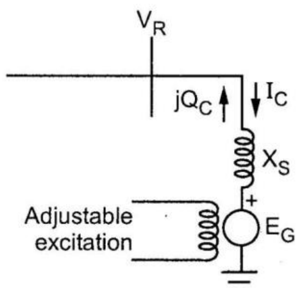
$$Q_C = \frac{|V_R|^2}{X_c}\ MVAR$$

If inductors are used instead of capacitors

$$Q_L = -\frac{|V_R|^2}{X_L}\ MVAR$$

When the load on power system is high then positive VARs are required. In this case capacitor banks are used while when light load is there on the system, negative VARs are required then inductor banks are switched on If it is required to have a smooth control of VAR then silicon controlled rectifier (SCR) may be used. With the considerable harmonics say fifth harmonics may result in overloading of capacitors. At harmonic frequencies there is chance of series resonance to occur. The capacitors act as short circuit when they are switched on. It can also be seen that the variation of Q is proportional to V^2_R. So under heavy load condition when voltage decreases Qc may not prove to be effective.

ROTATING VAR GENERATOR: It is nothing but a synchronous motor running at no load. The excitation **of this** motor can be adjusted over a wide range. In overexcited condition it supplies **positive** VARs whereas gives negative VARs when under excited. The synchronous motor running under this condition is called synchronous condenser. It is shown in below figure.



The synchronous condenser is connected to the receiving end bus bars and runs under no load condition. It takes negligibly small real power such that EG and VR are almost in phase. Xs is the synchronous reactance of' the motor. The motor is having negligible resistance. We have,

$$I_C = \frac{(|V_R| - |E_G|)\angle 0°}{\sqrt{3} \times jX_S}$$

Reactive power, $jQ_C = j3\frac{|V_R|\angle 0°}{\sqrt{3}} I_C^*$

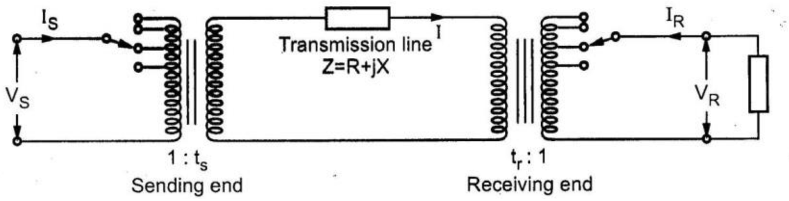
$$= j3\ \frac{|V_R|}{\sqrt{3}}\left[+\frac{|V_R| - |E_G|}{\sqrt{3} \times (-jX_S)}\right]$$

$$Q_C = |V_R|\{[|E_G| - |V_R|]/X_s\}MVAR$$

When |EG|> |V R |, the machine is overexcited and provides positive VARs whereas I |EG| <| V R| the machine is under excited the machine is under excited and provides negative VARs. Thus positive and negative continuously adjustable VARs can be obtained with this method. At a given excitation the V AR injection is less sensitive to changes in $|V_R|$ As $|V_R|$ decreases, |EG|-|VR| increases with corresponding smaller reduction in Qc.

From the above discussion it can be concluded that rotating VAR generator is more effective than static V AR generator. Hence it may be preferred. But its limiting factors are economic considerations, installation and maintenance problems.

CONTROL BY TAP CHANGING TRANSFORMER: This method is employed for narrow range of voltage control. Due to VAR demands of load, the receiving end voltage tends to decrease which can be raised by simultaneous tap changing on sending and receiving end transformers. It can be done either on no load or on load. Thus there are two types of tap changing transformers via on load and on no load. Consider the operation of a transmission line with a tap changing transformer at each end as shown in below figure.



The impedances of the transformers are taken along with line impedances. These tap changing transformers do not control the voltage by controlling the flow of V ARs but by changing the transformation ratio, the voltage in the secondary circuit is varied and voltage control is achieved. Let ts and tr are the fractions of the nominal transformation ratios i.e. tap ratio/nominal ratio. The product of t_s and tr is taken as unity for ensuring uniformity in voltage level. From the above figure,

The approximate line drop is given as

$$IZ = \Delta V = IR\cos\emptyset + IX\sin\emptyset$$
$$= RI\cos\emptyset + XI\sin\emptyset$$
$$= \frac{RP}{t_rV_r} + \frac{XQ}{t_rV_r}$$
$$= \frac{R.PX.Q}{t_rV_r}$$
$$t_SV_S = t_rV_r + \frac{R.P + X.Q}{t_rV_r}$$

$$t_S = \frac{1}{V_S}\left[t_rV_r + \frac{R.P + X.Q}{t_rV_r}\right]$$
$$t_St_r = 1$$

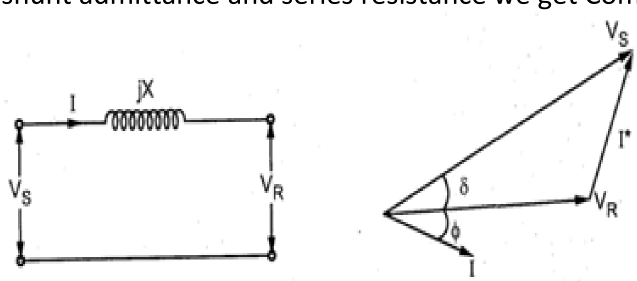
$$t_S = \frac{1}{V_S}\left[\frac{V_r}{t_S} + \frac{R.P + X.Q}{V_r/t_S}\right]$$

$$t_S = \frac{1}{V_S}\left[\frac{V_r}{t_S} + \frac{t_S(R.P + X.Q)}{V_r}\right]$$
$$t_S^2 = \frac{V_R}{V_S} + \left(\frac{R.P + X.Q}{V_RV_S}\right)t_S^2$$
$$t_S^2\left[1 - \frac{R.P + X.Q}{V_RV_S}\right] = \frac{V_R}{V_S}$$

From the above equation it can be seen that for particular values of V_R and V_S and the load requirements P and Q the value of t_s can be determined.

The flow of active power (P) and the reactive power (Q) through transmission system has influence on voltage magnitudes and phase difference of voltages at terminals and voltage along the line. Now let us consider active and reactive power flow through short transmission line. Consider a short transmission line as shown in figure.

Neglecting shunt admittance and series resistance we get Complex power, $S_S = P_S + jQ_S = V_S\bar{I}_S^*$



$$\bar{I} = \frac{1}{jX}(\bar{V_S} - \bar{V_R}), \bar{I}^* = \frac{1}{-jX}(\bar{V_S}^* - \bar{V_R}^*)$$

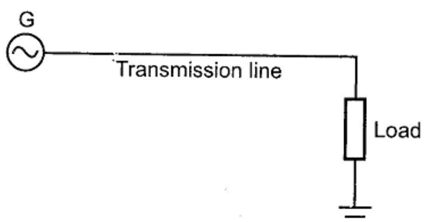
$$S_S = \frac{\bar{V_S}}{-jX}(\bar{V_S}^* - \bar{V_R}^*)$$

From the phasor diagram, $\bar{V_S} = |V_S|\angle\delta, \quad \bar{V_R} = |V_R|\angle 0$

$$S_S = \frac{|V_S|^2 - |V_R||V_S|[\cos\delta + j\sin\delta]}{-jX}$$

$$= j\frac{|V_S|^2}{X} - \left[j\frac{|V_R||V_S|}{X}[\cos\delta + j\sin\delta]\right]$$

POWER SYSTEM STABILITY: The term stability with respect to the transmission line refers to the stable operation of the power system with sending end and receiving end terminals in synchronism with each other. When this synchronism is lost it is said to be the unstable operation. The stability limit corresponds to maximum power flow possible without losing the stability.



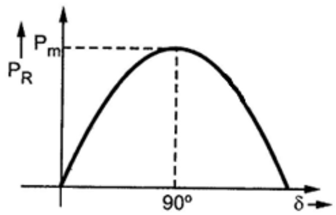
Consider the generator supplying power to the load through the transmission line as shown in above figure. The load may consist of either impedance, induction motor or synchronous motor. With the load of the type static impedance, there is limit for generator to supply power to the load but the system can never lose synchronism or become unstable. Similarly for the induction motor there is limit and it can become unstable only when motor stalls but. it can never lose the synchronism. But for synchronous motor type of load, it can cause un-stability and loss of synchronism.

Thus it is required that under steady state and under dynamic conditions, the synchronism must be maintained. The steady state stability limit refers to maximum power transfer that is possible with small changes in power flow or gradual disturbance, without losing stability. The transient stability refers to the maximum power transfer that is possible for given amount of sudden or large changes in power disturbance without loss of stability. The voltage stability corresponds to limit on maximum power transfer through the transmission line beyond which the voltage collapses and stability is lost.

POWER ANGLE DIAGRAM: After neglecting resistance and shunt admittance of the line the power at the receiving end is given by

$$P_R = \frac{|V_S||V_R|}{X_L}\sin\delta$$

The angle δ is called **phase angle** or the **torque angle** or **load angle** between sending and receiving end voltages. With increase in load, angle δ also increases. But it has limit beyond which power flow is not increased. This upper limit is called stability limit. The variation of power flow with from the above equation it can be clearly seen that when δ = 0, P_R is also zero while when δ = 90° then P_R is maximum when δ goes beyond 90°, P_R goes on reducing and at δ = 180°, it reduces to zero.



When there is sudden change in transmission system, change in load, tripping of generator or load, sudden switching load, any fault etc. brings about oscillations in angle O. If load angle δ goes beyond 90°, the synchronism is lost and the transmission system fails to transfer the power. Pm is called steady state stability limit and is given by

$$P_m = \frac{|V_S||V_R|}{X_L}$$

Transient state stability is one half of steady state stability

For $\delta = 30°, \sin\delta = 1/2$

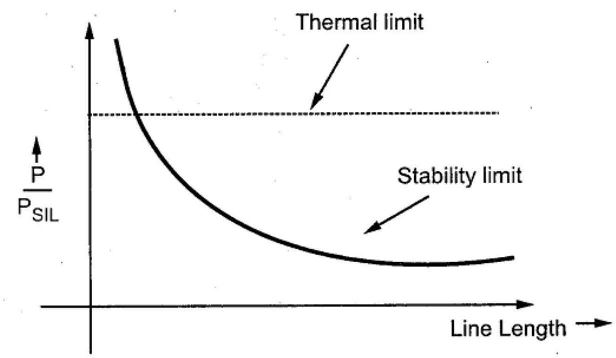
$$P_t = \frac{|V_S||V_R|}{X_L}\sin\delta = \frac{|V_S||V_R|}{2X_L}$$

If the mechanical power input to the alternator and the load on the system is unchanged for arbitrary disturbances; the system returns to the stable working point. With large disturbance the operating point is shifted and the system becomes unstable.

6. **Explain how the steady state stability limit affects the power transfer capability of transmission lines (6)** (NOV/2012)

POWER, TRANSFER CAPABILITY OF TRANSMISSION LINES:

The main constraints in the capability of power transfer for transmission line are thermal limit, voltage drop limit and the stability limit. When the current flows through the transmission line conductors, due to its resistance there is loss which generates heat increasing the temperature. This gives the thermal limit. Thus it is required to keep the temperature of overhead line conductors within a safe limit. This avoids excessive line .sag between the towers. It also helps in preventing irreversible stretching maintaining the proper ground clearance. Due to this there is limit on maximum safe current carried by overhead line. In addition to current carried by line conductors, the other factors such as geometry and size of conductors, spacing between towers influence the temperature rise. The ambient temperature, wind velocity are some of the influencing operating factors. The underground cables are more sensitive towards the thermal limit as there is limited possibility for heat transfer. But there is no question of sag in case of cables. If the cables are overheated then the insulation will start deteriorating and may get completely damaged in the near future. The stability limit is another consideration in the power transfer capability of transmission lines. The equation for power at receiving end given by



For short transmission line the limit for lon capability as per above equation is given by = 90°. But normally a is limited to 30 to 60° fm maintaining the synchronism in the line. In case of short transmission lines, the power transfer capability is set by the thermal limit instead by stability limit. But it is exactly opposite in case of long lines. This can be seen from figure For a long transmission line

$$V_S = V_R \cosh rl + I_R Z_C \sinh rl$$

Equating the above equation with $V_S = A\,V_R + BI_R$

$$\therefore \qquad B = Z_C \sinh rl$$

Now we have, $PR = \frac{|V_S||V_R|}{|B|} \sin\delta$

If the line is lossless, then $|V_S| = |V_R| = |V|(say)$ $and\ Y = j\beta$

$$P_R = \frac{|V|^2}{Z_c \sinh(j\beta l)} \sin\delta = \frac{|V|^2}{Z_c \sin\beta l} \sin\delta$$

$$Surge\ impedance\ loading, P_{SIL} = \frac{|V|^2}{Z_C}$$

$$\therefore \quad P_R = P_{SIL} \frac{\sin\delta}{\sin(\beta l)}$$

With the increase in line length, βl increases and P_R decreases.

The voltage drop in the line is the main consideration in case of medium transmission lines for maximum power transfer. There is always rating for line in terms of current beyond which a line is not be operated for longer duration. The transmission lines are always designed for particular voltage level depending on string insulators and clearances. Sometimes the rating of line is given in terms of power which is multiplication of current and voltage. For extra high voltage lines (EHV AC), the MVA rating is almost equal to its MW rating reactive power. Under light load conditions or no load conditions the .capacitance associated with the line generate more reactive power than the reactive power which is absorbed hence the voltage at the receiving end is found to be greater than that at sending end.

7. **Explain in detail about shunt and series compensation** (11) (APRIL/2015)

LINE COMPENSATION:

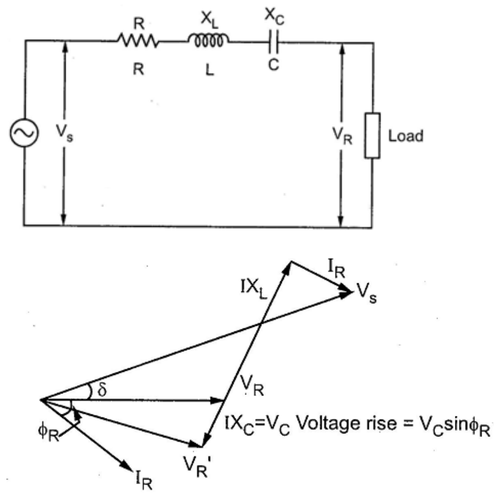
With increase in load demand, it becomes necessary to make use of high voltage transmission lines' for transmitting the power over long distances. With improved design and other technical consideration, the high voltage lines can be used for transmitting power for maximum possible length of line. But this may turn out to be expensive in certain cases. In such cases the alternative is to increase the transmission capability of EHV transmission systems. The capacity of these power transmission lines can be increased by using conventional methods such as choosing higher transmission voltages, higher speed breakers, intermediate switching stations and reduced reactance of generators and the transformers. The transient stability limit can be increased using high speed excitation systems. The series impedance of the line can be reduced by the use of bundled conductors which increases the stability limits. The modern technique of artificially reducing the series reactance and shunt susceptance of the lines by using series capacitors and shunt. susceptance of the lines by using series capacitors and shunt reactors is called compensation. With this compensation the system stability is improved. Similarly the power transmission efficiency is increased along with voltage control. It also helps in reducing transient overvoltage.

If series capacitors are used the line reactance is compensated directly and losses are reduced. The voltage conditions will be improved instantaneously with wide fluctuating loads. Power transfer ability is improved along with power factor. With shunt capacitors the phase angle between the voltage and the current is reduced which has various advantages. When total reactive power obtained from series and shunt compensation is known then the maximum power transfer capability, voltage control conditions and efficiency of line depend on number, location and circuit arrangements of series capacitor and shunt reactor.

For long transmission line it is required to find the most appropriate location for capacitors and reactors in addition to compensation required for a particular line. The optimum possible solution must be obtained.

SERIES COMPENSATION:

This is one of the methods of reactive power control. Compensation of a transmission line with the help of series capacitor is called as series compensation. For compensating the series reactance of the line the series capacitor is inserted in the line at a specified point. This type of compensation is provided for long transmission line IM having voltages 220 kV and above. The capacitors are connected in series with the line for the compensation of inductive reactance of the line as shown in the below figure.



The figure shown above R and XL are the total series resistance and inductive reactance in ohms. Xc is the ohmic reactance of a series capacitor. Vs and V_R are the sending and receiving end voltages. The corresponding phasor diagram is shown in the above figure.

A series capacitor in an ac circuit introduces negative or leading reactance. Current through this negative reactance causes a voltage drop that leads the current by 90°. This drop is opposite to that across an inductive reactance. Thus a series capacitor at rated frequency compensates for the drop or part of the drop through the inductive reactance of the feeder. Neglecting the effects of line charging current or shunt capacitance and considering lumped values for the line constants as shown in the figure, the phase to neutral voltage between sending end and receiving end can be written as

$$V_S = V_R - IX_C \sin \emptyset_R + IX_L \sin \emptyset_R + IR \cos \emptyset_R$$

$$V_S - V_R = IR \cos \emptyset_R + I(X_L - X_C) \sin \emptyset_R$$

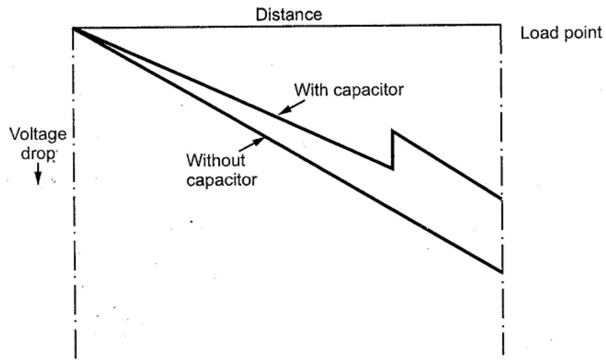
$\therefore$ Drop in voltage, $\Delta V = IR \cos \emptyset_R + I(X_L - X_C) \sin \emptyset_R$ with series compensation.

In the absence of series compensation

$$\Delta V = IR \cos \emptyset_R + IX_L \sin \emptyset_R$$

$$X_L < X_C, \qquad X_L = X_C, \qquad X_L > X_C$$

The conditions are referred to as overcompensation, full compensation and under compensation respectively. Over compensation is not used in transmission systems, But application of this type is sometimes found in distribution systems. By varying the quantity Xc the regulation of the line can be increased or decreased depending on the requirement provided that ($\sin \Phi_R \neq 0$) The below shows how the voltage drop increases with the distance from the sending end and how the voltage increases due to series capacitor.



The voltage change obtained takes the form of sudden rise at the capacitor terminal so that its beneficial effects are felt on the load side of the capacitor. Thus the load voltage will be larger than receiving end' voltage, when no capacitors are installed. Since the voltage rise is dependent on the load current and the power, factor (i.e. voltage rise V c sin<l>R =IR Xc sin <l>R), a change in IR produces a change in V c and the capacitor automatically acts as a voltage regulator.

Advantages of Series Compensation:

- Increase in power transmission capacity of the line:-
- Improvements in system stability
- Improved voltage regulation
- Load division between parallel circuits
- Damping Effect

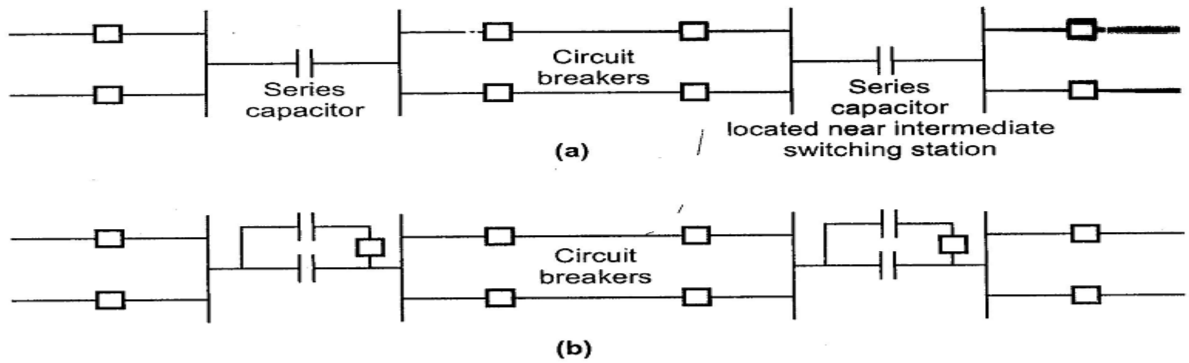
Disadvantages of Series Compensation:

- The series capacitor adversely affects the short circuit rating of circuit breaker and/or fuses in case the system encounters a fault as the series capacitor reduces the reactance of line and increases the fault current level.
- A series capacitor changes the natural resonant frequency of the transmission system
- When a series capacitor is installed in EHV line between a transformer and source of supply a phenomenon known as Ferro resonance may occur. Under this condition a high voltage may appear across the capacitor terminals which may damage capacitor itself. Similarly it may cause severe over voltage problems in associated network.
- The series capacitor may cause faulty operation of distance relays of the line protection if the degree of compensation and location of capacitor is not proper.
- Because of series capacitor, the inductive reactance reduces so the possibility of hunting increases.
- When a fault occurs on a line carrying the series capacitors then the fault current flows through the series capacitors which increases voltage across capacitor to high value which may damage the series capacitor and break the continuity of the supply. Hence the protection circuitry should be installed.

 If the series capacitor is taken out of the line due to internal faults or external faults then to maintain the continuity of supply, the circuit breakers, isolators and control circuitry which is quite costly is required. So overall cost of series capacitor increases.

CIRCUIT ARRANGEMENTS WITH SERIES CAPACITOR:

In transmission line the series capacitors can be connected in various ways. Some of these various arrangements are shown in below figure. The series capacitors can be located in line sections and switched on as part of the line.

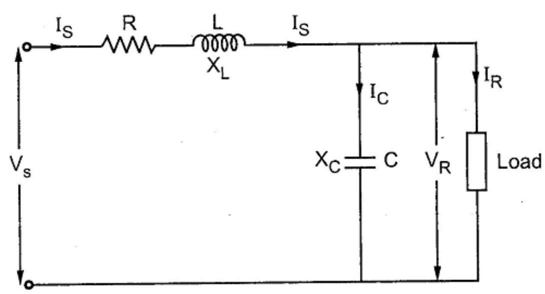


The various factors on which transmission line capability depends are as follows:

- ***Thermal limits of conductor*** When heating due to current flow exceeds the allowable limit then we say that thermal limit of conductors is reached. It is experienced on short circuits.
- ***Transient and steady state stability*** Transient stability is the limit on long lines while steady state stability is the limit on short lines. With series compensation, the series reactance of line reduces. Thus the steady state stability criterion may limit the capability of compensated lines.
- **Transmission line capability:** Depends on overvoltage at the capacitor terminals of series compensated line.

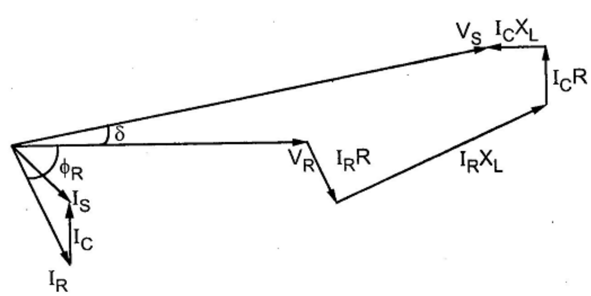
8. **Explain how the shunt compensation affects the surge impedance and phase constant of transmission line.** (5) (NOV/2012)

SHUNT COMPENSATION:

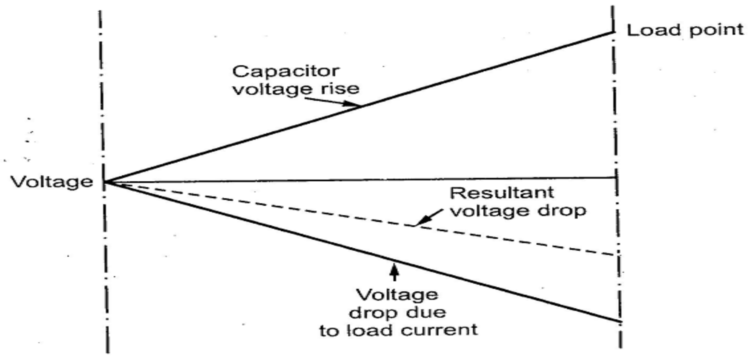


The provision of shunt capacitor involves insertion of shunt capacitor across the line in order to improve the power factor and voltage as well as to reduce losses.

The simplified equivalent of a transmission line with shunt connected capacitor is shown in the above figure and the corresponding phasor diagram is shown in the below figure



The below figure shows that, unlike the effect with a series capacitor, the voltage rise is distributed uniformly along the length of the line.



The phase angle between the voltage and the capacitor is applied. It has the following effects. Current is reduced when shunt

- It reduces line current losses owing to generation of reactive power.
- It reduces the transmission line current to a value less than the current in the load. ➢ It improves the power factor of the transmitted power.
- It reduces the voltage drop uniformly along the length of the line.

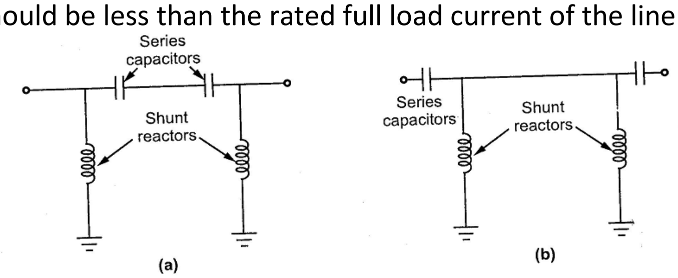
ADVANTAGES

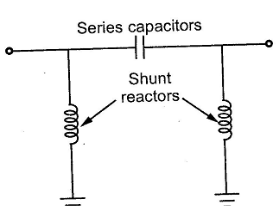
As the power factor is improved with shunt capacitor, we get following advantages

- The kW of alternators, transformers and lines are increased.
- The line current is reduced.
- The losses in power transformer and cables are reduced which saves energy.
- It prevents overloading of transformers and switchgears.
- Improved voltage is obtained at the receiving end.
- The life of connected equipment likes cables, switchgear etc. is increased due to improved voltage and reduced current.
- It saves penalty imposed by electricity boards for lower power factor.

DISADVANTAGE

The only disadvantage with shunt capacitor is that the response to voltage dips is not as rapid as with series capacitor since the switching of the bank is initiated by change in voltage. In some of the cases the shunt compensation is done with the help of shunt reactors especially for long transmission line. When the long transmission lines are running under no load or light load conditions then it is required that the charging current should be less than the rated full load current of the line.





This can be achieved by connecting several inductors between line and neutral at appropriate places along the line. The other advantage of connecting shunt reactor is that the receiving end voltage is kept within the permissible limits which would otherwise be high due to Ferrenti effect. The shunt reactors absorb some of the leading V ARs for achieving voltage control. Capacitors are connected either directly to a bus or through tertiary winding of the main transformer.

UNIT-4

Insulators and Cables : *Insulators – types and comparison – voltage distribution in string insulator – string efficiency – methods of improving string efficiency – Stress and sag calculations – effect of wind and ice – supports at different levels – stinging chart - cables – types – capacitance of cables – insulation resistance - dielectric stress and grading - dielectric loss - thermal characteristics - capacitance of three core cables*

2 marks

1. What are the requirements of cables used in underground system? (or) ***What are the requirements of underground cables?*** (NOV/2014)

- The conductors used in cables should be stranded one in order to provide flexibility and carry more current.
- The cross sectional area of the conductors should be such that they carry desired load current without overheating and causes voltage drop within permissible range.
- The insulation used in a cable should have proper thickness, so that it provides a high degree of safety and reliability at the voltage for which a cable is designed.
- The cables must be provided with a mechanical protection so as to withstand the rough usage in laying it.
- The materials used in the manufacture of cables should be such as to give complete chemical and physical stability throughout.

2. List the properties of insulating materials used for cables? (APRIL/2013)

- High resistivity
- High dielectric strength
- High mechanical strength.
- Non hygroscopic
- Non inflammable capable of withstanding high rupturing voltage.
- Unaffected by acids and alkalis to avoid any chemical action.
- Low cost so as to make the underground system a viable proposition.

Capable of withstanding high temperature without any deterioration.

3. How are cables classified based on an operating voltage? (or) ***Classify the cables according to their voltage level.*** (APRIL/2013)

- Low tension cable(LT)- upto 1000 V
- High tension cable(HT)- upto 11,000 V
- Super tension cable(ST)- from 22,000 V to 33,000 V
- Extra high tension cable(EHT)- from 33 to 66kV
- Extra super voltage cable- beyond 132kV

4. What is dielectric stress? (APRIL/2014)

Under operating conditions, the insulation of a cable is subjected to electrostatic force known as dielectric stress.

5. ***What is grading of cables*** (NOV/2013) (or) ***What is meant by grading of cables*** (NOV/2012)

The process of achieving uniform electrostatic stress in the dielectric of the cables is called grading of cables.

6. Define string efficiency?

String efficiency is defined as the ratio of voltage across the whole string to the product of number of discs and the voltage across the unit nearest to the conductor.

$$\textbf{String efficiency} = \frac{voltageacrossthestring}{nXvoltageacrossthediscnearetconducter}$$

Where, n= number of discs in the strings.

7. What are the methods to improve string efficiency (or) *what are the different types of improving string efficiency?* (NOV/2012)

The following methods are used to improve string efficiency are

- By grading the insulators
- By using a guard ring
- By using longer cross arms

8. Define safety factor.

The ratio of puncture strength to flashover voltage is known as safety factor.

Puncture Strength Safety factor of Insulator = Flash over voltage

$$\text{Safety factor of Insulator} = \frac{\text{Puncture Strength}}{\text{Flash over voltage}}$$

9. List the advantages and disadvantages of suspension type insulators (APRIL/2015) (NOV/2013)

Advantages:

- Economical for voltage above 33 kV
- Failure in any unit can be replaced easily without changing the whole string
- Flexible in extending the voltage rating by adding more units
- Less mechanical stress

10. Mention the different types of insulators (APRIL/2015) (or) **Enumerate the different types of insulators used for overhead transmission lines.** (NOV/2012)

- Pin type,
- Suspension type,
- Strain insulator
- Shackle insulator

11. Define sag. (NOV/2012)

The difference in level between the points of supports and the lowest point in the conductor is called Sag

12. What are the factors affecting the sag? (APRIL/2014)

The following factors affecting the sag in overhead transmission lines are

- Weight of the conductor
- Span length
- Temperature
- Working tensile strength

13. *Define touch potential* (APRIL/2012)

Touch potential is the voltage between the energized object and the feet of a person in contact with the object.

14. What are screened cables? (APRIL/2012)

Screened cables are cables used for voltage upto 33 kV. These cables are used to eliminate the tangential stress in belted cables, individual core is provided with metallic screening over the insulation but no belt insulation is required. The screen is perforated aluminium foil or copper tape with narrow gap between the turns.

15. Define the term "Interference with neighbouring circuits". (APRIL/2012)
When the power line is running along the communication line, there will be interference in the communication line due to electrostatic and electromagnetic effects. The electrostatic effect induces voltage and electromagnetic effect produces current in the communication line which is dangerous to human.

11marks

1. What is meant by insulator? Explain about the properties and insulating material used in insulator.

Insulators

The overhead line conductors should be supported on the poles or towers in such a way that currents from conductors do not flow to earth through supports i.e., line conductors must be properly insulated from supports. This is achieved by securing line conductors to supports with the help of insulators. The insulators provide necessary insulation between line conductors and supports and thus prevent any leakage current from conductors to earth.

Properties of Insulator:

- High mechanical strength in order to withstand conductor load, wind load etc.
- High electrical resistance of insulator material in order to avoid leakage currents to earth.
- High relative permittivity of insulator material in order that dielectric strength is high.
- Should be non-porous;
- Free from impurities
- Should with stand temperature changes
- Free from cracks otherwise the permittivity will be lowered.
- High ratio of puncture strength to flashover.

Insulating material

The following material are commonly used for manufacturing insulators

- PORCELAIN
- GLASS
- STEATITE
- SYNTHETIC RESIN

Porcelain:

- It is the most commonly used material for insulators on overhead lines. It is made from china clay, ball clay, quartz and feldspar, finally powdered and mixed with water. The plasticity of mixture is regulated by clay. Quartz and feldspar act as filler and flux respectively. The ingredients are processed in the mill, shaked and covered with glaze. Glazing of insulator is very much necessary to keep it relatively free from dust and moisture.
- It is mechanically stronger than glass.
- This material is usually weak in tension and does not withstand tensile strength more than 5oMN/m2.

Glass:

- It is cheaper than porcelain in the simple shapes
- The glass insulators are mainly used for EHV AC and DC system
- Glass insulators can be used up to 25 kV under ordinary atmospheric conditions and up to 50 kV in dry conditions

Steatite:

- It is prepared from hydrated magnesium silicate mixed with small proportions of clay and feldspar. The firing mixture is carried up to 1400 0C when it forms into a dense homogenous mass
- It has a much higher tensile strength and bending stress than porcelain and can be advantageously used at tension towers or when the transmission line takes a sharp turn.
- Insulation resistance is high

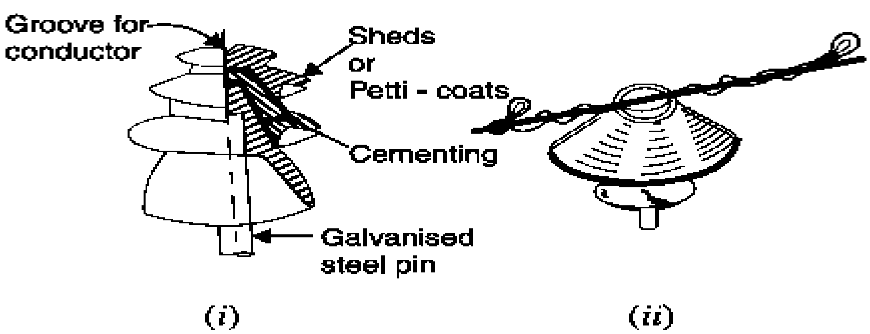
Synthetic Resin:

- This type of insulators contains compounds of silicon, rubber, resin etc
- These insulators have higher strength and lower weight
- They are comparatively cheaper
- These types of insulators are use in various indoor applications. They are extensively used as bushings

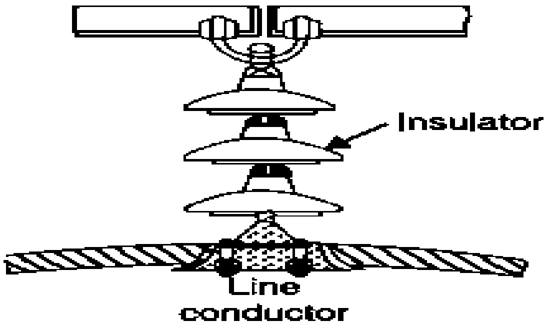
2. Briefly explain about the types of insulators
TYPES OF INSULATORS:
The successful operation of an overhead line depends to a considerable extent upon the proper selection of insulators. There are several types of insulators but the most commonly used are

- Pin type,
- Suspension type,
- Strain insulator
- Shackle insulator.

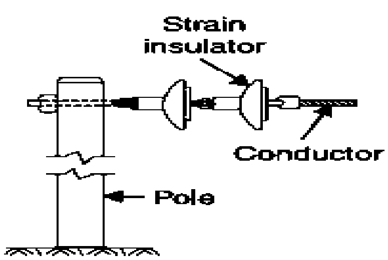
1. Pin type insulators:
The part section of a pin type insulator is shown. As the name suggests, the pin type insulator is secured to the cross-arm on the Pole. There is a groove on the upper end of the insulator for housing the conductor. The conductor passes through this groove and is bound by the annealed wire of the same material as the conductor Pin type insulators are used for transmission and distribution of electric power at voltages upto 33 kV. Beyond operating voltage of 33 kV, the pin type insulators become too bulky and hence uneconomical.



2. **Suspension type insulators**:
The cost of pin type insulator increases rapidly as the working voltage is increased. Therefore, pin type of insulator is not economical beyond 33 kV. For high voltages (>33 kV), it is a usual practice to use suspension type insulators shown in figure**.** They consist of a number of porcelain discs connected in series by metal links in the form of a string. The conductor is suspended at the bottom end of this string while the other end of the string is secured to the cross-arm of the tower. Each unit or disc is designed for low voltage, say 11 kV. The number of discs in series would obviously depend upon the working voltage. For instance, if the working voltage is 66 kV, then six discs in series will be provided on the string.

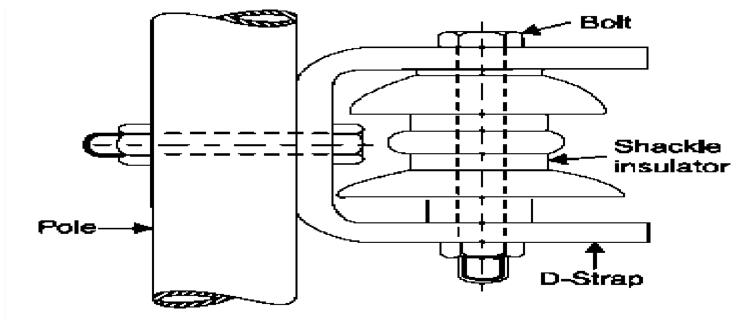


Advantages:-
(i) Suspension type insulators are cheaper than pin type insulators for voltages beyond 33 kV.
(ii) Each unit or disc of suspension type insulator is designed for low voltage, usually 11 kV. Depending upon the working voltage, the desired number of discs can be connected in series.
(iii) If anyone disc is damaged, the whole string does not become useless because the damaged disc can be replaced by the sound one.
(iv) The suspension arrangement provides greater flexibility to the line. The connection at the cross arm is such that insulator string is free to swing in any direction and can take up the position where mechanical stresses are minimum.
(v) In case of increased demand on the transmission line, it is found more satisfactory to supply the greater demand by raising the line voltage than to provide another set of conductors. The additional insulation required for the raised voltage can be easily obtained in the suspension arrangement by adding the desired number of discs.
(vi) The suspension type insulators are generally used with steel towers. As the conductors run below the earthed cross-arm of the tower, therefore, this arrangement provides partial protection from lightning.
3. **Strain insulators**:
When there is a dead end of the line or there is corner or sharp curve, the line is subjected to greater tension. In order to relieve the line of excessive tension, strain insulators are used. For low voltage lines (< 11 kV), shackle insulators are used as strain insulators. However, for high voltage transmission lines, strain insulator consists of an assembly of suspension insulators as shown in figure. The discs of strain insulators are used in the vertical plane. When the tension in lines is exceedingly high, as at long river spans, two or more strings are used in parallel.



Strain insulator.

4. **Shackle insulators**:
In early days, the shackle insulators were used as strain insulators. But now a day, they are frequently used for low voltage distribution lines. Such insulators can be used either in a horizontal position or in a vertical position. They can be directly fixed to the pole with a bolt or to the cross arm. Figure shows a shackle insulator fixed to the pole. The conductor in the groove is fixed with a soft binding wire.



3. What is meant by string efficiency? Derive the mathematical expression for string efficiency for three units string

STRING EFFICIENCY:

The voltage applied across the string of suspension insulators is not uniformly distributed across various units or discs. The disc nearest to the conductor has much higher potential than the other discs. This unequal potential distribution is undesirable and 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"

$$String\ efficiency = \frac{Voltage\ across\ the\ string}{n\ \times Voltage\ across\ disc\ nearest\ to\ conductor}$$

$$n = number\ of\ discs\ in\ the\ string$$

String efficiency is an important consideration since it decides the potential distribution along the string. The greater the string efficiency, the more uniform is the voltage distribution. Thus 100 % string efficiency is an ideal case for which the voltage across each disc will be exactly the same. Although it is impossible to achieve 100% string efficiency, yet efforts should be made to improve it as close to this value as possible

.**Mathematical expression over Suspension Insulator String**:-

Figure shows the equivalent circuit for a 3-disc string.

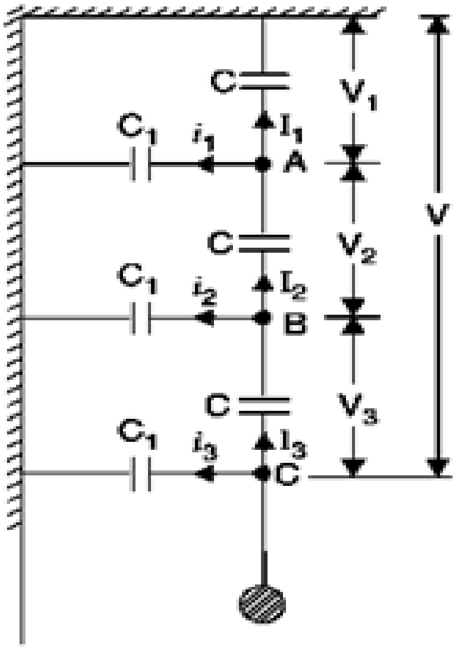
Let us suppose that self-capacitance of each disc is C.

Let us further assume that shunt capacitance C1 is some fraction K of self-capacitance i.e.,

C1 = KC.

Starting from the cross-arm or tower, the voltage across each unit is V1, V2 and V3 respectively as shown.

Applying Kirchhoff's current law to node A, we get,



$$I_2 = I_1 + i_1$$
$$V_2\omega C = V_1\omega C + V_1\omega C_1$$
$$V_2\omega C = V_1\omega C + V_1\omega KC$$
$$\boldsymbol{V_2 = V_1(1+K)}$$

Applying Kirchhoff's current law to node B, we get,

$$I_3 = I_2 + i_2$$
$$V_3\omega C = V_2\omega C + (V_1 + V_2)\omega C_1$$

Sub C_1 = KC

$$V_3\omega C = V_2\omega C + (V_1 + V_2)\omega KC$$
$$V_3 = V_2 + (V_1 + V_2)K$$
$$= KV_1 + V_2(1+K)$$
$$= KV_1 + V_1(1+K)^2$$
$$[\because V_2 = V_1(1+K)] \qquad = V_1[K + (1+K)^2]$$
$$\therefore\ \boldsymbol{V_3 = V_1[1 + 3K + K^2]}$$

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

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

From expression (i), (ii) and (iii), we get,

$$\frac{V_1}{1} = \frac{V_2}{1+K} = \frac{V_3}{1+3K+K^2} = \frac{V}{(1+K)(3+K)}$$
$$\therefore \quad \textit{Voltage across top unit}, V_1 = \frac{V}{(1+K)(3+K)}$$
$$\textit{Voltage across second unit from top}, V_2 = V_1(1+K)$$
$$\textit{Voltage across third unit from top}, V_3 = V_1(1+3K+K^2)$$
$$\%\textit{age String efficiency} = \frac{\textit{Voltage across string}}{n \times \textit{Voltage across disc nearest to conductor}} \times 100$$
$$= \frac{V}{3 \times V_3} \times 100$$

The following points may be noted from the above mathematical analysis:
i) If K=0.2(say), then from exp.(iv), we get $V_2 = 1.2V_1$ and $V_3=1.64V_1$. this clearly shows that disc nearest to the conductor has maximum voltage across it, the voltage across other discs decreasing progressively as the cross-arm is approached.
ii) The greater the value of K (=C1/C), the more non-uniform is the potential across the discs and lesser is the string efficiency.
iii) The inequality in voltage distribution increases with the increase of number of discs in the string. Therefore, shorter string has more efficiency than the larger one.

4. Explain various method of improving string efficiency.(7) (APRIL/2015) (or) **Discuss briefly about the various methods of improving string efficiency** (5) (NOV/2013) (11)(APRIL/2012)

Methods of Improving String Efficiency:

It has been seen above that potential distribution in a string of suspension insulators is not uniform. The maximum voltage appears across the insulator nearest to the line conductor and decreases progressively as the cross arm is approached.

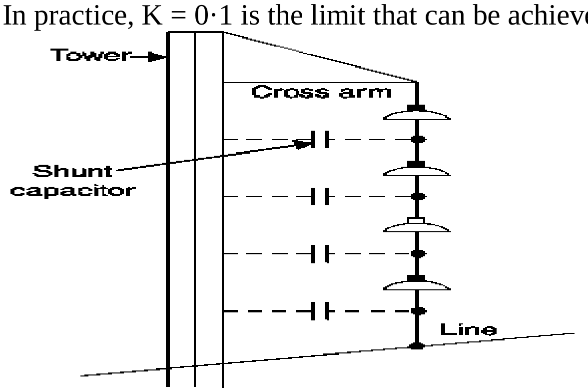
If the insulation of the highest stressed insulator (i.e. nearest to conductor) breaks down or flash over takes place, the breakdown of other units will take place in succession. This necessitates equalizing the potential across the various units of the string i.e. to improve the string efficiency.

The various methods for this purpose are

- USING LONGER CROSS-ARMS
- BY GRADING INSULATOR
- BY USING STATIC SHIELD OR GUARD RING

(i) By using longer cross-arms:-

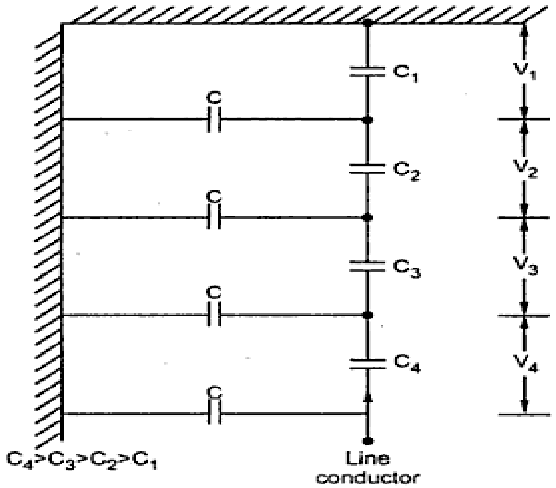
The value of string efficiency depends upon the value of K i.e., ratio of shunt capacitance to mutual capacitance. The lesser the value of K, the greater is the string efficiency and more uniform is the voltage distribution. The value of K can be decreased by reducing the shunt capacitance. In order to reduce shunt capacitance, the distance of conductor from tower must be increased i.e., longer cross-arms should be used. However, limitations of cost and strength of tower do not allow the use of very long cross-arms.
In practice, K = 0·1 is the limit that can be achieved by this method.



(ii) The By grading insulators:-

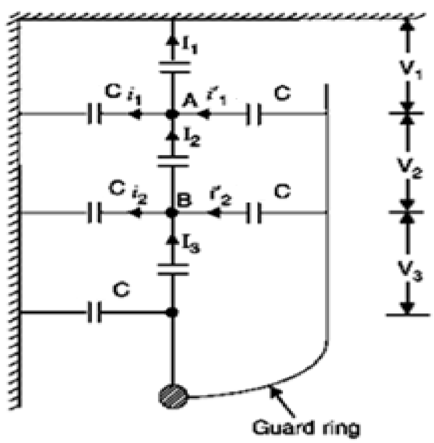
In this method, insulators of different dimensions are so chosen that each has a different capacitance. The insulators are capacitance graded i.e. they are assembled in the string in such a way that the top unit has the minimum capacitance, increasing progressively as the bottom unit (i.e., nearest to conductor) is reached. Since voltage is inversely proportional to capacitance, this method tends to equalize the potential distribution across the units in the string.

This method has the disadvantage that a large number of different-sized insulators are required. However, good results can be obtained by using standard insulators for most of the string and larger units for that near to the line conductor.



(iii) By using a guard ring:-

The potential across each unit in a string can be equalized by using a guard ring which is a metal ring electrically connected to the conductor and surrounding the bottom insulator as shown in the Figure. The guard ring introduces capacitance between metal fittings and the line conductor. The guard ring is contoured in such a way that shunt capacitance currentsi1, i2 etc. are equal to metal fitting line capacitance currents i′1, i′2 etc. The result is that same charging current I flows through each unit of string. Consequently, there will be uniform potential distribution across the units.



Points to be considered while doing problems

(i) The maximum voltage appears across the disc nearest to the conductor (i.e., line conductor).

(ii) The voltage across the string is equal to phase voltage i.e.,

Voltage across string = Voltage between line and earth = Phase Voltage

(iii) Line Voltage = 3x V Voltage across string (3x voltage across string)

Problem 1: **In a 33 kV overhead line, there are three units in the string of insulators. If the capacitance between each insulator pin and earth is 11% of self-capacitance of each insulator, find (i) the distribution of voltage over 3 insulators and (ii) string efficiency.**

Solution:

Figure shows the equivalent circuit of string insulators.

Let V1, V2 and V3 be the voltage across top, middle and bottom unit respectively.

If C is the self-capacitance of each unit, then KC will be the shunt capacitance.

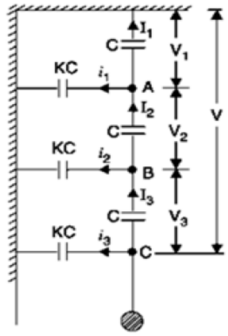
$$K = \frac{Shunt\ Capacitance}{Self - capacitance} = 0.11$$

$$Voltage\ across\ string, V = \frac{33}{\sqrt{3}} = 19.05kV$$

At junction A

$$I_2 = I_1 + i_1$$
$$V_2\omega C = V_1\omega C + V_1 K\omega C$$
$$V_2 = V_1(1+K) = V_1(1+0.11)$$

$V_2 = 1.11V_1$



At junction B

$$I_3 = I_2 + i_2$$
$$V_3\omega C = V_2\omega C + (V_1 + V_2)K\omega C$$
$$V_3 = V_2 + (V_2 + V_1)K$$
$$= 1.11V_1 + (V_1 + 1.11V_1)0.11$$
$$V_2 = 1.342V_1$$

i) Voltage across the whole string is

$$V = V_1 + V_2 + V_3 = V_1 + 1.11V_1 + 1.342V_1 = 3.452V_1$$
$$19.05 = 3.452V_2$$
$$\therefore Voltage\ across\ top\ unit, V_1 = 19.05/3.452 = 5.52kV$$
$$Voltage\ across\ middle\ unit, V_2 = 1.11\ V_1 = 1.11 \times 5.52$$
$$= 6.13kV$$
$$Voltage\ across\ bottom\ unit, V_3 = 1.342V_1 = 1.342V_1$$
$$= 1.342 \times 5.52 = 7.4kV$$

String efficiency = $\frac{Voltage\ across\ string}{No. of\ insulators\ \times V_3} \times 100 = \frac{19.05}{3 \times 7.4} \times 100 = 85.8\%$

Problem 2: **A 3-phase transmission line is being supported by three disc insulators. The potentials across top unit (i.e., near to the tower) and middle unit are 8 kV and 11 kV respectively. Calculate(i) the ratio of capacitance between pin and earth to the self-capacitance of each unit (ii)the line voltage and (iii) string efficiency.**

Solution:

It is given that V1 = 8 kV and V2 = 11 kV. (i) Let K be the ratio of capacitance between pin and earth to self-capacitance. If C farad is the self-capacitance of each unit, then capacitance between pin and earth = KC. Applying Kirchhoff's current law to Junction A,

$$I_2 = I_1 + i_1$$
$$V_2\omega C = V_1\omega C + V_1 K\omega C$$
$$V_2 = V_1(1+K)$$
$$\therefore K = \frac{V_2 - V_1}{V_1} = \frac{11-8}{8} = 0.375$$

Applying Kirchhoff's current law to junction B.

$$I_3 = I_2 + i_2$$
$$V_3\omega C = V_2\omega C + (V_1 + V_2)K\omega C$$
$$V_3 = V_2 + (V_1 + V_2)K = 11 + (8 + 11) \times 0.375 = 18.12kV$$
$$Voltage\ between\ line\ and\ earth = V_1 + V_2 + V_3 = 8 + 11 + 18.12 = 37.12kV$$
$$\therefore Line\ voltage = \sqrt{3} \times 37.12 = 64.28kV$$

String efficiency

$$String\ efficiency = \frac{Voltage\ across\ string}{No\ of\ insulators\ \times V_3} \times 100 = \frac{37.12}{3 \times 18.12} \times 100 = 68.28\%$$

Problem 3: **Each line of a 3-phase system is suspended by a string of 3 similar insulators. If the voltage across the line unit is 17.5kV, calculate the line to neutral voltage. Assume that the shunt capacitance between each insulator and earth is 1/8th of the capacitance of the insulator itself. Also find the string efficiency.**

Solution:

If C is the self capacitance of each unit, ten KC will be shunt capacitance where K = 1/8 = 0.125

At junction A

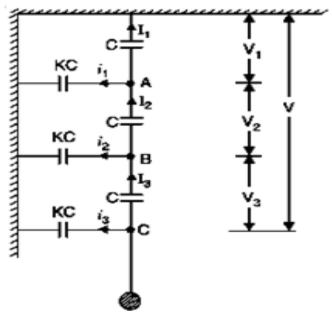
$$I_2 = I_1 + i_1$$
$$V_2\omega C = V_1\omega C + V_1 K\omega C$$
$$V_2 = V_1(1+K) = V_1(1+0.125)$$
$$\therefore \quad V_2 = 1.125V_1$$

At junction B

$$I_3 = I_2 + i_2$$
$$V_3\omega C = V_2\omega C + (V_2+V_1)K\omega C$$
$$V_3 = V_2 + (V_1+V_2)K = 1.125V_1 + (V_1 + 1.125V_1) \times 0.125$$
$$\therefore \quad V_3 = 1.39V_1$$
$$Voltage\ across\ top\ unit, V_1 = V_3/1.39 = \frac{17.5}{1.39} = 12.59kV$$
$$Voltage\ across\ middle\ unit, V_2 = 1.125V_1 = 1.125 \times 12.59 = 14.16kV$$

∴Voltage between line and earth (i.e. line to neutral)

$$= V_1 + V_2 + V_3 = 12.59 + 14.16 + 17.5 = 44.25kV$$
$$String\ efficiency = \frac{44.25}{3 \times 17.5} \times 100 = 84.28\%$$



Problem 4: **The three bus-bar conductors in an outdoor substation are supported by units of post type insulators. Each unit consists of a stack of 3 pin type insulators fixed one on the top of the other. The voltage across the lowest insulator is 13·1 kV and that across the next unit is 11 kV. Find the bus-bar voltage of the station.**

Solution:

It is given thatV3 = 13·1 kVandV2 = 11 kV. Let K be the ratio of shunt capacitance to self-capacitance of each unit. Applying Kirchhoff's current law to Junctions A and B, we can easily derive the following

$$V_2 = V_1(1+K)$$
$$V_1 = \frac{V_2}{1+K}$$
$$V_3 = V_2 + (V_1+V_2)K$$

Putting the values of $V_1 = V_2(1+K)$ in equation (ii), we get,

$$V_3 = V_2 + \left[\frac{V_2}{1+K} + V_2\right]K$$

equat

$$V_3(1+K) = V_2(1+K) + [V_2 + V_2(1+K)]K$$

$$= V_2\,[(1+K) + K + (K + K^2)]$$

$$= V_2(1 + K + K^2)$$

$$\therefore \qquad 13.1(1+K) = 11[1 + 3K + K^2]$$

$$11K^2 + 19.9K - 2.1 = 0$$

Solving this equation, we get, K = 0.1

$$\therefore \qquad V_1 = \frac{V_2}{1+K} = \frac{11}{1+0.1} = 10kV$$

Voltage between line and earth = V_1+ V_2+ V_3 = 10+11+13.1 = 34.1kV

∴ Voltage between bus-bars (i.e., line voltage) = $34.1 \times \sqrt{3} = 59kV$

Problem 5: **String of 4 insulators has a self-capacitance equal to 10 times the pin to earth capacitance. Find (i) the voltage distribution across various units expressed as a percentage of total voltage across the string and (ii) string efficiency.**

Solution:

When the number of insulators in a string exceeds 3, the nodal equation method becomes laborious. Under such circumstances, there is a simple method to solve the problem. In this method, shunt capacitance (C1) and self-capacitance (C) of each insulator are represented by their equivalent reactance's. As it is only the ratio of capacitances which determines the voltage distribution,

therefore, the problem can be simplified by assigning unity value to XC i.e., assuming

X_C= 1. Ω If ratio of C/C1 = 10, then we have X_C= 1 Ω and X_{C1} = 10 Ω (i) Suppose X_C = 1 Ω As the ratio of self-capacitance to shunt capacitance (i.e., C/C1 is 10, therefore, X_{C1} = 10 Ω as shown in Figure, Suppose that potential V across the string is such that 1 A current flows in the top insulator. Now the potential across each insulator can be easily determined. **Thus:**

Voltage across top unit, V1 = 1 Ωx1 A = 1

volt Voltage across 2nd unit, V2 = 1 Ωx1·1 A = 1·1 volts

Voltage across 3rd unit, V3 = 1 Ωx1·31 A = 1·31 volts

Voltage across 4th unit, V4 = 1 Ωx1·65 A = 1·65 volts

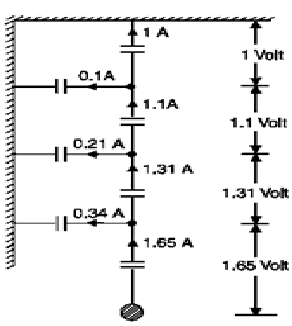
Voltage obtained across the string, V = 1 + 1·1 + 1·31 + 1·65 = 5·06 volts

The voltage across each unit expresses as a percentage of V (i.e., 5.06 volts) becomes:

Top unit = (1/5.06)*100 = 19.76% , Second from top = (1.1/5.0)*100 = 21.74%

Third from top = (1.31/5.06)*100 = 25.9% , Fourth from top = (1.65/5.06)*100 = 32.6%

$$String\ efficiency = \frac{V}{4 + V_4} \times 100 = \frac{5.06}{4 \times 1.65} \times 100 = 76.6\%$$



Problem 6: **A string of 5 insulators is connected across a 100kV line. If the capacitance of each disc to earth is 0.1 of the capacitance of the insulator, calculate (i) the distribution of voltage on the insulator discs and (ii) the string efficiency**.

Solution:

Suppose Xc = 1Ω. As the ratio of self capacitance to shunt capacitance is 10, therefore, Xc1 = 10Ω as shown in fig (i). Suppose that potential V across the string is such that 1A current flows in the top insulator. The potential across each insulator will be as shown in fig (ii) The value obtained for V= 1+1.11+1.31+1.65+2.16 = 7.22 volts and starting from top, the percentage of V (i.e.,7.22 volts) across various units are: 13.8%, 15.2%, 18.2%, 22.8% and 30%

Voltage across string = √ i) Voltage across top insulator,

V1 = 0.138*57.7 = 7.96kV

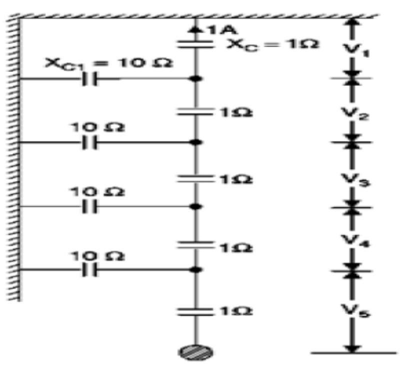
ii) Voltage across 2nd from top, V2 = 0.152 * 57.7 = 8.77kV

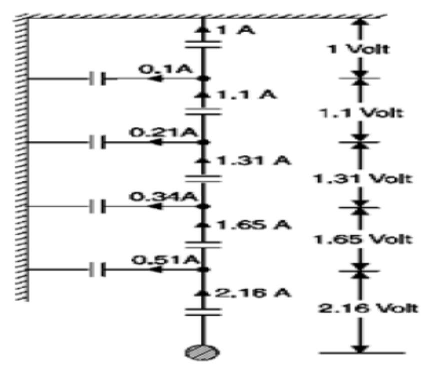
Voltage across 3rd from top, V3 = 0.182*57.7 = 10.5kV

Voltage across 4th from top, V4 = 0.228*57.7 = 13.16kV

Voltage across 5th from top, V5 = 0.3*57.7 = 17.3kV

$$String\ efficiency = \frac{57.7}{5 \times 17.3} \times 100 = 66.7\%$$





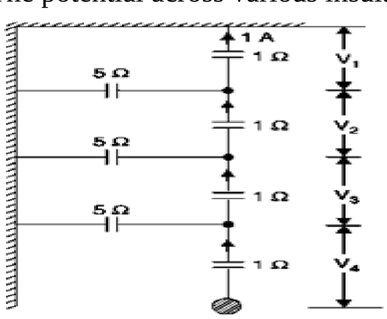
Problem 7: **A string of four insulators has a self-capacitance equal to 5 times pin to earth capacitance. Find (i) the voltage distribution across various units as a percentage of total voltage across the string and (ii) string efficiency.**

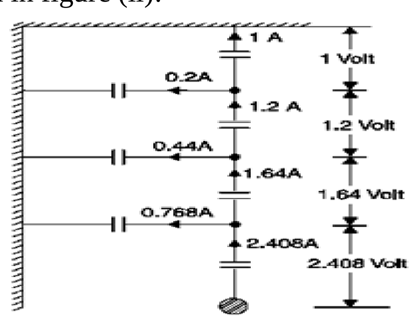
Solution:

The ratio of self-capacitance (C) to pin-earth capacitance (C1) is C/C1 = 5.

Suppose Xc=1Ω. Then Xc1 = 5Ω.

Suppose the voltage V across string is such that current in the top insulator is 1A as shown in figure (i). The potential across various insulators will be as shown in figure (ii).





The voltage obtained across the string is given by: V = 1+1.2+1.64+2.408 = 6.248volts

i) The voltage across each unit expressed as a percentage of V (i.e., 6.248 volts) is given by:

Top unit = (1/6.248)*100 = 16%

Second from top = (1.2/6.248)*100 = 19.2%

Third from top = (1.64/6.248)*100 = 26.3%

Fourth from top = (2.408/6.248)*100 = 38.5%

ii) String efficiency $= \frac{6.248}{4\times 2.408} \times 100 = 64.86\%$

Problem 8: **The self capacitance of each unit in a string of three suspension insulators is C. The shunting of the connecting metal work of each insulator to earth is 0.15 C while for line it is 0.1 C. Calculate (i) The voltage across each insulator as a percentage of the line voltage to earth and (ii) String Efficiency**

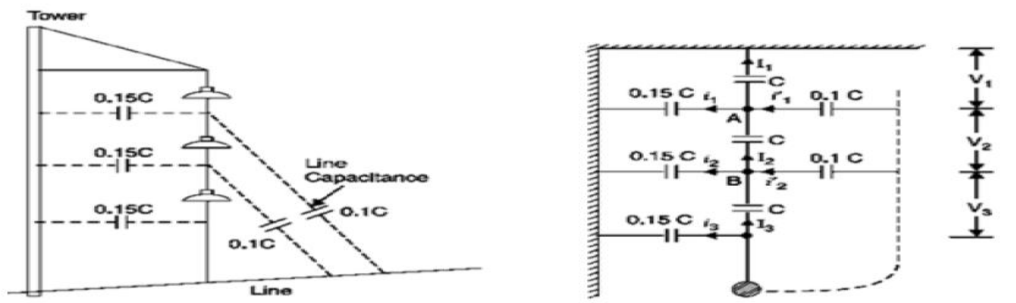
Solution:

In an actual string of insulators, three capacitances exist viz., self-capacitance of each insulator, shunt capacitance and capacitance of each unit to line as shown in Figure (i). However, capacitance of each unit to line is very small and is usually neglected. Figure (ii) shows the equivalent circuit of string insulators.

At junction A

$$I_2 + i_1' = I_1 + i_1$$
$$V_2\omega C + (V_2 + V_3)0.1\omega C = V_1\omega C + 0.15CV_1\omega$$
$$0.1V_3 = 1.15V_1 - 1.1V_2$$
$$V_3 = 11.5V_1 - 11V_2$$

$$I_3 + i_2' = I_2 + i_2$$
$$V_3\omega C + V_3 \times 0.1C \times \omega = V_2\omega C + (V_1 + V_2)\omega \times 0.15C$$
$$1.11\ V_3 = 1.15V_2 + 0.15V_1$$



(i) (ii)

Substituting the value of V_3, we get

$$1.1\,(11.5V_1 - 11V_2) = 1.15V_2 + 0.15V_1$$
$$13.25V_2 = 12.5V_1$$
$$V_2 = \frac{12.5}{13.25}V_1$$

Substituting the value of V_2, we get

$$V_3 = 11.5V_1 - 11\left(\frac{12.5V_1}{13.25}\right) = \left(\frac{14.8}{13.25}\right)V_1$$

Now voltage between conductor and earth is

$$V = V_1 + V_2 + V_3 = V_1\left(1 + \frac{12.5}{13.25} + \frac{14.8}{13.25}\right) = \left(\frac{40.55V_1}{13.25}\right) volts$$

∴ V_1 = 13.25V/40.55 = 0.326V volts

V_2 = 12.5*0.326 V / 13.25 = 0.307V volts

V_3 = 14.8 * 0.326 V/13.25 = 0.364V volts

The voltage across each unit expressed as a percentage of V becomes:

Top unit = V_1 * 100/V = 0.326*100 = 32.6%

Second from top = V2 * 100/V = 0.307*100 = 30.7%

Third from top = V3 * 100/V = 0.364*100 = 36.4%

String efficiency $= \frac{V}{3\times 0.364V} \times 100 = 91.5\%$

Problem 9: **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:

The capacitance between each unit and line is artificially increased by using a guard ring as shown in figure. This arrangement tends to equalize the potential across various units and hence leads to improved string efficiency. It is given that with the use of guard ring, capacitance of the insulator link-pin to the line of the lowest unit is increased from 0.1 C to 0.3C.

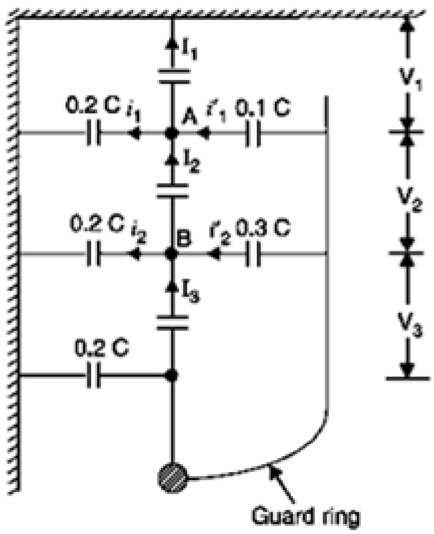
At junction A

$$I_2 + i_1' = I_1 + i_1$$
$$V_2\omega C + (V_2 - V_3)\omega \times 0.1C = V_1\omega C + V_1 \times 0.2C\omega$$
$$V_3 = 12V_1 - 11V_2$$

At junction B

$$I_3 + i_2' = I_2 + i_2$$
$$V_3\omega C + V_3 \times 0.3C \times \omega = V_2\omega C + (V_1 + V_2)\omega + 0.2C$$

$$1.3V_3 = 1.2V_2 + 0.2V_1$$



Substituting the value of V_3, we get

$$1.3(12V_1 - 11V_2) = 1.2V_2 + 0.2V_1$$
$$15.5V_2 = 15.4V_1$$

$$\therefore V_2 = \frac{15.4V_1}{15.5} = 0.993V_1$$

Substituting the value of V_2, we get

$$V_3 = 12V_1 - 11 \times 0.993V_1 = 1.077V_1$$

Voltage between conductor and earth (i.e. phase voltage)

$$= V_1 + V_2 + V_3 = V_1 + 0.993V_1 + 1.077V_1 = 3.07V_1$$

$$String\ efficiency = \frac{3.07V_1}{3 \times 1.077V_1} \times 100 = 95\%$$

SAG IN OVERHEAD LINES

Sag: ***"The difference in level between the points of supports and the lowest point in the conductor is called Sag"*** Span: ***"The distance between the adjacent supporting tower is called is called SPAN"***

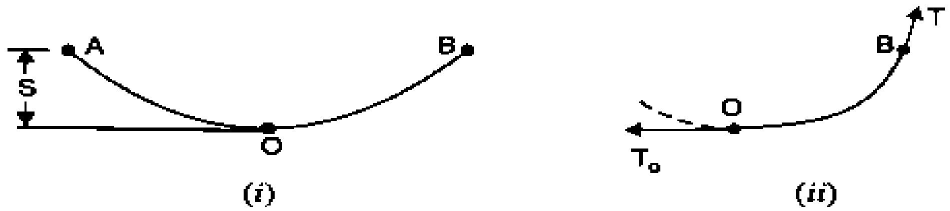
Factors affecting the sag:

The following factors affecting the sag in overhead transmission lines are

- **WEIGHT OF THE CONDUCTOR-** *heavier the conductor, greater will be the sag*
- **SPAN LENGTH** – *sag is directly proportional to the square of the span length other conditions remaining unchanged*
- **TEMPERATURE-** *sag increases with increase in temperature*
- **WORKING TENSILE STRENGTH-** *other condition remaining the same, the sag is inversely proportional to the working tensile strength* Under varying weather conditions of ambient temperature, the conductor tension, which is maximum near the tower ends, should not exceed the permissible limit.

$$Working\ Tensile\ Strength = \frac{breaking\ strength\ of\ the\ conductor}{safety\ factor\ of\ 2\ to\ 2.5}$$

While erecting an overhead line, it is very important that conductors are under safe tension. If the conductors are too much stretched between supports in a bid to save conductor material, the stress in the conductor may reach unsafe value and in certain cases the conductor may break due to excessive tension. In order to permit safe tension in the conductors, they are not fully stretched but are allowed to have a dip or sag. The difference in level between points of supports and the lowest point on the conductor is called sag. Figure shows a conductor suspended between two equal level supports A and B. The conductors not fully stretched but are allowed to have a dip. The lowest point on the conductor is O and the sag is S.



The following points may be noted:

(i) When the conductor is suspended between two supports at the same level, it takes the shape of catenary. However, if the sag is very small compared with the span, then sag-span curve is like a parabola.

(ii) The tension at any point on the conductor acts tangentially. Thus tension T0 at the lowest point O acts horizontally as shown in Fig.

(iii) The horizontal component of tension is constant throughout the length of the wire.

(iv) The tension at supports is approximately equal to the horizontal tension acting at any point on the wire. Thus if T is the tension at the support B, then T=T0.

CONDUCTOR SAG AND TENSION.

This is an important consideration in the mechanical design of overhead lines. The conductor sag should be kept to a minimum in order to reduce the conductor material required and to avoid extra pole height for sufficient clearance above ground level.

It is also desirable that tension in the conductor should be low to avoid the mechanical failure of conductor and to permit the use of less strong supports. However, low conductor tension and minimum sag are not possible. It is because low sag means a tight wire and high tension, whereas a low tension means a loose wire and increased sag. Therefore, in actual practice, a compromise in made between the two.

5. Derive an expression for sag in OH lines, when (11) (APRIL/2015) (NOV/2013)

(a)Supports are at equal levels (b)Supports are at unequal levels

CALCULATION OF SAG:

In an overhead line, the sag should be so adjusted that tension in the conductors is within safe limits. The tension is governed by conductor weight, effects of wind, ice loading and temperature variations. We shall now calculate sag and tension of a conductor when

- *Supports are at equal levels and*
- *Supports are at unequal levels*

(i) When supports are at equal levels. Consider a conductor between two equi level supports A and B with O as the lowest point as shown in Figure. It can be proved that lowest point will be at the mid-span.

Let, L = *Length of span*

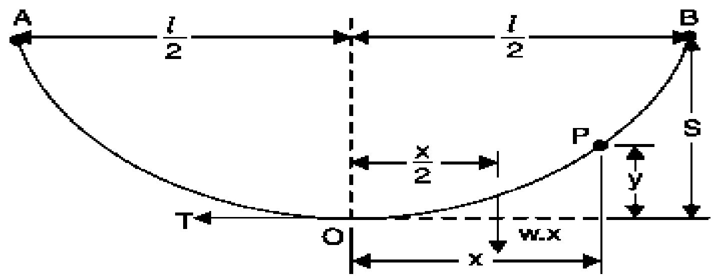
W = *Weight per unit length of conductor*

T = *Tension in the conductor*.

Consider a point P on the conductor taking the lowest point O as the origin, let the coordinates of point P be x and y. Assuming that the curvature is so small that curved length is equal to its horizontal projection (i.e., OP = x), the two forces acting on the portion OP of the conductor are :

(a) The weight **wx** of conductor acting at a distance x/2 from O.

(b) The tension **T** acting at O.



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

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

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

The maximum dip (sag) is represented by the value of y at either of the supports A and B. At support A, x=l/2 and y = S

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

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

(ii) **When supports are at unequal levels:** In hilly areas, we generally come across conductors suspended between supports at unequal levels. Figure shows a conductor suspended between two supports A and B which are at different levels. The lowest point on the conductor is O.

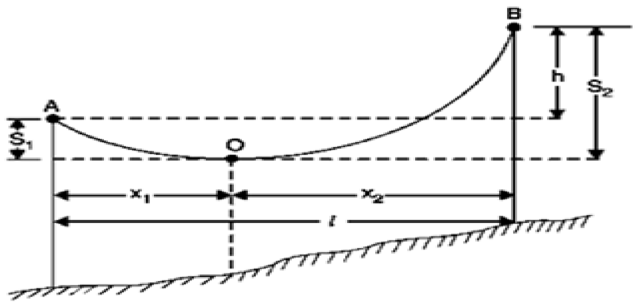
Let l = Span length

h = Difference in levels between two supports

x1 = Distance of support at lower level (i.e. A) from O

x2 = Distance of support at higher level (i.e. B) from O

T = Tension in the conductor



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

$$Sag\ S_1 = \frac{wx_1^2}{2T}$$

And

$$Sag\ S_2 = \frac{wx_2^2}{2T}$$

Also $\quad x_1 + x_2 = l$

Now

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

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

But $\quad S_2 - S_1 = h$

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

$$x_2 - x_1 = \frac{2Th}{wl}$$

On solving we get,

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

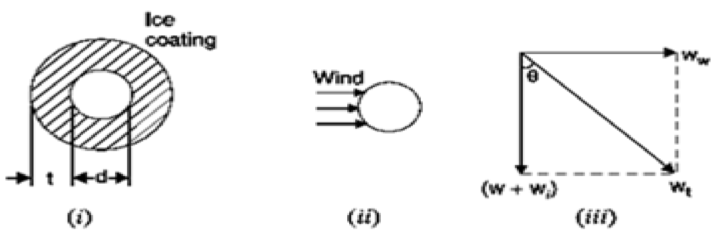
$$x_2 = \frac{l}{2} + \frac{Th}{wl}$$

Having found x_1 and x_2, values of S_1 and S_2 can be easily calculated.

EFFECT OF WIND AND ICE LOADING:

The above formulae for sag are true only in still air and at normal temperature when the conductor is acted by its weight only. However, in actual practice, a conductor may have ice coating and simultaneously subjected to wind pressure. The weight of ice acts vertically downwards i.e., in the same direction as the weight of conductor. The force due to the wind is assumed to act horizontally i.e., at right angle to the projected surface of the conductor.

Hence, the total force on the conductor is the vector sum of horizontal and vertical forces as shown in Figure



Total weight of conductor per unit length is

$$w_t = \sqrt{(w + W_i)^2 + (W_w)^2}$$

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

When the conductor has wind and ice loading also, the following points ma be noted:

(i) The conductor sets itself in aplane at an angle θ to the vertical where

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

(ii) The sag in the conductor is given by

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

Hence the S represents the slant sag in a direction making an angle θ to the vertical. If no specific mention is made in the problem, then slant sag is calculated b using in above formula.

The vertical slag = S cos θ

Problem 1: **A 132KV transmission line has the following data; Wt of conductor=680 kg/km ; length of span=260m Ultimate strength=3100 kg ; safety factor=2 Calculate the height above ground at which the conductor should be supported. Ground clearance required is 10 meters.**

Solution:

Weight of conductor/meter run, $w = 680/1000 = 0.68kg$

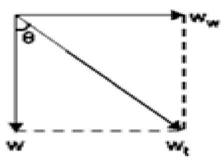
Working tension, $T = \frac{Ultimate\ strength}{Safety\ factor} = \frac{3100}{2} = 1550kg$

Span length, $l = 260m$

$$\therefore \quad sag = \frac{wl^2}{8T} = \frac{0.68 \times (260)^2}{8 \times 1550} = 3.7m$$

∴ Conductor should be supported at a height of 10+3.7=13.7m

Problem 2: **A transmission line has a span of 150m between level supports. The conductor has a cross-sectional area of 2cm2. The tension in the conductor is 2000kg. If the specific gravity of the conductor material is 9.9gm/cm3 and wind pressure is 1.5 kg/m length. Calculate the sag. What is the vertical sag?**



Span length, l=150m; working tension,

T= 2000kg Wind force/m length of conductor,

W_W=1.5kg Wt of conductor/m length,

W= Sp. Gravity * volume of 1m conductor = 9.9*2*100=1980gm=1.98kg

Total weight of 1m length of conductor is

$$w_i = \sqrt{w^2 + w_W^2} = \sqrt{(1.98)^2 + (1.5)^2} = 2.48kg$$

$$\therefore \qquad sag, \quad s = \frac{w_r l^2}{gT} = \frac{2.48 \times (150)^2}{8 \times 2000} = 3.48m$$

This is the value of slant sag in a different making an angle θ with the vertical referring to fig.4.23, the value of θ is given by;

$$\tan\theta = \frac{w_W}{w} = \frac{1.5}{1.98} = 0.76$$

$$\therefore \quad \theta = tan^{-1}0.76 = 37.23°$$

$$\therefore \qquad vertical\ sag = s\cos\theta$$

$$= 3.48 \times \cos 37.23° = 2.77m$$

Problem 3: **A transmission line has a span of 200 meters between level supports. The conductors has a cross-sectional area of 1.29cm2, weighs 1170kg/km and has a breaking stress of 4218 kg/cm2. Calculate the sag for a safety factor of 5, allowing a wind pressure of 122kg per square meter of projected area. What is the vertical sag?**

Solution:

Span length, l=200m

Wt of conductor/m length, $w = \frac{1170}{1000} = 1.17kg$

Working tension, $T = 4218 \times \frac{1.29}{5} = 1088kg$

$$Diameter\ of\ conductor, \qquad d = \sqrt{\frac{4 \times area}{\pi}} = \sqrt{\frac{4 \times 1.29}{\pi}} = 1.28cm$$

$$wind\ Force/m \quad length, \qquad w_w = pressure \ \times projected\ area\ in\ m^2$$

Total weight of conductor per meter length is

$$W_i = \sqrt{w^2 + w^2{}_w} = \sqrt{(1.17)^2 + (1.56)^2} = 1.95kg$$

$$\therefore \qquad Slant\ sag, \quad S = \frac{w_{rl^2}}{8T} = \frac{1.95 \times (200)^2}{8 \times 1088} = 8.96m$$

The slant sag makes angle θ with the vertical where the value of θ is given by:

$$\theta = tan^{-1}\frac{w_W}{w} = tan^{-1}\frac{1.56}{1.17} = 53.13°$$

$$vertical\ sag = s\cos\theta = 8.96 \times \cos 53.13° = 5.37m$$

Problem 4: **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/cm2 of projected area, calculate sag for a safety factor of 2. Weight of 1c.c of ice is 0.91gm.**

Solution:

Span length, l=275m; wt of conductor/m length, w=0.865kg Conductor diameter, d=1.96cm; ice coating thickness, t=1.27cm Working tension, T=8060/2=4030kg ,

Volume of ice per meter (i.e. 100cm) length of conductor

$$= \pi t(d + t) \times 100cm^3$$

$$= \pi \times 1.27 \times (1.96 + 1.27) \times 100 = 1288cm^3$$

Weight of ice per meter length of conductor is

$$w_i = 0.91 \times 1288 = 1172gm = 1.172kg$$

Weight force/m length of conductor is

$$w_w = [pressure] \times [(d + 2t) \times 100]$$

$$= [3.9] \times [(1.96 + 2 \times 1.27)] \times 100gm = 1755gm = 1.755kg$$

Total weight of conductor per meter length of conductor is

$$w_t = \sqrt{(w + w_t)^2 + (w_w)^2} = \sqrt{(0.865 + 1.172)^2 + (1.755)^2} = 2.688kg$$

$$\therefore \quad sag, \quad S = \frac{w_{rl^2}}{8T} = \frac{2.688 \times (275)^2}{8 \times 4030} = 6.3m$$

Problem 5: **A transmission line has a span of 214 meters between level supports. The conductor have a cross-sectional area of 3.25cm2.calculate the factor of safety under the following conditions: Vertical sag=2.35m; wind pressure=1.5kg/m run Breakage stress=2540kg/cm2; wt of conductor=1.125kg/m run**

Solution:

Here l=214m; w=1.125kg; w_w=1.5kg Total weight of one meter length of conductor is

$$W_t = \sqrt{w^2 + w^2{}_w} = \sqrt{(1.25)^2 + (1.5)^2} = 1.875kg$$

If f is the factor of safety, then.

Working tension, T= (Breaking stress*conductor area)/ safety factor

$$= \frac{2540 \times 3.255}{f} = \frac{8191}{f}kg$$

$$slant\ sag, \quad S = \frac{vertical\ sag}{cos\theta} = \frac{2.35 \times 1.875}{1.125} = 3.92m$$

$$Now \quad s = \frac{wl^2}{8T}$$

$$Or \quad T = \frac{wl^2}{8T}$$

$$\therefore \quad \frac{8191}{f} = \frac{1.875 \times (214)^2}{8 \times 3.92}$$

$$safety\ factor \quad f = \frac{8191 \times 8 \times 3.92}{1.875 \times (214)^2} = 3$$

Problem 6: **The towers of height 30 m and 90 m respectively support a transmission line conductor at water crossing. The horizontal distance between the towers is 500 m. If the tension in the conductor is 1600 kg, find the minimum clearance of the conductor and water and clearance mid-way between the supports. Weight of conductor is 1·5 kg/m. Bases of the towers can be considered to be at water level.**

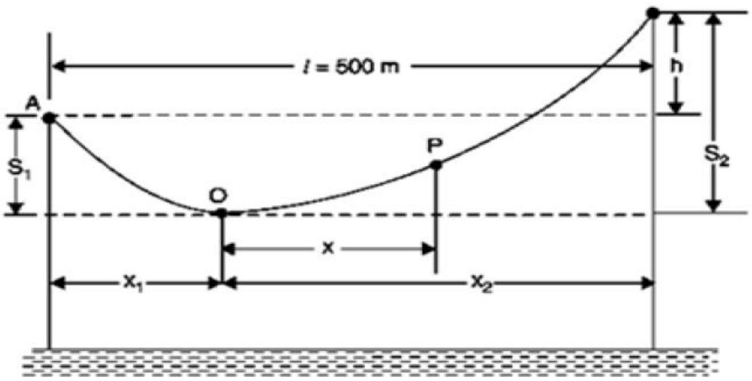
Solution: Figure shows the conductor suspended between two supports A and B at different levels with O as the lowest point on the conductor. Here, l = 500 m ; w = 1·5 kg ; T = 1600 kg. Difference in levels between supports, h = 90-30 = 60 m. Let the lowest point O of the conductor be at a distance x_1 from the support at lower level (i.e., support A) and at a distance x_2 from the support at higher level (i.e., support . Now

$$sag\ s_1 = \frac{w\,x_1{}^2}{2T} \ and\ sag\ s_2 = \frac{w\,x_2{}^2}{2T}$$

$$\therefore \quad h = s_2 - s_1 = \frac{w\,x_2{}^2}{2T} - \frac{w\,x_1{}^2}{2T}$$

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

$$\therefore\ x_2 - x_1 = \frac{60 \times 2 \times 1600}{1.5 \times 500} = 256m$$



Solving the exp, we get x_1=122m; x_2=378m

Now $$s_1 = \frac{w\,x_1{}^2}{2T} = \frac{1.5\times(122)^2}{2\times1600} = 7m$$

Clearance of the lowest point O from water level $= 30 - 723m$

Let the mid-point P be at a distance x from the lowest point O.

Clearly, $$x = 250 - x_1 = 250 - 122 = 128m$$

Sag at mid point P,

$$S_{mid} = \frac{w\,x_1{}^2}{2T} = \frac{1.5\times(128)^2}{2\times1600} = 7.68m$$

Clearance of the mid point P from water level

$$= 23 + 7.68 = 30.68m$$

Problem 7: **An overhead transmission line conductor having a parabolic configuration weighs 1.925kg per meter of length. The area of cross-section of the conductor is 2.2cm2 and the ultimate strength is 8000kg/cm2. The supports are 600m apart having 15m difference of levels. Calculate the sag from the taller of the two supports which must be allowed so that the factor of safet shall be 5. Assume that ice load is 1kg per meter run and there is no wind pressure.**

Solution:

Figure shows the conductor suspended between two supports at A and B at different levels with O as the lowest point on the conductor:

Here , l=600m; w_t=1kg; h=15m; w=1.925kg; T=8000*2.2/5=3520kg

Total weight of 1m length of conductor is $w_t = w + w_i$ =1.925+1=2.925kg

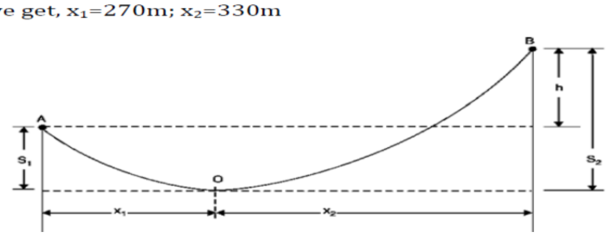
Let the lowest point O of the conductor be at a distance x_1 from the support at lower level and at a distance x_2 from the support at higher level Clearly, x_1+x_2=600m (i)

Now, $$h = s_2 - s_1 = \frac{w_t\,x_2{}^2}{2T} - \frac{w_t\,x_1{}^2}{2T}$$

$$15 = \frac{w_t}{2T}(x_2 + x_1)(x_2 - x_1)$$

$$x_2 - x_1 = \frac{2\times15\times3520}{2.925\times600} = 60m \qquad (ii)$$

Solving exp (i) & (ii), we get, x_1=270m; x_2=330m



Sag from the taller of the two towers is

$$S_2 = \frac{w_t x_2{}^2}{2T} = \frac{2.935 \times (330)^2}{2 \times 3520} = 45.24m$$

Some Mechanical Principles:

Mechanical factors of safety to be used in transmission line design should depend to some extent on the importance of continuity of operation in the line under consideration. In general, the strength of the line should be such as to provide against the worst probable weather conditions. We now discuss some important points in the mechanical design of overhead transmission lines.

(i) Tower height: Tower height depends upon the length of span. With long spans, relatively few towers are required but they must be tall and correspondingly costly. It is not usually possible to determine the tower height and span length on the basis of direct construction costs because the lightning hazards increase greatly as the height of the conductors above ground is increased. This is one reason that horizontal spacing is favored in spite of the wider right of way required.

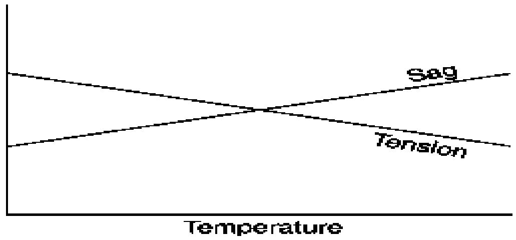
(ii) **Conductor clearance to ground**: The conductor clearance to ground at the time of greatest sag should not be less than some specified distance (usually between 6 and 12 m), depending on the voltage, on the nature of the country and on the local laws. The greatest sag may occur on the hottest day of summer on account of the expansion of the wire or it may occur in winter owing to the formation of a heavy coating of ice on the wires. Special provisions must be made for melting ice from the power lines.

(iii) **Sag and tension**: When laying overhead transmission lines, it is necessary to allow a reasonable factor of safety in respect of the tension to which the conductor is subjected. The tension is governed by the effects of wind, ice loading and temperature variations. The relationship between tension and sag is dependent on the loading conditions and temperature variations. For example, the tension increases when the temperature decreases and there is a corresponding decrease in the sag. Icing-up of the line and wind loading will cause stretching of the conductor by an amount dependent on the line tension. In planning the sag, tension and clearance to ground of a given span, a maximum stress is selected. It is then aimed to have this stress developed at the worst probable weather conditions (i.e. minimum expected temperature, maximum ice loading and maximum wind). Wind loading increases the sag in the direction of resultant loading but decreases the vertical component. Therefore, in clearance calculations, the effect of wind should not be included unless horizontal clearance is important.

(iv) **Stringing charts**: For use in the field work of stringing the conductors, temperature-sag and temperature tension charts are plotted for the given conductor and loading conditions. Such curves are called stringing charts (see Figure). These charts are very helpful while stringing overhead lines.

(v) **Conductor spacing**: Spacing of conductors should be such so as to provide safety against flash-over when the wires are swinging in the wind. The proper spacing is a function of span length, voltage and weather conditions. The use of horizontal spacing eliminates the danger caused by unequal ice loading. Small wires or wires of light material are subjected to more swinging by the wind than heavy conductors. Therefore, light wires should be given greater spacing’s.

(vi) **Conductor vibration**: Wind exerts pressure on the exposed surface of the conductor. If the wind velocity is small, the swinging of conductors is harmless provided the clearance is sufficiently large so that conductors do not approach within the sparking distance of each other. A completely different type of vibration, called dancing, is caused by the action of fairly strong wind on awire covered with ice, when the ice coating happens to take a form which makes a good air-foil section. Then the whole span may sail up like a kite until it reaches the limit of its slack, stops with a jerk and falls or sails back. The harmful effects of these vibrations occur at the clamps or supports where the conductor suffers fatigue and breaks eventually. In order to protect the conductors, dampers are used.



STRINGING CHART:

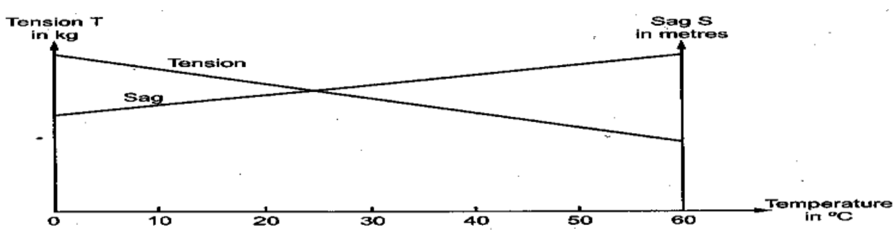
Sag at creation section that the tension T2 at, the time of erection is given by,

$$T_2^2\left[T_2 - T_1 + (t_2 - t_1)a\,\alpha\,E + \frac{w_1^2 l^2 aE}{6T_1^2}\right] - \frac{w_2^2 l^2 aE}{6} = 0$$

It is a cubic equation and is very difficult and time consuming to solve. The use of T2 is to obtain sag at the time of erection given by,

$$S_2 = \frac{w_2 l^2}{2T_2}$$

So instead of solving the cubic equation, it is, possible to obtain the graph of tension in kg against temperature in °C and the graph of sag in meters against temperature in °C. Such graphs is called stringing chart. The stringing chart is shown in the Figure



CABLES

"An underground cable essentially consists of one or more conductors covered with suitable insulation and surrounded by a protecting covers used for transferring or distributing electrical power under the ground surface"

Merits of underground cable:

- High Public safety
- Low Maintenance cost
- Less Frequency of faults and failures
- Less Frequency of accidents
- Low Voltage drop
- Good appearance
- Free from interruption of service
- No interference to communication circuits
- Long life

Demerits of underground cable:

- High initial cost
- High insulation required for high voltage
- Less working voltage
- Less flexibility
- High charging current

- No tapping for loads and service mains

Requirement of cables

The conductor used in cables should be tinned (coating the wire with tin provides it with more durability and strength) stranded copper or aluminium of high conductivity. Stranding is done so that conductor may become flexible and carry more current.

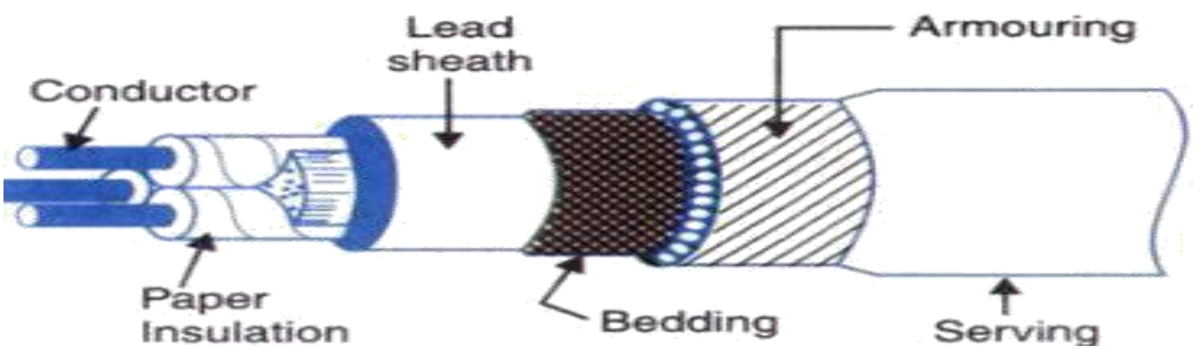
- The conductor size should be such that the cable carries the desired load current without overheating and causes voltage drop within permissible limits.
- The cable must have proper thickness of insulation in order to give high degree of safety and reliability at the voltage for which it is designed.
- The cable must be provided with suitable mechanical protection so that it may withstand the rough use in laying it.
- The materials used in the manufacture of cables should be such that there is complete chemical and physical stability throughout.

With neat diagram, show and explain the various parts of a high voltage single core cable(APRIL/2012) (or) **Draw and explain the general construction of underground cables.** (APRIL/2013)

CONSTRUCTION OF A CABLE

The various parts of cable are

- Cores (or) Conductors
- Insulation
- Metallic Sheath
- Bedding
- Armouring
- Serving



The Figure shows the general construction of a cable. The cable shown is a single Conductor underground cable. Its various parts are

1. <u>Conductor or core:</u>This section consists of single; conductor or more than one conductor. The conductors are also called cores. A cable with three conductors is called three corecables. The conductors used are aluminum or annealed copper. The conductors are stranded conductors in order to provide, flexibility to the cable

2. <u>Insulation</u>

Each conductor or core is covered by insulation of proper thickness. The commonly used insulating materials are varnished cambric, vulcanized bitumen and impregnated paper.

3. <u>Metallic sheath:</u>

The insulated conductors are covered by lead sheath or aluminum sheath. This provides the mechanical protection but mainly restricts moisture and other gases to reach to the insulation.

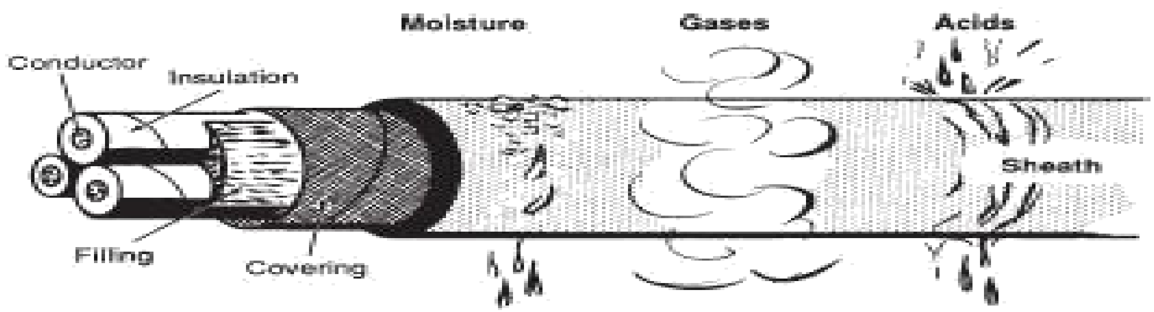
4. <u>Bedding</u>:

The metallic sheath is covered by another layer called bedding. The bedding consists of paper tape compounded with a fibrous material like jute strands or hessian tape. The purpose of bedding is to protect the metallic sheath from corrosion and from mechanical injury resulting due to armouring,

5. Armouring:

This layer consists of the layers of galvanized steel wires which provide protection to the cable from the mechanical injury.

6.Serving: The last layer above the armouring is serving. It is a layer of fibrous material like jute cloth which protects the armouring from the atmospheric conditions.



Properties of insulating material

- High insulation resistance to avoid leakage current.
- High dielectric strength to avoid electrical breakdown of the cable
- High mechanical strength to withstand the mechanical handling
- Low thermal co-efficient.
- Non- hygroscopic
- Low water absorption.
- Non – inflammable.
- Chemical stability.
- Capability to with stand high rupturing voltage.
- High tensile strength and plasticity

No one insulating material possesses all the mentioned properties. The types of insulating material depends upon the purpose for which cable is used and quality of insulation to be aimed

The principle insulation materials used in cables are

- Rubber
- Vulcanized India rubber [VIR]
- Impregnated paper
- Varnished cambric
- Polyvinyl chloride

6. Explain about types of cables. (NOV/2012)

TYPES OF CABLES:

The type of a cable is basically decided

Based on the voltage level for which it is manufactured

The material used for the insulation such as paper, cotton, rubber etc. The classification of cables according to the voltage levels are,

- **LOW TENSION (LT) CABLE** –up to 1000 V

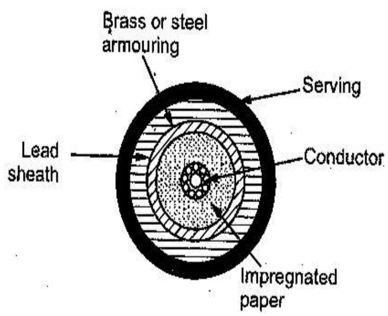
- **HIGH TENSION (H.T.) CABLE** –up to 11000 V
- **SUPER TENSION (S.T.) CABLE** –from 22 kV to 33 kV
- **EXTRA HIGH TENSION (E.H.T) CABLE** – from 33 kV to 66 kV

EXTRA SUPER VOLTAGE CABLE- beyond 132 kV

SINGLE PHASE SERVICE: (L.T. cables):

These are used for the voltage levels up to 6.6kV. The electrostatic stresses in L.T. cables are not severe hence no special construction is used for L.T. cables. The paper is used as insulation in these cables. Sometimes resin is also used which increases the viscosity and helps to prevent drainage.

The Figure shows the cross-section of a single core L.T. cable. It consists of circular core of stranded copper or aluminium. The conductor is insulated by impregnated paper. Over the paper insulation, the lead sheath is provided. Then a layer of compounded fibrous material is provided. Then armouring is provided and finally covered again with a layer of fibrous compounded material. Many a times, L.T. cables are not provided with armouring, to avoid excessive sheath losses. The simple construction and the availability of more copper section are the advantages of L.T. single core cable.

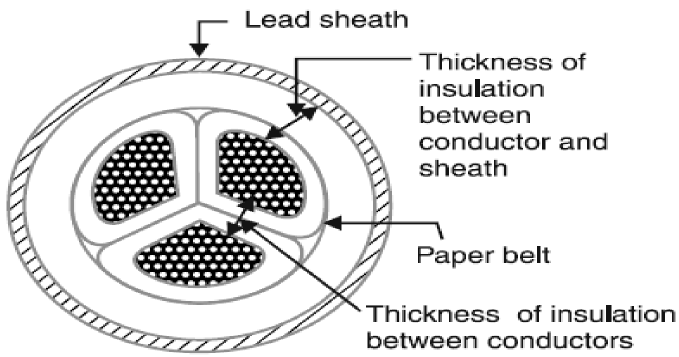


8. Explain cables used for 3-phase services. (NOV/2014)

THREE PHASE SERVICE (H.T. cables) : The three phase medium and H.T. cables are three core cables. For voltages upto 66 kV, the three core cables i.e. multi-core cables are used. For voltages beyond 66 kV, three corecables become too large and bulky and, therefore, three separate single-core cables are used. The following types of cables are generally used for 3-phase service:

- ***Belted cables*** — upto 11 kV
- ***Screened cables*** — from 22 kV to 66 kV
- ***Pressure cables*** — beyond 66 kV. Let us see the constructional features of these types of three core cables.

BELTED CABLES: As mentioned earlier, these are used for the voltage levels up to 11 kV. The cores are not circular in shape. The cores are insulated from each other by use of impregnated paper. The three cores are grouped together and belted with the help of a paper belt. The gaps are filled fibrous material like jute this gives circular cross-sectional shape to cable the cable. The belt is covered with lead sheath which protects cable from moisture and also gives mechanical strength.



The electric field in single Core cable is radial while it is tangential in case of three core cables. Hence the insulation is subjected to tangential electrical stresses rather than radial one. The paper has good radial strength but not tangential strength. Similarly paper resistance along the radius is much larger than resistance along tangential path.

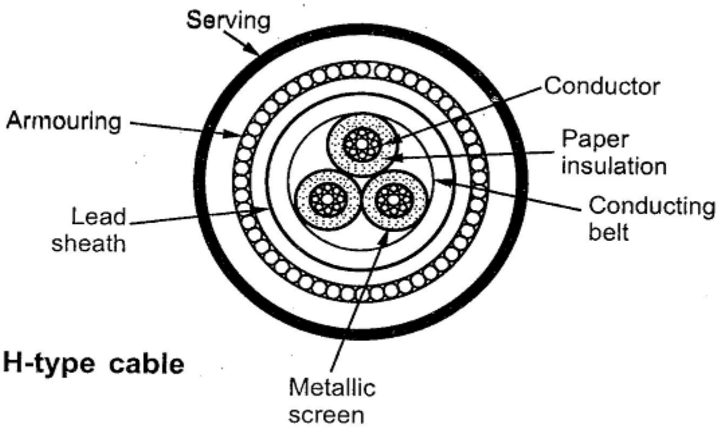
The same is true for dielectric strength also. The fibrous material is also subjected to the' tangential electrical stresses, for which, the material is weak. Hence under high voltage cases, the cumulative effect of tangential electrical stresses to form spaces inside the cable due to leakage currents. Such air spaces formed inside the insulation is called void formation. This void formation is dangerous because under high voltage, spaces are ionized which deteriorates the insulation which may lead to the breakdown of the insulation. Hence the belted cables are not used for the high voltage levels. Another disadvantage of the belted cable is large diameter of paper belt. Due to this, wrinkles are formed and gaps may be developed if the cable is bended. To overcome all these difficulties, the screened type cables are used.

SCREENED TYPE CABLES: These cables are used for the voltage level upto 33 kV. The two types of screened cables are

- H type cables
- S.L. type cables

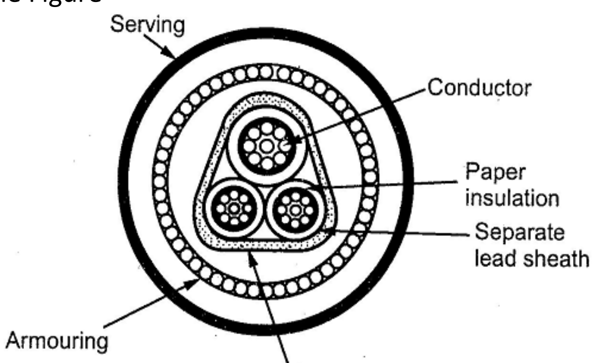
1. H Type Cables: The cable is designed by **M. HOCHSTETLER** and hence the name given to it is H type cable. There is no paper belt in this type of cable. Each conductor in this cable is insulated with a paper, covered with a metallic screen which is generally an aluminium foil. The construction is shown in the Figure. The metallic screen touches each other. Instead of paper belt, the three cores are wrapped with a conducting belt which is usually copper woven fabric tape. Then there is lead sheath. The conducting belt is in electrical contact with the metallic screen and lead sheath. After lead sheath there are layers of bedding, armouring and serving. The metallic screen helps to completely impregnate the cable which avoids the possibility of formation of voids and spaces. The conducting, the three metallic screen and lead sheath are at earth potential, due to which electrical stresses are radial in nature. This keeps dielectric losses to minimum:

Another advantage of metallic screens is increase in the heat dissipation which reduces sheath losses. Due to the advantages, current carry capacity of these cab increases. In special cases, the use of these cables can extended up to the 66kV level.



H-type cable

2. S L Cables:- The name S.L. stands for **SEPARATE LEAD** screened cables. In this cable, each core insulated with an impregnated paper and each one is then covered by separate lead sheath. Then there is a cotton tape covering the three cores together using a prop filler material. Then there are the layers of armouring and serving. The different between H-type and S.L. type cable is that in S.L. type common lead sheath covering , the three cores is absent while each core is provided with separate lead sheath. This allows bending of the cables as per the requirement. The construction of S.L. type cable is shown in the Figure



S.L. type cable

Advantages of S.L. type cable:

- Due to individual lead sheath, core to core fault possibility gets minimized.
- The electrical stresses are radial in nature.
- Due to absence of overall lead sheath, bending of cable is easy.
- The dielectric which gets subjected to electric stresses is paper which is homogeneous hence there is no possibility of formation of voids.
- Metal sheath increases the heat dissipation which increases the current carrying cap city. ***A combination of H-type and S.L. type cable called HSL cable also can be used***. **Disadvantages of S.L. type cable:** The limitations of screened cables which are also called solid type cables are,
- It uses solid insulation only like paper. When the conductor temperature increases, the paper gets expanded. This eventually stretches the lead sheath.
- When the load on the cable decreases, it cools down and there is contraction of lead sheath. Due to this air may be drawn into the cable forming voids. This deteriorates the cable insulation.
- Moisture may be drawn in along with the air which deteriorates the dielectric strength of dielectric.
- Mechanical shock can cause voids. The breakdown strength of voids is much less than insulation. Hence voids can cause permanent damage to the cables.

PRESSURE CABLES: In screened type cables separate arrangement for avoiding void formation and increasing dielectric strength is not provided. Hence those cables are used maximum upto 66 kV level.

The pressure cables are intended for 132 kV to 275 kV Voltage levels. In such cables, the following methods are specially used to eliminate the possibility of void formation:
1. Instead of solid type insulation, low viscosity oils under pressure is used for impregnation. The channels are used for oil circulation and oil is always kept under pressure. The pressure eliminates completely, the formation of voids.
2. Using inert gas at high pressure in between the lead sheath and dielectric. Such cables using oil or gas under pressure are called pressure cables and are of two types,

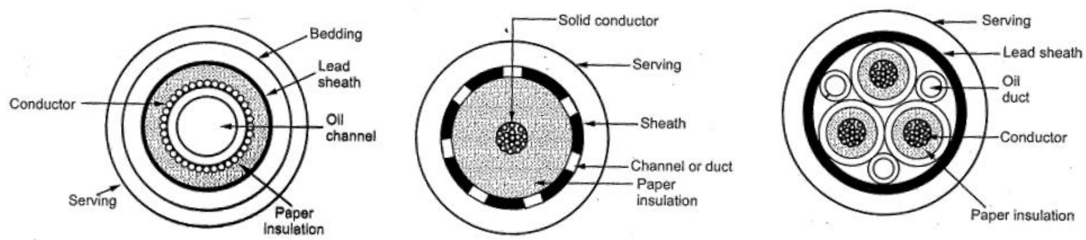
- Oil filled cables
- Gas pressure cables

OIL FILLED CABLES: In case of oil filled cables, the, channels or ducts are provided within or adjacent to the cores, through which oil under pressure is circulated. The figure (i) shows the construction of single core oil filled cable. It consists of concentric stranded conductor but built around a hollow cylindrical steel spiral core. This hollow core acts as a channel for the oil. The oil channel is filled in a factory and the pressure is maintained in the oil by connecting the oil channel to the tanks which are placed at the suitable distances along the path of the cable. The oil pressure compresses the insulation paper insulation, eliminating the possibility of formation of voids.

When the cable is heated the oil expands but expanded oil is collected in the tank. While when cable is cooled, extra oil is supplied by the tank to maintain the oil pressure. In this type of cable the oil channel is within the conductor, hence it is called single core conductor channel oil filled cable Another type of single core oil filled cable is the sheath channel oil filled cable.

In this type, the conductor is solid with paper insulation. While the oil ducts are provided between the dielectric and the lead sheath. The construction of sheath channel oil filled cable is shown in the figure (ii) the laying of such cables must be done very carefully. The three core oil filled cables use the shielded type construction.

The oil channels are located in the spaces which are normally occupied by the filler material. The three oil channels are of perforated metal ribbon tubing. All the channels are at earth potential. The construction is shown in, the figure (iii) as the pressure tanks are required all along the route of these' cables, the lengths of these cables are limited. Leakage of oil is another serious problem associated with these cables. A unit is located to indicate the fall in oil pressure in any of the phase.



Conductor channel single core oil filled cable | **Sheath channel single core oil filled cable** | **Oil filled three core cable**

Advantages:- The various advantages of oil filled cables are,

- The thickness of insulation required is less hence smaller in size and weight.
- The thermal resistance is less hence current carrying capacity is more.
- The possibility of voids is completely eliminated.
- The allowable temperature range is more than solid type cables.
- Reduced possibility of earth fault. This is because in case of any defect in lead sheath, oil leakage starts, which can be noticed before earth fault occurs.
- Perfect impregnation is possible.

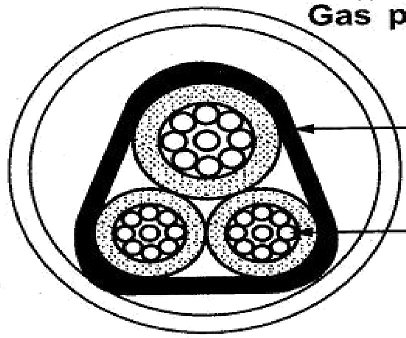
Disadvantages: The disadvantages of oil filled cables are,

- The initial cost is very high.
- The long lengths are not possible.

- The oil leakage is serious problem hence automatic signaling equipment is necessary.
- The laying of cable is difficult and must be done very carefully.
- Maintenance of the cables is also complicated.

GAS PRESSURE CABLES: In case of gas pressure cables, an inert gas like nitrogen at high pressure is introduced between lead sheath and dielectric. The pressure is about 12 to 15 atmospheres. Due to such a high pressure there is a radial compression due to which the ionization is totally eliminated. The working power factor of such cables is also high. The figure shows the section of a gas pressure cable. The cable is triangular in shape and installed in the steel pipe. The pipe is filled with the nitrogen at 12 to 15 atmospheric pressure. The remaining construction is similar to that shape of solid type cable but the thickness of lead sheath is 75% of that of solid type cable. There is no bedding and serving.

Gas pressure cable



The triangular shape lead sheath acts as a pressure membrane. The shape reduces the weight and provides the low thermal resistance. The high pressure creates the radial compression to close any voids. The steel pipe is coated with a paint to avoid corrosion. During heating, the cable compound expands and a sheath which acts as a membrane becomes circular in such a case. When cable cools down the gas pressure acting via sheath forces compound to come back to the noncircular normal shape. Due to good thermal characteristics, fire quenching property and high dielectric strength, the gas SF6, is also used in such cables.

Advantages: The various advantages of gas pressure cables are,

- Gas pressure cables can carry 1.5 times the normal [load current and can withstand double the voltage. Hence such cables can be used for ultra high voltage (UHV) levels.
- Maintenance cost is small.
- The nitrogen in the steel tube, helps in quenching any fire or flame.
- No reservoirs or ranks required.
- The power factor is improved.
- The steel tubes Used make the cable laying easy.
- The ionization and possibility of voids is completely eliminated.

Disadvantage: The only disadvantage of this type of cables is

- Very high initial Cost.

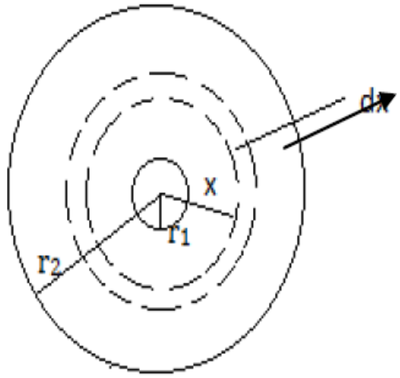
9. Derive an expression for insulation resistance of a single core cable (4) (APRIL/2015)

INSULATION RESISTANCE OF A CABLE:

The figure shows the section of a single core cable which is insulated with the help of layer of an insulating material. In such cables, the leakage current flows radially from centre towards the surface as shown in the figure. Hence the cross-section of the path of such current is not constant but changes with its length.

The resistance offered by cable to path of the leakage current is called an insulation resistance.

Consider a single core cable of conductor radius r_1 and internal sheath radius r_2 as shown in below figure. Let l be the length of the cable and ρ is the resistivity of the insulation.



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 cross section offered to this flow is **2πx l** Insulation resistance of considered layer

$$= \rho \frac{dx}{2\pi x l}$$

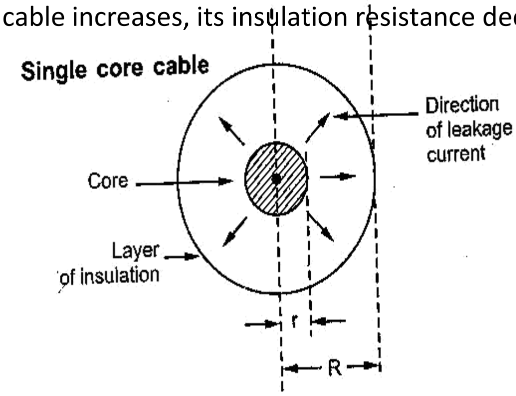
The insulation resistance of the whole cable is

$$R = \int_{r1}^{r2} \rho \frac{dx}{2\pi x l}$$

$$R = \frac{\rho}{2\pi l} \int_{r1}^{r2} \frac{dx}{x}$$

$$R = \frac{\rho}{2\pi l} \ln\left(\frac{r2}{r1}\right)$$

This shows that insulation resistance of a cable is inversely proportional to its length. In other words if the length of the cable increases, its insulation resistance decreases and vice-versa

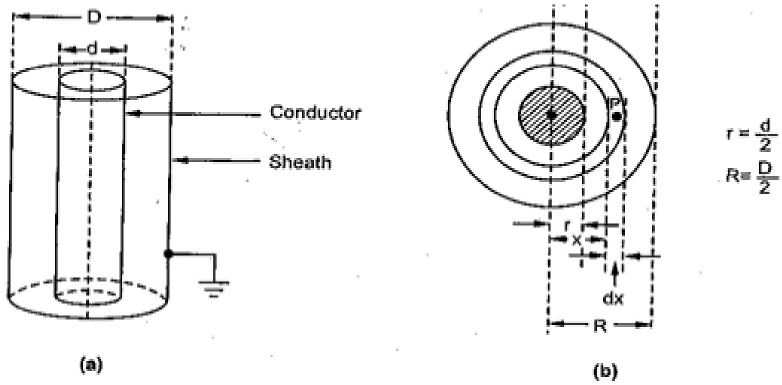


10. Derive an expression for an capacitance of a single core cable (6) (NOV/2013)

CAPACITANCE OF A SINGLE CORE CABLE : A single core cable is equivalent to two long co-axial cylinders. The inner cylinder is the conductor itself while the outer cylinder is the lead sheath.

The lead sheath is always at earth potential.

Let , d = conductor diameter, D = total diameter with sheath The co-axial cylindrical form of cable and its section are shown in the Figures (a) and (b).



Let Q=Charge per meter length of conductor in coulombs =Permittivity of material between core and sheath Now $\varepsilon = \varepsilon_0 \varepsilon_r$

Where, ε0=permittivity of free space=8.854*10-12 F/m

εr =relative permittivity of the medium

Consider an elementary cylinder with radius x and axial length of 1m. The thickness of the cylinder is dx.

According to Gauss's theorem, the lines of flux emanating due to charge Q on the conductor are in radial direction and total flux lines are equal to the total charge possessed i.e. Q lines. As lines are in radial direction, the cross-sectional area through which lines pass is surface area. For a cylinder with radius x, the surface area is (2n x axial length) m2. As axial length considered is 1m, the surface area is 2 πx m2

$$Flux\ density = \frac{Q}{surface\ area} = \frac{\frac{Q}{2\pi x}C}{m^2}$$

The electric field intensity at an point P on the elementary cylinder is given by,

$$g_x = \frac{D_x}{\varepsilon}\ \ where\ D_x = electric\ flux\ density$$

$$= \frac{Q}{2\pi \times \varepsilon} = \frac{Q}{2\pi \times \varepsilon_0 \varepsilon_r}\frac{V}{m}$$

Hence the work done in moving a unit charge through a distance dx in the direction of an electric field is g_x dx.

Therefore the work done in moving a unit charge from the conductor to sheath is the potential difference between the conductor and the sheath given by,

$$V = \int_{\frac{d}{2}}^{\frac{D}{2}} g_x dx = \int_{\frac{d}{2}}^{\frac{D}{2}} \frac{Q}{2\pi \times \varepsilon_r} dx$$

$$= \frac{Q}{2\pi\varepsilon_0\varepsilon_r}\int_{\frac{d}{2}}^{\frac{D}{2}} \frac{dx}{x} = \frac{Q}{2\pi\varepsilon_0\varepsilon_r}[l_n\, x]_{\frac{d}{2}}^{\frac{D}{2}}$$

$$= \frac{Q}{2\pi\varepsilon_0\varepsilon_r}\,[l_n \frac{D}{2} - l_n \frac{d}{2}]$$

$$V = \frac{Q}{2\pi\varepsilon_0\varepsilon_r} l_n \frac{D}{d} = \frac{Q}{2\pi\varepsilon_0\varepsilon_r} l_n \frac{R}{r}$$

The Capacitance of a cable is given by,

$$C = \frac{Q}{V} = \frac{Q}{[\frac{Q}{2\pi\varepsilon_0\varepsilon_r}\, l_n \frac{R}{r}]}$$

$$C = \frac{2\pi\varepsilon_0\varepsilon_r}{l_n \frac{R}{r}} \;\; F/m = \frac{2\pi\varepsilon_0\varepsilon_r}{l_n \frac{D}{d}} \;\; F/m$$

Note that as length considered is 1m, the capacitance is F/m.

Substituting value of ε_0,

$$C = \frac{2\pi \times 8.854 \times 10^{-12}\varepsilon_r}{l_n \frac{R}{r}} = \frac{5.563 \times 10^{-11}\varepsilon_r}{l_n \frac{R}{r}}$$

$$= \frac{55.63 \times 10^{-12}\varepsilon_r}{l_n \frac{R}{r}} = \frac{\varepsilon_r \times 10^{-6}}{\left[\frac{1}{55.63}\right] l_n \frac{R}{r}} \quad \mu\, F/m$$

$$= \frac{\varepsilon_r \times 10^{-6}}{[0.0179 \times 10^{-3}] l_n \frac{R}{r}} \quad \mu\, F/m \qquad \ldots expressed\ per\ km$$

$$= \frac{\varepsilon_r}{[17.9] l_n \frac{R}{r}}$$

$$C = \frac{\varepsilon_r}{18 l_n \frac{R}{r}} = \frac{\varepsilon_r}{18 l_n \frac{D}{d}} \qquad \mu F/km$$

If the length l of the cable is known then the total capacitance of cable is,

$$C = \frac{\varepsilon_r l}{18 l_n \frac{D}{d}} \qquad \mu F$$

...if l is in km

Charging Current: when the capacitance C of a cable is known then its reactance is given by,

$$X_c = \frac{1}{\omega C} = \frac{1}{2\pi f C}\ \Omega$$

Then the charging current of the cable is given by

$$I = \frac{V_{ph}}{X_c}$$

Where, V_{ph}= phase voltage between core and sheath

$=V_{line} / \sqrt{3}$

11. Drive the expression for the electrical stress formed in single core cable Stress in Insulation:

The electrical stress in insulation is the electric field intensity acting at y point in insulation.

g_x= electrical stress at point P at a distance X

$$= \frac{Q}{2\pi\varepsilon_0\varepsilon_r X} \; V/m$$

Now

$$V = \frac{Q}{2\pi\varepsilon_0\varepsilon_r} l_n \frac{D}{d}$$

$$Q = \frac{2\pi\varepsilon_0\varepsilon_r V}{l_n \frac{D}{d}}$$

Substituting g_x,

$$g_x = \frac{2\pi\varepsilon_0\varepsilon_r V}{l_n \frac{D}{d} \, 2\pi\varepsilon_0\varepsilon_r X}$$

$$g_x = \frac{V}{X l_n \frac{D}{d}} = stress\ in\ insulation \quad V/m$$

The stress is maximum at the surface of the conductor i.e. when X=r.

$$g_{max} = \frac{V}{r l_n \frac{D}{d}} \quad V/m$$

Now $r = \frac{d}{2'}$

$$g_{max} = \frac{V}{d l_n \frac{D}{d}} \quad V/m$$

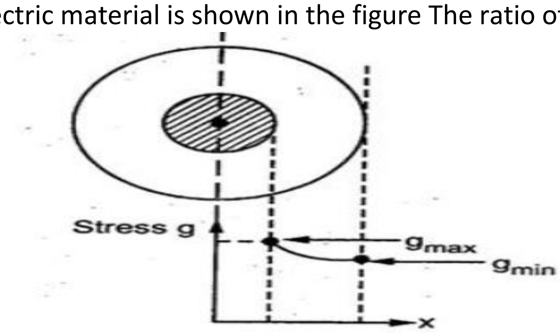
Similarly the minimum stress will be at the sheath i.e. x=R hence,

$$g_{min} = \frac{V}{R l_n \frac{D}{d}} \quad V/m$$

Now $R = \frac{D}{2'}$

$$g_{min} = \frac{2V}{D l_n \frac{D}{d}} \quad V/m$$

The variation of stress in the dielectric material is shown in the figure The ratio of maximum and



$$\frac{g_{max}}{g_{min}} = \frac{\frac{2V}{d l_n \frac{D}{d}}}{\frac{2V}{D l_n \frac{D}{d}}}$$

minimum stress is,

$$\therefore \quad \frac{g_{max}}{g_{min}} = \frac{D}{d}$$

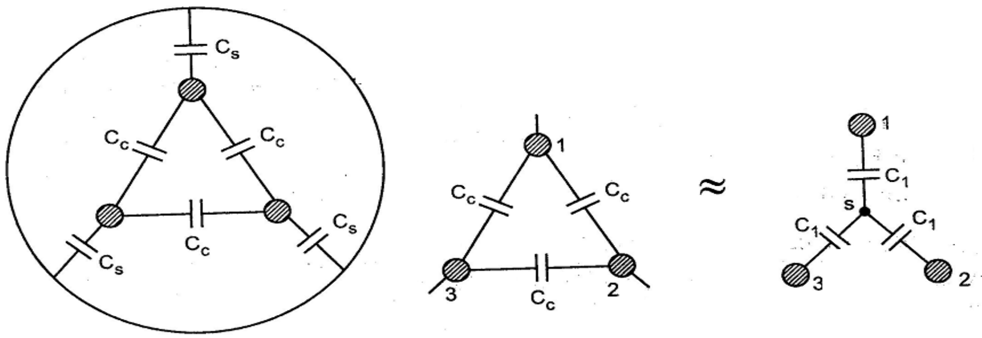
Note that if value of voltage used is R.M.S. we get R.M.S, values of stresses and if value of voltage used is peak, we get peak values of stresses.

12. Derive an expression for an capacitance of a single core cable

Capacitance of Three Core cable:

In three core cables, capacitances play an important role because in such cables capacitances exist between the cores as well as each core and the sheath. These capacitances are dominating as the dielectric constant of the dielectric used in cables is much more than the air. The capacitances are shown in the figure

The core to core capacitances are denoted as Cc while core to sheath capacitances are denoted as Cs the core to core capacitances Cc are in delta and can be represented in the equivalent star as shown in the figure



The impedance between core 1 and the star point, Z_1 can be obtained as,

$$Z_1 = \frac{Z_{12} \times Z_{13}}{Z_{12} + Z_{13} + Z_{23}} \quad from\ delta - star\ conversion$$

Now
$$Z_{12} = Z_{13} = Z_{23} = \frac{1}{\omega C_c}$$

$$Z_1 = \frac{\frac{1}{\omega C_c} \times \frac{1}{\omega C_c}}{\frac{3}{\omega C_c}} = \frac{1}{3} \cdot \frac{1}{\omega C_c}$$

And
$$Z_1 = \frac{1}{\omega C_1}$$

$$\frac{1}{\omega C_1} = \frac{1}{3} \cdot \frac{1}{\omega C_c}$$

$$C_1 = 3C_c$$

If star point is assumed to be at earth potential and if sheath is also earthed then the capacitance of each conductor to neutral is $C_N = C_S + C_1 = C_S + 3C_C$

If V_{ph} is the phase voltage then charging current per phase is,

$$I = \frac{V_{ph}}{Capacitive\ reactance\ per\ phase}$$

$$= \frac{V_{ph}}{X_{CN}} = \frac{\frac{V_{ph}}{1}}{\frac{1}{\omega_{CN}}}$$

$$I = \omega_{CN} V_{ph}\ A$$

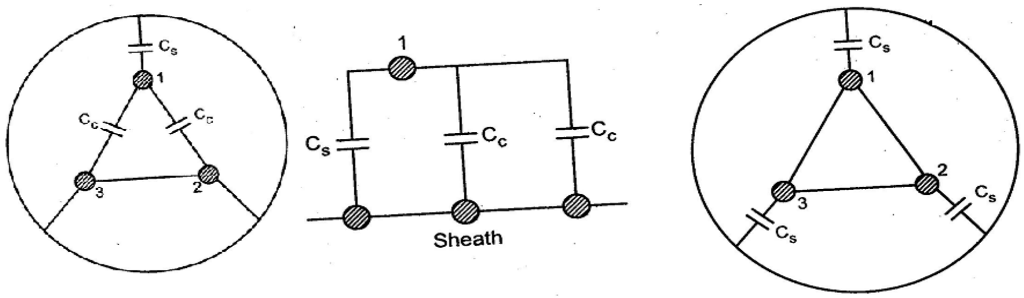
Measurement of Cs and Cc :

The total capacitance C_N is not easy to calculate but by actual practical measurement Cs and Cc can be determined,

Practical measurement involves two cases:

Case 1: The cores 2 and 3 are connected to sheath.

Thus the Cc between cores 2 and 3 and C, between cores 2, 3 and sheath get eliminated as shown in the figure. All the three capacitances are now in parallel across core 1 and the sheath. The capacitance of core 1 with sheath is measured practically and denoted by Ca



Ca = Cs + 2Cc
This eliminates all the core capacitances. This is shown in the figure. The capacitances C, are in parallel between the common core and sheath. This capacitance is practically measured and denotedas C_b.
C_b = 3 Cs Solving (1) and (2) simultaneously,
Ca = (C_b/3) + 2C_c C_c=(Ca/2) –(C_b/6) and
Cs = (C_b/3) Thus both the capacitances can be determined.

$$C_N = C_s + 3C_c$$

= (Cb/3) + 3[(Ca/2)-(Cb/6)]
C_N=(3Ca/2)-(Cb/6)

Problem 1 : **A 3 core, 3 phase metal sheathed cable on testing for the capacitance gave the following results : i) Capacitance between all conductors bunched and sheath = 0.6 μF ii) Capacitance between two conductors bunched with sheath and third conductance 0.36μF With the sheath insulated find, a) Capacitance between any two conductors b) Capacitance to neutral c) Charging current if cable is connected to 11 k V, 3 phase, 50 Hz system.**
Solution: - The methods used to measure the capacitances are described earlier.

$$C_b = 0.6\mu F \quad and \;\; C_a = 0.36\mu F$$

$$C_s = \frac{C_b}{3} = \frac{0.6}{3} = 0.2\mu F$$

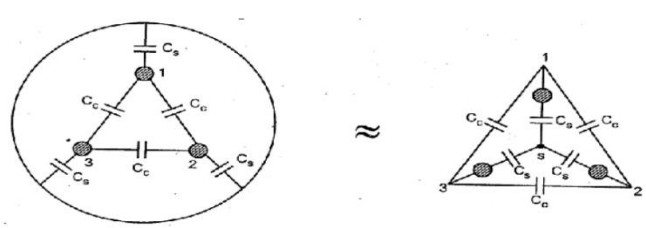
And

$$C_c = \frac{C_a}{2} - \frac{C_b}{6} = \frac{0.36}{2} - \frac{0.6}{6} = 0.08\mu F$$

a) To find capacitance between an two conductors converting internal star to equivalent delta,

$$Z_{12} = Z_{1s} + Z_{2s} + \frac{Z_{1s}\,Z_{2s}}{Z_{3s}}$$

$$= \frac{1}{\omega C_s} + \frac{1}{\omega C_s} + \frac{\frac{1}{\omega C_s}\cdot\frac{1}{\omega C_s}}{\frac{1}{\omega C_s}} = \frac{3}{\omega C_s}$$

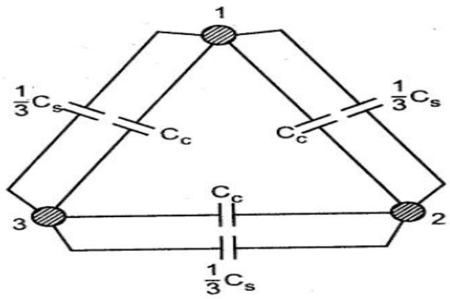


Let

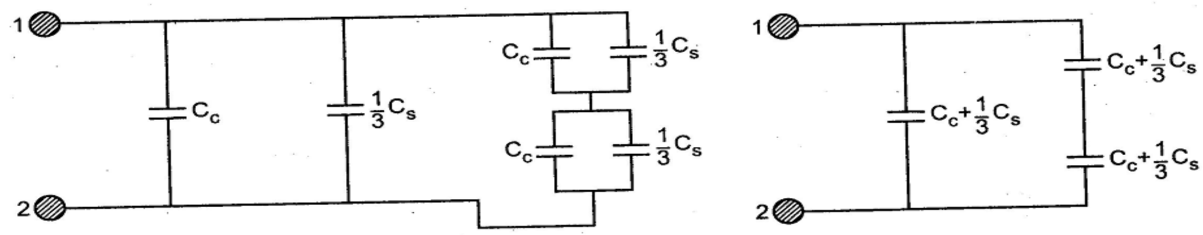
$$Z_{12} = \frac{1}{\omega C_{eq}} = Z_{23} = Z_{31}$$

$$\therefore \frac{1}{\omega C_{eq}} = \frac{3}{\omega C_s}$$

$$\therefore C_{eq} = \frac{1}{3} C_s$$



The equivalent circuit is shown in the figure. Hence capacitance between any two conductors is also shown in the figure



Two equal capacitances in series give equivalent equal to half the value of each capacitance.

$C_{12}=C_C+1/3\ C_S+1/2[C_C+1/3\ C_S]$

$=0.08+(0.2/3)+1/2[0.08+0.2/3] = 0.22\mu F = C_{23} = C_{31}$

$C_N=C_S+3C_C=0.2+3*0.08 = 0.44\ \mu F$

$V_{ph}=V_{line}/\sqrt{3} = 11KV/\sqrt{3} = 6.3508KV$

f=50Hz

$I=\omega C_N V_{ph} = 2\pi * 50 * 0.44 * 10^{-6} * 6.3508 * 10^3$

I = 0.8778 A

FORMULA FOR CAPACITANCE OF THREE CORE CABLE :

There is one empirical formula to calculate the capacitance of a three core belted cable, stated by Simon. It is applicable for the circular conductors. The formula give the capacitance of a three core cable to neutral per phase per kilometer length of the cable. The formula is given as,

$$C_N = \frac{0.0299\varepsilon_r}{l_n\left[1+\frac{T+t}{d}\left\{3.84-1.7\frac{t}{T}+0.52\frac{t^2}{T^2}\right\}\right]}\ \mu F/km$$

Where,

ε_r=relative permittivity of the dielectric

d=conductor diameter

t=belt insulation thickness

T=conductor insulation thickness

The formula can be used when the test results are not available. This gives approximate value of the capacitance. If there is not given, it can be assumed to be 3.5. It must be remembered that all the values of d, t and T must be used in the same units while using the formula.

13. Explain grading of cables (APRIL/2013) (or) **what is grading of cables? Describe the inter sheath grading methods of cables.** (APRIL/2014)

GRADING OF CABLES: We have seen that the stress in the insulation is maximum at the conductor surface and minimum at the sheath to avoid the breakdown of the insulation, it is necessary to have uniform distribution of stress all along the Insulation. Practically some methods are used to obtain uniform distribution of stress. "***The process of obtaining, uniform distribution of stress in the insulation of cables is called grading of cables***".

The unequal distribution of stress has two effects,

- Greater insulation thickness is required, which increases the cost and size.
- It may lead to the breakdown of insulation.

Hence the grading of cable is done. There are two methods or grading the cables which are,

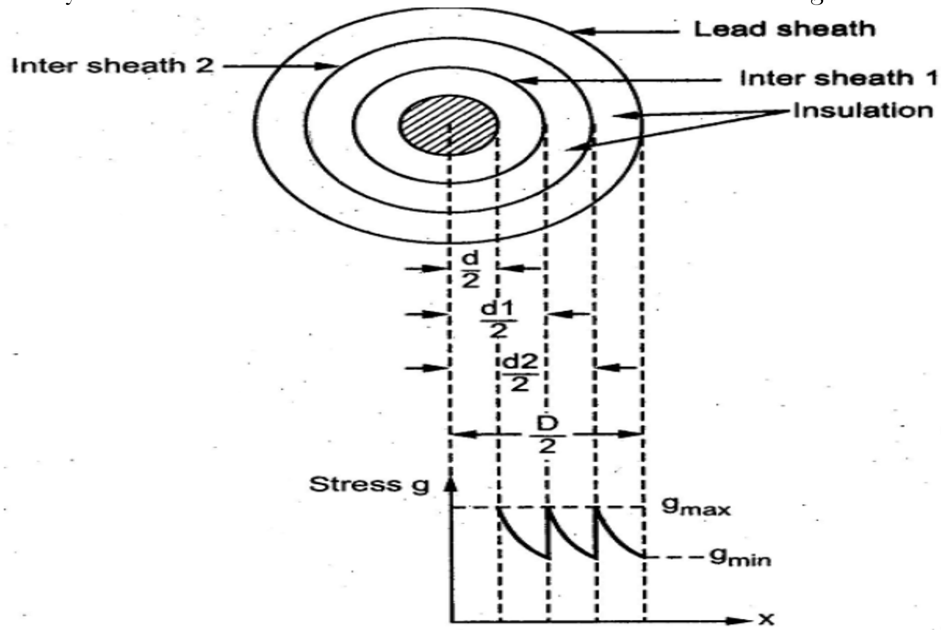
- Use of intersheaths for grading
- Capacitance grading

USE OF INTERSHEATHS FOR GRADING:

In this method of grading, in between the core and the lead sheath number of metallic sheaths are placed which are called intersheaths. All these intersheaths are maintained at different potentials by connecting them to the tappings of the transformer secondary.

These potentials are between the core potential and earth potential. Generally lead is used for these sheaths as it is flexible and corrosion. Resistance but as its mechanical strength is less, aluminum also can be used. Aluminums is low weight and mechanically strong but it is much costlier than lead Using the intersheaths, maintaining at different potential, uniform distribution of stress is in obtained m the cables. Consider a cable with core diameter d and overall diameter with lead sheath as D.

Let two intersheaths are used, having diameter d1 and d2 which are kept at the potentials V1 and V2 respectively. The intersheaths and stress distribution is shown in the figure.



Let, V1=voltage of intersheath 1 with respect to earth V2= voltage of intersheath 2 with respect to earth It has proved that stress at a point which is at a distance x is inversel proportional to distance x and given by,

$$g_x = \frac{Q}{2\pi\varepsilon x} = \frac{K}{x} \qquad \dots\dots\dots\dots\dots (i)$$

Where k is constant,

So electric stress g_1 between the conductor and intersheath 1 is,

$$g_1 = \frac{k_1}{x} \quad where\ k_1 = constant \quad \dots\dots\dots\dots (ii)$$

Now the potential difference between core and the first intersheath is $V-V_1$

$$V - V_1 = \int_{\frac{d}{2}}^{\frac{d_1}{2}} g_1 dx = k_1 \int_{\frac{d}{2}}^{\frac{d_1}{2}} \frac{dx}{x}$$

$$= K_1 \, [l_n \, x]_{\frac{d}{2}}^{\frac{d_1}{2}} = K_1 \left[l_n \frac{d1}{2} - l_n \frac{d}{2} \right]$$

$$= K_1 l_n \frac{d1}{d}$$

$$K_1 = \frac{V - V_1}{l_n \frac{d1}{d}} \qquad \dots\dots\dots (iii)$$

Substituting in equation (ii) we get,

$$g_1 = \frac{V - V_1}{x l_n \frac{d1}{d}} \qquad \dots\dots\dots (iv)$$

Now this stress is maximum at x=d/2 on core surface

$$\therefore \quad g_{1max} = \frac{V - V_1}{\frac{d}{2} l_n \frac{d1}{d}} \qquad \dots\dots\dots (v)$$

Similarly poetential difference between intersheath 1 and intersheath 2 is $V-V_1$

$$g_2 = \frac{V - V_2}{x l_n \frac{d2}{d}} \qquad \dots\dots\dots (vi)$$

Now this stress is maximum at x=d/2 on core surface

$$\therefore \quad g_{1max} = \frac{V - V_1}{\frac{d}{2} l_n \frac{d1}{d}} \qquad \dots\dots\dots (v)$$

Similarly poetential difference between intersheath 1 and intersheath 2 is $V-V_1$

$$g_2 = \frac{V - V_2}{x l_n \frac{d2}{d}} \qquad \dots\dots\dots (vi)$$

Now g_2 wil be maximum at the surface of intersheath 1 i.e. $x=d_1/2$

$$\therefore \quad g_{2max} = \frac{V - V_2}{\frac{d1}{2} l_n \frac{d2}{d}} \qquad \dots\dots\dots (vii)$$

The potential difference between inter sheath 2 and outermost sheath is v2 only as potential difference of inte rsheath is maintained at v2 with respect to earth

$$g_3 = \frac{V_2}{x l_n \frac{D}{d2}} \qquad \dots\dots\dots (vii)$$

This g3 will be maximum at x=d2/2

$$\therefore \quad g_{3max} = \frac{V_2}{\frac{d2}{2} l_n \frac{D}{d2}} \qquad \dots\dots\dots (ix)$$

Choosing proper values of Vl and V2 glmax g2max etc. can be made equal and hence uniform distribution of stress can be obtained. The stress can be made to vary between same maximum and minimum values as shown in the figure, by choosing d1 and d2 such that,

$$\frac{d1}{d} = \frac{d2}{d1} = \frac{D}{d2} = \alpha$$

And $\quad g_{1max} = g_{2max} = g_{3max}$

$$\frac{V - V_1}{\frac{d}{2} l_n \alpha} = \frac{V_1 - V_2}{\frac{d1}{2} l_n \alpha} = \frac{V_2}{\frac{d2}{2} l_n \alpha}$$

$$\frac{V_2}{d_2 l_n \alpha} = \frac{V_1 - V_2}{d_1 l_n \alpha} = \frac{V - V_1}{d\ l_n \alpha}$$

$$\therefore \quad \frac{V_2}{d_2} = \frac{V_1 - V_2}{d_1} = \frac{V - V_1}{d} \qquad \dots\dots\dots\dots (x)$$

$$\therefore \quad V_2 = \frac{d2}{d1}[V_1 - V_2] = \alpha\,[V_1 - V_2]$$

$$\therefore \quad V_2 = \alpha V_1 - \alpha V_2$$

$$\therefore \quad (1 + \alpha)V_2 = \alpha V_1$$

$$\therefore \quad V_2 = \frac{\alpha}{1 + \alpha} V_1 \qquad \dots\dots\dots\dots (xi)$$

Let us try to express voltages V_1 and V_2 interms of v and ,

Now,

$$\frac{V_1 - V_2}{d_1} = \frac{V - V_1}{d}$$

$$V_1 - V_2 = \frac{d1}{d}\,(V - V_1)$$

$$= \alpha\,(V - V_1)$$

$$V_1 - V_2 = \alpha\, V - \alpha\, V_1$$

$$\therefore\ \ (1+\alpha)V_1 = \alpha\, V + \frac{\alpha}{1+\alpha}V_1$$

$$\therefore\ \ V_1 = \left[1+\alpha - \frac{\alpha}{1+\alpha}\right] = \alpha\, V$$

$$\therefore\ \ V_1\left[\frac{(1+\alpha)(1+\alpha)-\alpha}{(1+\alpha)}\right] = \alpha\, V$$

$$\therefore\ \ V_1\left[\frac{1+2\alpha+\alpha^2-\alpha}{(1+\alpha)}\right] = \alpha\, V$$

$$\therefore\ \ V_1 = \frac{\alpha(1+\alpha)V}{\alpha^2+\alpha+1} = \frac{V\left(1+\frac{1}{\alpha}\right)}{\left(1+\frac{1}{\alpha}\right)\left(1+\frac{1}{\alpha}+\frac{1}{\alpha^2}\right)} \quad \dots\dots\dots\dots (xii)$$

And

$$V_2 = \frac{\alpha}{1+\alpha}V_1 = \frac{V_1}{\left(1+\frac{1}{\alpha}\right)} = \frac{V\left(1+\frac{1}{\alpha}\right)}{\left(1+\frac{1}{\alpha}\right)\left(1+\frac{1}{\alpha}+\frac{1}{\alpha^2}\right)}$$

$$\therefore\qquad V_2 = \frac{V}{\left(1+\frac{1}{\alpha}+\frac{1}{\alpha^2}\right)} \qquad \dots\dots\dots\dots\dots (xiii)$$

$$\therefore\qquad g_{1max} = \frac{V-V_1}{\frac{d}{2}l_n\frac{d1}{d}}$$

$$\therefore\qquad g_{1max} = \frac{V - \frac{V\left(1+\frac{1}{\alpha}\right)}{\left(1+\frac{1}{\alpha}+\frac{1}{\alpha^2}\right)}}{\frac{d}{2}l_n\alpha} = \frac{V\left[1-\frac{\left(1+\frac{1}{\alpha}\right)}{\left(1+\frac{1}{\alpha}+\frac{1}{\alpha^2}\right)}\right]}{\frac{d}{2}l_n\alpha}$$

$$= \frac{V\left[\frac{1+\frac{1}{\alpha}+\frac{1}{\alpha^2}-1-\frac{1}{\alpha}}{\left(1+\frac{1}{\alpha}+\frac{1}{\alpha^2}\right)}\right]}{\frac{d}{2}l_n\alpha}$$

$$\therefore\ \ g_{1max} = \frac{V}{\alpha^2\left(1+\frac{1}{\alpha}+\frac{1}{\alpha^2}\right)\frac{d}{2}l_n\alpha}$$

$$\therefore\ \ g_{1max} = \frac{V}{(1+\alpha+\alpha^2)\frac{d}{2}l_n\alpha} \qquad \dots\dots\dots . (xiv)$$

$$\frac{d1}{d}\times\frac{d2}{d1}\times\frac{D}{d2} = \alpha^3$$

$$\frac{D}{d} = \alpha^3$$

$$l_n\left(\frac{D}{d}\right) = l_n(\alpha^3) = 3l_n\,\alpha$$

$$l_n\,\alpha = \frac{1}{3}l_n\left(\frac{D}{d}\right)$$

$$\therefore\ \ g_{1max} = \frac{V}{\frac{1}{3}(1+\alpha+\alpha^2)\frac{d}{2}l_n\left(\frac{D}{d}\right)} \qquad \dots\dots\dots . (xv)$$

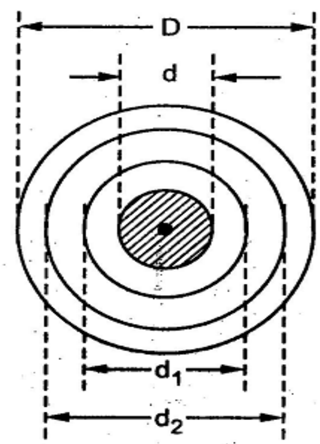
If intersheath is not used, g_{1max} is $\frac{V}{\frac{d}{2}l_n\left(\frac{D}{d}\right)}$ hence with intersheath is gets reduced factor $\frac{1}{\frac{1}{3}(1+\alpha+\alpha^2)}$

Problem 1: **A .single core cable of conductor diameter 1.8 cm and lead sheath of diameter 5.4cm is to be used on a 66 kV, 3 phase system. Two intersheaths of diameter 3cm and 4.2 cm are used in between them to obtain uniform distribution of stress. Find the voltages at which the two inter sheaths are maintained if the maximum stress in the layers is same.**

Solution: d=1.8cm; D=5.4cm; d_1=3cm; d_2=4.2cm

$$\therefore \quad V_{ph} = \frac{66}{\sqrt{3}} = 38.105\,KV \quad (r.m.s)$$

$$\therefore \quad V = \sqrt{2} \times V_{ph} = 53.888\,KV\,(peak)$$



Let V_1= voltage of intersheath 1 w.r.t outer sheath

V_2= voltage of intersheath 2 w.r.t outer sheath

The maximum stress in the 3 layers are given by,

$$\therefore \quad g_{1max} = \frac{V - V_1}{\frac{d}{2} l_n \frac{d1}{d}}$$

$$\therefore \quad g_{2max} = \frac{V_1 - V_2}{\frac{d1}{2} l_n \frac{d2}{d1}}$$

$$\therefore \quad g_{3max} = \frac{V_2}{\frac{d2}{2} l_n \frac{D}{d2}}$$

All stresses are equal,

$$g_{1max} = \frac{V - V_1}{\frac{d}{2} l_n \frac{d1}{d}} = \frac{V_1 - V_2}{\frac{d1}{2} l_n \frac{d2}{d1}}$$

$$\therefore \quad \frac{53.888 - V_1}{\frac{1.8}{2} \times 10^{-12} l_n \frac{3}{1.8}} = \frac{V_1 - V_2}{\frac{3}{2} \times 10^{-12} l_n \frac{4.2}{3}}$$

$$\therefore \quad 217.5127\,(53.888 - V_1) = 198.1342\,(V_1 - V_2)$$

$$(53.888 - V_1) = 0.9109\,(V_1 - V_2)$$

$$\therefore \quad 1.9109\ V_1 - 0.9109\,V_2 = 53.888$$

$$\frac{V_1 - V_2}{\frac{d1}{2} l_n \frac{d2}{d1}} = \frac{V_2}{\frac{d2}{2} l_n \frac{D}{d2}}$$

$$= 198.1342\,(V_1 - V_2) = \frac{V_2}{\frac{4.2}{2} \times 10^{-12} l_n \frac{5.4}{4.2}}$$

$$\therefore \quad 198.1342\,(V_1 - V_2) = 189.48\,V_2$$

$$\therefore \quad V_1 - V_2 = 0.9563\,V_2$$

$$V_1 = 1.9563\,V_2$$

Putting in (iv),

$$\therefore \quad 1.9109\,(1.9563\,V_2) - \ 0.9563\,V_2 = 53.888$$

$$3.7383\,V_2 - 0.9563\,V_2 = 53.888$$

$$3.7383\,V_2 - 0.9563\,V_2 = 53.888$$

$$2.8274\ 0.9563\,V_2 = 53.888$$

$$\therefore \quad V_2 = 19.0592\ KV \qquad \ldots\ldots \textit{voltage on intersheath}\ \ 2$$

And $$\therefore \quad V_1 = 37.2855\ KV \qquad \ldots\ldots \textit{voltage on intersheath}\ 1$$

Problem 2: **A single core cable has a conductor of diameter 2.5 cm and a sheath of inside diameter 6 cm. Calculate the maximum, stress. It is desired to reduce the maximum stress by using two intersheaths. Determine their best positions, the maximum stress and the voltages on each system. Voltage is 66 kV, 3 phase**.

Solution: d=2.5cm; D=6cm; V_{line}=66kv

$$V_{ph} = \frac{66}{\sqrt{3}} = 38.105\ KV \quad (r.m.s)$$

For designing use peak value of the voltage.

$$V = \sqrt{2} \times V_{ph} = \sqrt{2} \times 38.105 = 53.888\ KV\ (peak)$$

Without intersheath the maximum stress is,

$$g_{max} = \frac{V_2}{d\ l_n \frac{D}{d}} = \frac{2 \times 53.888 \times 10^3}{2.5 \times 10^{-2} l_n \frac{6}{2.5}}$$

$$= 4.9242 \times 10^6 \frac{V}{m} = \frac{4.9242 \times 10^3 \times 10^3}{10^2} V/cm$$

$$= 49.242\ KV/cm$$

Now two intersheath are to be used. Let d1 and d2 be the diameters of the two sheaths and maintained at the voltage V1 and V2 respectively. The best position is such that the stress in all the sections vary between the same maximum and minimum values which is possible when,

$$\frac{d1}{d} = \frac{d2}{d1} = \frac{D}{d2} = \alpha$$

$$\therefore \qquad \frac{D}{d} = \alpha^3$$

$$\alpha^3 = \frac{6}{2.5} = 2.4$$

$$\alpha = 1.3888$$

$$\therefore \qquad \frac{d1}{d} = \alpha$$

$$d1 = d\alpha = 2.5 \times 1.3888$$

$$= 3.347\ cm$$

$$\frac{d2}{d1} = \alpha$$

$$d2 = d1\alpha = 3.347 \times 1.3888 = 4.48\ cm$$

The voltages on the two intersheaths are,

$$V_1 = \frac{V\left(1 + \frac{1}{\alpha}\right)}{\left(1 + \frac{1}{\alpha} + \frac{1}{\alpha^2}\right)} = \frac{53.888\left(1 + \frac{1}{1.3388}\right)}{\left(1 + \frac{1}{1.3388} + \frac{1}{1.3388^2}\right)} = 40.84\ KV$$

$$V_2 = \frac{V}{\left(1 + \frac{1}{\alpha} + \frac{1}{\alpha^2}\right)} = \frac{53.888}{\left(1 + \frac{1}{1.3388} + \frac{1}{1.3388^2}\right)} = 23.38\ KV$$

The maximum stress with intersheath is,

$$g_{1max} = \frac{V - V_1}{\frac{d}{2} l_n \frac{d1}{d}} = \frac{53.888 - 40.84}{\frac{2.5}{2} \times 10^{-2}\, l_n \frac{3.347}{2.5}}$$

$$= 3577.567\, KV/m = 35.7756\, KV/cm$$

$$g_{1max} = \frac{V}{\frac{1}{3}(1 + \alpha + \alpha^2)\frac{d}{2} l_n \left(\frac{D}{d}\right)} = 35.76\, KV/cm$$

The maximum stress gets reduced by the factor

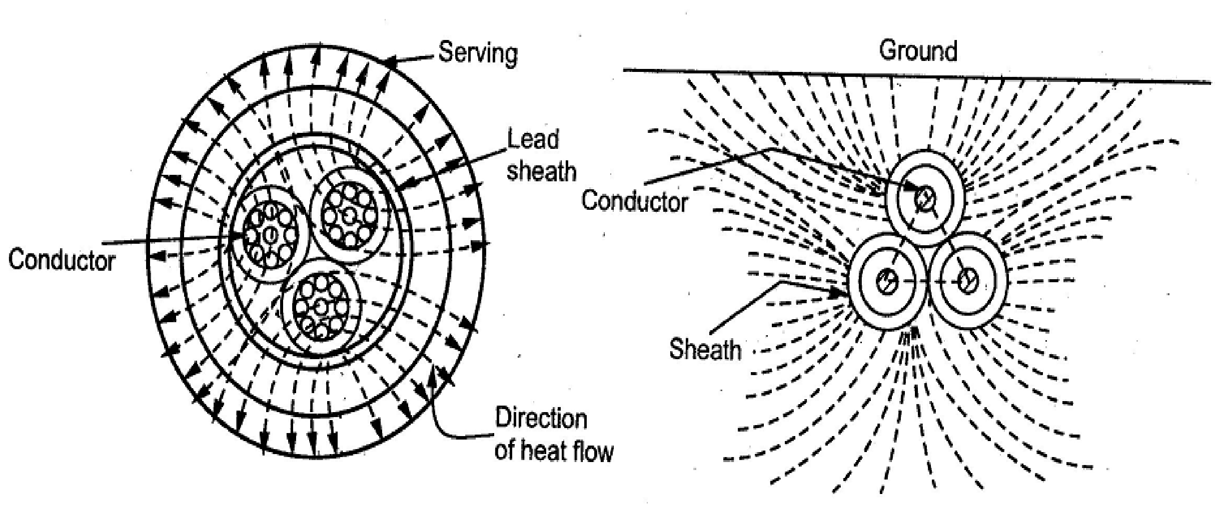
$$\frac{1}{\frac{1}{3}(1 + \alpha + \alpha^2)}$$

HEAT FLOW IN A CABLE:

As seen earlier, the current in the cable, dielectric loss and sheath loss together cause the increase in the temperature of the cable. The heat produced due to increase in temperature must be dissipated to the soil. When rate of heat generation and dissipation becomes equal then temperature becomes constant.

This temperature in fact is the important factor for deciding current carrying capacity of the cable. The path for the heat dissipation is through the dielectric then sheath, bedding, serving and finally into the surrounding soil or air. The heat flow in a 3 phase belted cable is shown in the figure (a) while heat flow due to a three single core cable to ground is shown in figure (b)

In case of three phase belted cable, the heat flows through three parallel paths and all the three conductors are at same temperature. The overall heat flow in a cable is similar to the flow of leakage current in an electric circuit; flowing radially out from core to ground through dielectric, sheath, bedding, armoring and serving.



(a) Three phase belted cable (b) Three single core cable

THERMAL CHARACTERISTICS OF CABLE:

The current in an electric circuit is given by,

$$I = \frac{potential\ difference}{resistance} = \frac{V}{R}$$

Similarly heat flow H is given by,

$$H = \frac{temperature\ difference}{thermal\ resistance} = \frac{\theta}{S}$$

Thermal resistance S is defined as the resistance which allows the heat flow of 1 watt when a temperature difference of 1^0 C is maintained. It is given by,

$$S = \frac{Kl}{A}$$

Where, K= thermal resistivity of the material

l=length of the path of heat flow

A=area of section through which heat flows

The thermal resistivity is expressed in °C / watt / cm

UNIT-V

2 marks:

1) **What is the significance of FACTS devices in power system (APRIL/2015) (or) State the objectives of FACTS technology. (NOV/2012)**

- Rapid control of reactive power flow and voltage profile using series and shunt connected controllers.
- Secure loading of lines close to their thermal limits
- Improve power transferability, transient stability and dynamic stability during fault switching etc.

2) List out the terminal equipment for HVDC systems. (NOV/2014)

- convertor
- convertor transformers
- smoothing reactors
- harmonic filters
- overhead lines
- reactive power source
- Earth electrodes.

3) What are the advantages of HVDC transmission? (NOV/2014)

- HVDC can carry more power with two conductors
- Corona loss and radio interference is less
- Dielectric loss is less
- Absence of skin effect, reduces power losses
- Ground can be used as return conductor
- Economical for long distance transmission
- No charging current
- No transmission of short circuit power in case of any fault
- Fault clearing time is small

4) State the advantages of EHVDC transmission system. (APRIL/2014)

- Reduction of current and losses
- Reduction of volume of conductor material
- Improvement in voltage regulation
- Increase in transmission efficiency
- Reduction in % line drop

5) Give any two HVDC transmission lines in India (APRIL/2014)

- Rihand- Delhi HVDC transmission system.
- Talcher- Kolar HVDC transmission system
- Chandrapur- Padghe HVDC transmission system

6) What are the main equipment used in a converter station of a HVDC transmission system (NOV/2013)

The equipments that supply reactive power in HVDC converter stations are

- A.C filters static shunt capacitors
- Synchronous condensers
- Static VAR compensators, etc.

7) Mention any two disadvantages of HVDC transmission (NOV/2013)

Terminal equipment cost is high due to the presence of converters and filters

- Maintenance cost is high
- Cost of DC breakers are high

- Inability to use transformers to change voltage levels

8) **List out the types of HVDC-Link. (APRIL/2013) (or) What are the various types of HVDC systems? (NOV/2012)**

Depending upon the arrangement of pole and earth return,, HVDC systems are classified into three types

- Monopolar HVDC transmission system
- Bipolar HVDC transmission system
- Homo-polar HVDC transmission system

9) What is break-over distance in HVDC transmission? (APRIL/2013) (or) . (APRIL/2012)

On comparing the cost of AC&DC transmission the cost of ac transmission is less than DC transmission for distance less than breakeven distance and costlier for long distances. The distance where the cost remain same for transmitting power either in AC or DC is called as breakeven distance. It varies from 100-800km depending on the per unit cost

10) Compare EHVDC and HVDC. (NOV/2012)

S.NO	HVDC	EHV A.C
1	For line designed for same insulation level, it can carry more power with two conductors	it can carry much power with three conductors of the same size
2	For a given level, it requires fewer rights of way, cheaper towers, and reduced conductor costs.	For a given level, cost of towers, conductors are high.
3	Voltage control: DC converter station requires reactive power related to the line loadings, the line itself does not require reactive power control.	Requires reactive power control to maintain constant voltage at the ends from inductive to capacitive as the line loading is increased. Reactive power requirements increase in line length.
4	Short circuit current: The contribution of DC line to short circuit current is only upto rated current of DC line.	Interconnection of two AC systems by an Ac line increases the short circuit current in the system.

11) Write any four applications of HVDC. (NOV/2012)

Long distance Bulk power transmission

- Power transmission through underground or submarine cables
- Asynchronous interconnection of A.C systems operating at different frequencies or where independent control of system is desired
- A.C and D.C lines in parallel
- D.C transmission with A.C distribution systems
- Back to Back HVDC coupling stations

12) **What are the various methods of voltage control in a power system? (APRIL/2012)**

13) What is FACTS (APRIL/2012)

14) What is the voltage range of EHV transmission (APRIL/2012)

11 marks:

1) Describe the design of Rural electrification schemes

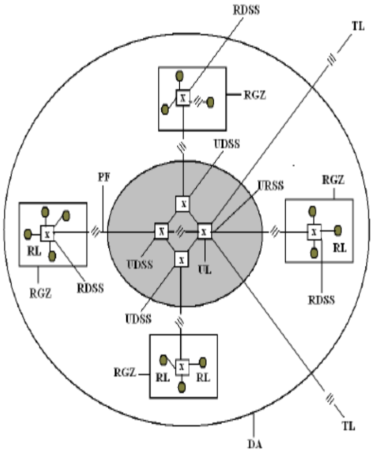
"Rural Electrification is the process of bringing electrical power to rural and remote areas"

Rural electrification is an extension to the urban distribution. Electricity is used not only for lighting and household purposes, but it also allows for mechanization of many farming operations, such as threshing, milking, and hoisting grain for storage. In areas facing labor shortages, this allows for greater productivity at reduced cost.

As village area are small and dispersed, separate three phase and single phase radial rural feeders are taken from nearby urban substations.

- Urban substation generally feed the rural feeders.
- Rural distribution is usually 1Ø or 3Ø radial system

Rural electrification scheme



TL-Transmission Line

DA-Distribution Area

PF-Primary Feeder

RGZ-Rural Growth Zone

URSS- Urban Receiving Station

UDSS-Urban Distribution Substation

RDSS-Rural Distribution Substation

Villages and rural consumers are located away from the urban area.

The rural distribution is composed of the 1Ø&3Ø primary feeder and distribution transformer.

The distribution system has

Primary feeders (3Ø)

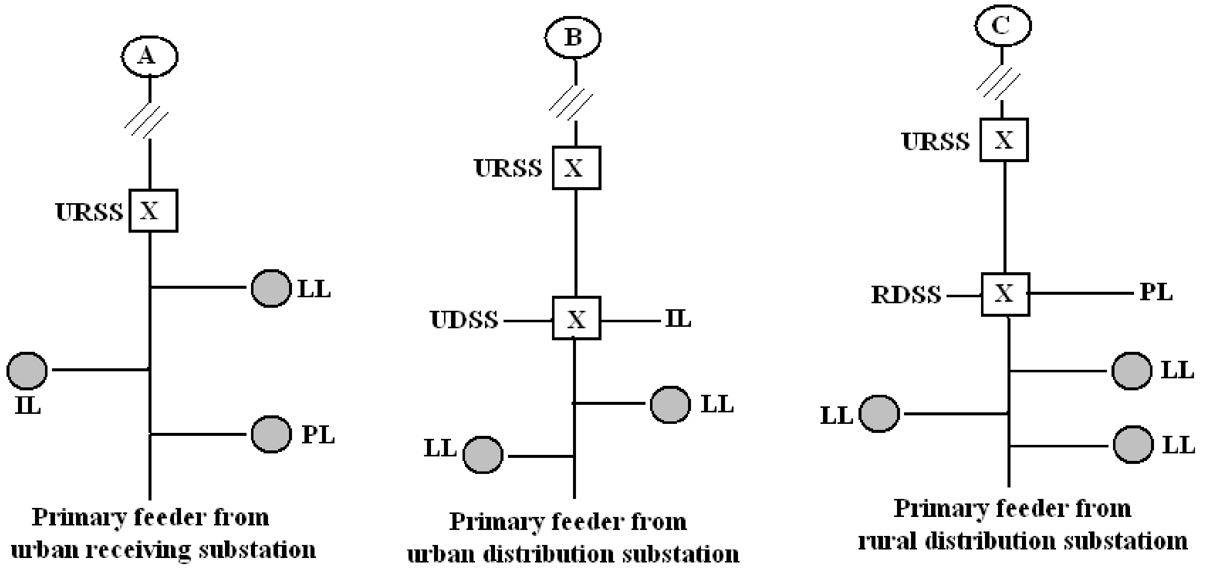
Auto reclosers and sectionalisers

Distribution transformers-RDSS

Secondary distribution lines- (1Ø or 3Ø)

Service connection

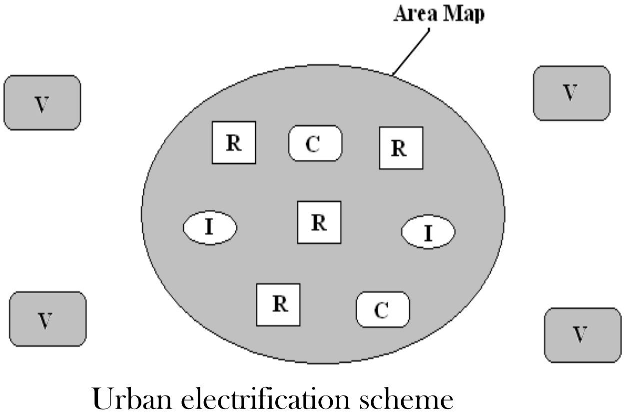
THREE METHODS FOR FEEDING RURAL PRIMARY FEEDERS



Three types of loads in rural area
LL- Lighting Load
PL- Pumping Load for Irrigation
IL- Industrial load
Rural primary feeders are at 11KV.
The distribution transformers (1Ø to 1Ø, 3Ø to 3Ø) are located near group load points and LT secondary lines radiates from secondary side of these transformers.
Rural distribution transformers are mounted on H-pole steel structure

2) Describe the design of town electrification schemes (6) (NOV/2013)

TOWN ELECTRIFICATION:



Urban electrification scheme

In town electrification scheme various loads are presented. They are
R-Residential Load
I-Industrial Load
C-Commercial Load
V-Village Load

The essential parts of the distribution system are
Subtransmission system
Distribution substation
Primary distribution system
Distribution transformer
Secondary distribution system

TYPES OF SUB TRANSMISSION SYSTEMS:

Simple radial sub transmission system
Improved sub transmission system
Loop circuit sub transmission system
Multiple sub transmission system
Grid circuit sub transmission system

TYPES OF PRIMARY DISTRIBUTION SYSTEMS:

Simple radial system
Radial system with tie-switches and sectionalising switch
Mesh primary distribution system
Loop or primary ring distribution system

TYPES OF SECONDARY DISTRIBUTION SYSTEMS:

Grid network , Spot network

3) Explain the principle of HVDC transmission system. Also bring out the various types of HVDC systems. Draw the relevant diagram. (APRIL/2014)

HIGH VOLTAGE DIRECT CURRENT TRANSMISSION [HVDC]

In early days the transmission, distribution and utilization of electrical energy was dominated by AC. After the introduction of mercury arc rectifier of large and high power lead to the development of transmission of electrical energy economically in DC also.

PRINCIPLE OF HVDC TRANSMISSION SYSTEM OPERATION

The present day trend is towards A.C for

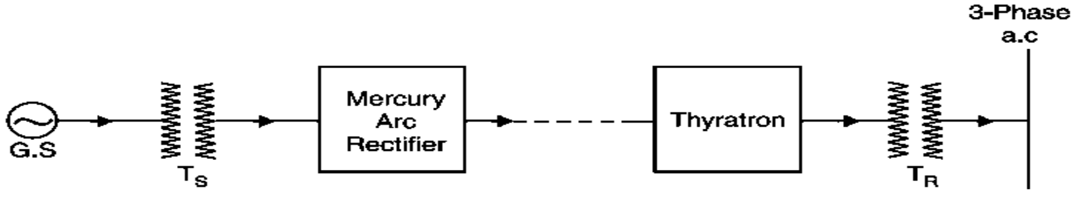


Figure shows the single line diagram of high voltage D.C transmission. The electric power is generated as A.C and is stepped up to high voltage by the sending end transformer (TS). The A.C power at high voltage is fed to the mercury arc rectifiers which convert A.C into D.C. The transmission of electric power is carried at high D.C voltage. At the receiving end, D.C is converted into A.C with the help of thyratrons. The A.C supply is stepped down to low voltage by receiving end transformer TR for distribution. **(Also refer Q. No.: 7)**

4) Explain the terminal equipment for HVDC systems. (APRIL/2013) (NOV/2014) (APRIL/2015)

TERMINAL EQUIPMENTS FOR HVDC:

For proper operation of DC transmission system, various additional auxiliary equipments are required. These equipments include
DC line inductors
Harmonic filters on DC side
Converter transformers
Reactive power source
Harmonic filters on AC side
Ground electrodes
Microwave communication link between the converter stations.

Inductors and Harmonic Filters on DC Side:

On DC and AC side of the DC transmission system harmonics are produced. Normally 6th and 12th harmonic currents are produced. If these currents are allowed to flow through line, it may produce undesirable noise in neighboring telephone lines. Thus to eliminate these harmonic currents, harmonic filters are used. This filter consists of two inductors and a shunt filter which short circuits the harmonic currents to ground by providing low impedance path.

With the use of these inductors the dc line current is prevented from increasing rapidly under faulty condition.

The inductors connected in series with the line are used to smoothen the DC current output of a converter. An air cored magnetically shielded reactor is used for this purpose.

Converter Transformers

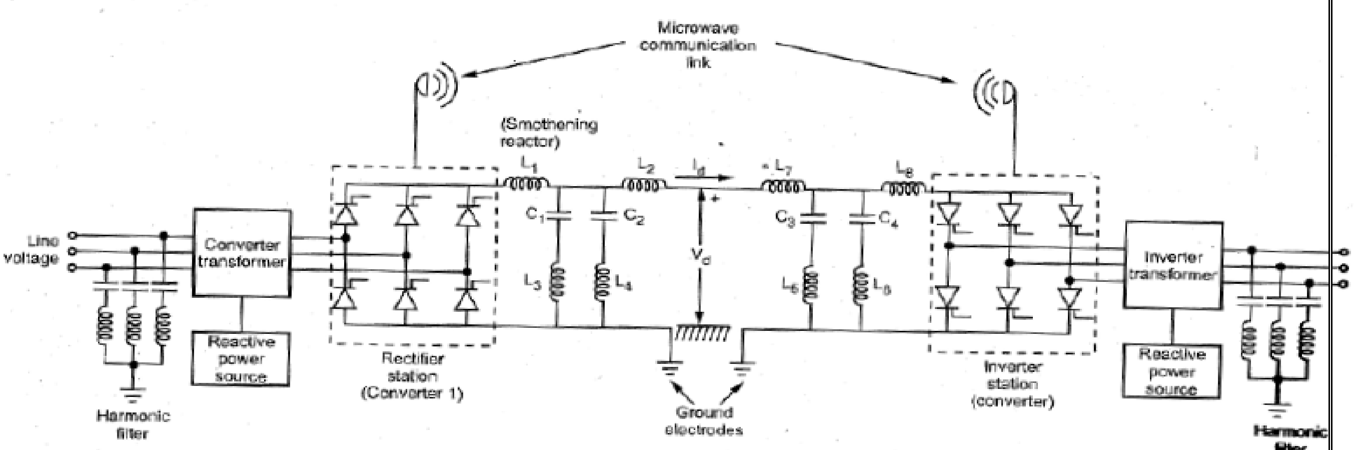
The converter transformer is used to provide AC voltage as required by the converter. Three phase transformers of the type star-star or star-delta may be used. A third winding called tertiary winding may sometimes be added for direct connection to source of the reactive power.

It is required to keep DC line voltage constant from no load to full load. Also for reducing the reactive power absorbed by converter the firing angle α should be kept small

It indicates that the ratio between input AC voltage and output DC voltage of the converter is fixed. But as DC line voltage is fixed, the input AC line voltage must also be fixed. But it may happen that the line voltage on input AC side may go on varying. Thus the converter transformers on rectifier side are provided with tappings which will maintain the AC input voltage nearly constant. The taps are automatically switched by a motorized tap changer. The taps are also needed on converter transformer on inverter side.

Reactive Power Source

The variable static capacitors or synchronous capacitors are required for absorbing reactive power by the converters. The amount of reactive power required increases with the firing angle α of a rectifier and the extinction angle γ of the inverter. This power requirement is about 50% to 60% of real power transfer. The reactive power consumption is provided by capacitors, filters or synchronous compensators. As the active power transmitted goes on varying, the reactive power must also be varied.



Harmonic Filters on AC Side

The three phase, 6-pulse converters produce 5th, 6th, 11th and 13th order harmonics on AC side. These currents are undesirable from the point of view of telephone interference. These currents are bypassed through low impedance filters connected between three phase lines and ground. The filters for each frequency are connected in star and the neutral point is grounded.

***Ground Electrode*:**

Proper attention must be given towards the ground electrode at each end of DC line. DC currents in the ground have a corrosive effect on pipes, cables and metallic structures. In order that the DC ground current does not produce any local problem around the station, the actual ground electrode is located away from converter station. At the grounding site, special means are used to minimize electrode resistance. When bipolar system is temporarily used as monopolar system, the ground current may exceed which may produce excessive heat then this electrode resistance factor is important.

Communication Link:

For controlling purpose of the converters at both the ends of the line, a communication link between them is necessary. e.g. to maintain the current margin ΔI the inverter side must know what is rectifier current setting is. This information is continually relayed by a high speed communication link between the two converters.

5) Compare the EHVAC and HVDC system (11) (APRIL/2012) (APRIL/2015)

COMPARISON BETWEEN EHV A.C AND HVDC TRANSMISSION:

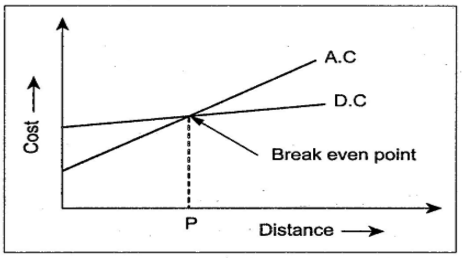
We are considering the following three factors for comparing A.C and D.C transmission.

1. Economics,
2. Technical performance
3. Reliability.

1. ECONOMICS OF POWER TRANSMISSION

The cost of transmission line includes the investment cost of right of way, transmission towers, conductors, insulators, terminal equipment's and the operational cost of losses.

S.NO	HVDC	EHV A.C
1	For line designed for same insulation level, it can carry more power with two conductors	it can carry much power with three conductors of the same size
2	For a given level, it requires fewer rights of way, cheaper towers, and reduced conductor costs.	For a given level, cost of towers, conductors are high.
3	Cable insulation required is less	Cable insulation required is more
4	Power losses are reduced because of two conductors therefore operational cost reduces.	Power losses are increased because of two conductors therefore operational cost increases.
5	Absence of skin effect reduces power losses, thereby operational cost reduces.	Due to skin effect, power losses increases, thereby operational cost increases.
6	Di electric losses in the power cables are less.	Di electric losses in the power cables are high.
7	Corona loss and radio interference is less.	Corona loss and radio interference is high.
8	Do not require compensation.	Cost for compensation devices is high.
9	Terminal equipment cost is high due to the presence of converters and filters.	Terminal equipment cost is high.
10	Maintenance cost is high.	Maintenance cost is low.

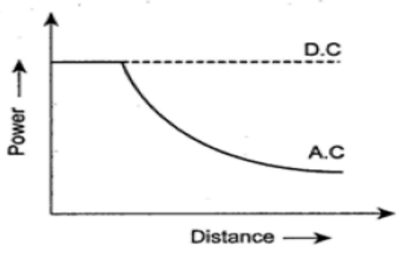


P – Break even distance

Figure shows the variation, of costs for D.C and A.C transmission system with distance.
A.C transmission is more economical upto the break-even distance and D.C transmission is more economical after the break-even distance. Break-even distances may vary from 500 km to 600 km depending on P.U line cost.

	control.	increase in line length.
3	Short circuit current: The contribution of DC line to short circuit current is only upto rated current of DC line.	Interconnection of two AC systems by an Ac line increases the short circuit current in the system.
4	Line compensation: Does not require line compensation.	Requires shunt and series compensation in long transmission lines to overcome line charging and stability limitations. Static VAR systems are used to increase the power transfer and voltage control.
5	Problems of AC interconnection: Two systems are interconnected which have different frequencies. For synchronous DC tie lines, no need of coordinated control for interconnection.	Two systems are not interconnected which have different frequencies. Two power systems are interconnected when they have coordinated using tie line power and frequency
6	Ground impedance: Ground impedance is negligible, so DC link can operate using one conductor with ground return.	Ground current cannot be permitted in steady state due to high magnitudes of ground impedance which will result telephone interference.
7	Economical use of underground cables or submarine cables are possible	Not possible
8	Fast control to limit fault currents in DC: DC breakers in two terminal DC links are avoided. But costs of DC breakers are high.	Cannot avoided breakers.
9	Inability to use transformers to change voltage levels.	Transformers are used to change voltage levels.
10	Cost of conversion equipment is high.	No conversion equipment cost.

2. *TECHNICAL PERFORMANCE*

S.NO	HVDC	EHV A.C
1	Full control over power transmitted:  Power carrying capacity of DC is unaffected b the distance of transmission as shown in figure.	Power transfer in AC depends on δ: $Power\ transfer = \frac{\lvert V_R \rvert \lvert V_S \rvert}{X} \sin\delta$ Where δ-Angle between sending and receiving end voltage. For a given power levels, δ increases with distance. Power carrying capacity of AC line decreases after some distance as shown in figure. Power transfer limited by the consideration of transient and steady state stability.
2	Voltage control: DC converter station requires reactive power related to the line loadings, the line itself does not require reactive power	Requires reactive power control to maintain constant voltage at the ends from inductive to capacitive as the line loading is increased. Reactive power requirements

3. RELIABILITY

It is the probability that an item or a collection of items will perform satisfactory, under the specified conditions during a given period. This is called reliability.

Reliability of D.C is good compared to that of A.C. The performance of thyristor valves is much reliable than mercury arc valves, and control and protection is to improve the reliability level. The development of direct light triggered thyristors (LTT) has been used to improve the reliability. There are two measures of overall system reliability.

(a) Energy availability

$$\text{Energy availability in percentage} = \left(1 - \frac{\text{Equivalent outage time}}{\text{Total time}}\right) \times 100$$

$$\text{where Equivalent outage time} = \text{Actual outage time} \times \begin{Bmatrix}\text{System capacity} \\ \text{loss due to} \\ \text{the outage}\end{Bmatrix}$$

(b) Transient reliability

This is a factor specifying the performance of HVDC systems during recordable faults on the associated A.C system,

$$\text{Transient reliability} = \frac{\begin{Bmatrix}\text{Number of times HVDC system} \\ \text{performed as designed}\end{Bmatrix}}{\text{Number of recordable A.C faults}} \times 100$$

Recordable A.C faults which are caused by phase voltages drop to below 90%. Energy availability and transient reliability of existing D.C systems with thyristor values is 95% or more.

Bipolar D.C line is more reliable than a double circuit A.C line with the same power capability. This is because of the fact that failure of one pole does not affect the operation of the other pole.

If the D.C line is overloaded and if the converters on the failed pole can be paralleled with the converters on the healthy pole, the prefault power level can be maintained even with permanent outage of one line

6) Explain in details about economic distances for DC transmission. (6) (APRIL/2015) (NOV/2013)

ECONOMIC DISTANCE FOR HVDC TRANSMISSION:

The total capital cost of a transmission system includes capital cost of substations and capital cost of the lines including the cost of land buildings and losses.

Total capital cost of transmission system = Cost of line + Capital cost of substation

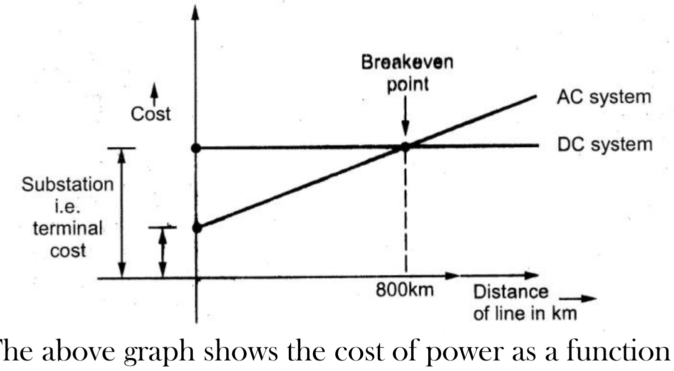
= (Cost of line per km x Length of line in km) + Capital cost of substation)

The cost per km for a DC line is less compared to AC line for the same power capacity and comparative reliability. The DC system requires only two conductors in contrast with three phase AC system requiring minimum three conductors.

The cost of tower insulators and conductors of HVDC line is comparatively less than the equivalent ac line. A bipolar HVDC system with midpoint earthed carry same power and gives same reliability of an equivalent double circuit.

The tower required for HVDC system is simpler, cheaper and easy to install than AC system. The number of line conductors increases with increase in line length for AC system.

Below certain length of line usually 800 km, the total capital cost of HVDC is more than AC line and in that case HVDC line is not preferred. This can be seen from the following graph shown in the Figure which gives comparison between DC and AC line.



The above graph shows the cost of power as a function of distance of line.

The vertical i.e. y axis intercept of both the curves represent cost of terminal equipment while slope of curve represents cost per unit length of line and cost of other accessories which changes with distance. The curves for AC and DC transmission intersect each other at a point called breakeven point which indicates that after certain length of line it is preferable to use HVDC rather than AC.

The break even distance is different for different projects because of variations in local conditions and cost of various equipments. The AC lines require intermediate substations after certain length (normally 300 km) which is not the case with HVDC system. But HVDC systems need additional converter stations with various terminal equipments at both the ends which increases their terminal cost.

When benefit of lower line cost is more compared to higher cost of substation definitely HVDC system becomes economical. For very long lengths (beyond 800km) AC lines requires intermediate substations as well as intermediate compensating networks. The cost of transformers used in AC system cannot be reduced beyond certain extent whereas lot of development and progress is going on in the field of HVDC system to reduce breakeven distance.

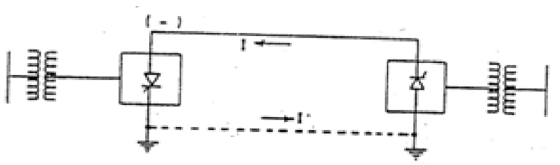
The dc lines prove to be more economical in case of long river crossings. After studying technical and economical aspect for project, the choice of AC or DC can be made.

7) Explain the various types of HVDC links. (APRIL/2013) (NOV/2014) (APRIL/2012)
DESCRIPTION OF DC TRANSMISSION SYSTEM: TYPES OF DC LINKS:

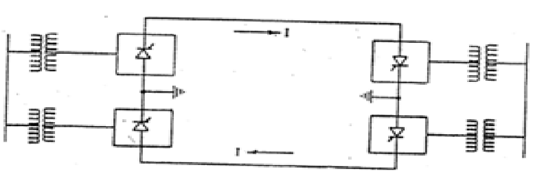
Depending upon the arrangement of pole and earth return, HVDC systems are classified into three types

- Monopolar HVDC transmission system
- Bipolar HVDC transmission system
- Homo-polar HVDC transmission system

1. **MONOPOLAR HVDC LINK**
   Monopolar link system is shown in figure (a). This system has one conductor usually of negative polarity and return path is provided by permanent ground or sea. Sometimes metallic return is also used. Full power and current is transmitted through a line conductor with earth or sea as a return path.

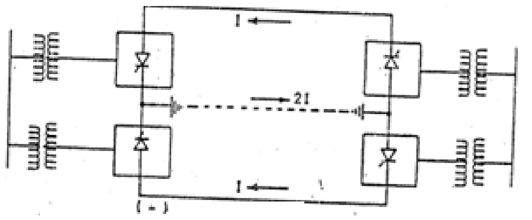


2. **BIPOLAR HVDC LINK**
   Bipolar link arrangement is shown in figure (b). This system has two conductors, one positive and the other negative with respect to earth. Each may be a double conductor in EHV lines. Each terminal has two sets of converters of identical ratings, in series on the DC side. The junction between the two sets of converters is grounded at one or both ends. Normally, both poles operate at equal currents and hence there is zero ground current flowing under these conditions This system is more commonly used for transmission of power over long distance.



3. HOMOPOLAR HVDC LINK

Homo-polar Link is represented in figure (c) has two or more conductors all having the same polarity (usually negative) and always operated with ground or metallic return.



(c) Homopolar

Because of the desirability of operating a DC link without ground return, bipolar links are most commonly used. Homopolar link has the advantage of reduced insulation costs, but the disadvantages of earth return outweigh the advantages, incidentally, the corona effects in a DC line are substantially less with negative polarity of the conductor as compared to the positive polarity. The mono polar operation is used in the first stage of the development of a bipolar line, as the investments on converters can be referred until the growth of load which requires bipolar operation at double the capacity of are monopolar link.

8) Discuss the points and factors to be connected while planning a distribution system. (APRIL/2012)

PLANNING FOR HVDC TRANSMISSION: The system planner must consider DC alternative in transmission expansion. The factors to be considered are

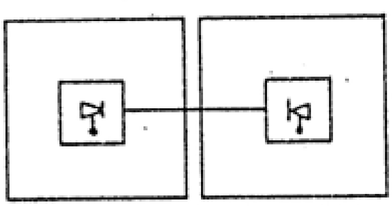
Cost ,Technical performance, and Reliability.

Generally, the last two factors are considered as constraints to be met and the minimum cost option is selected among various alternatives that meet the specifications on technical performance and reliability. For submarine, cable transmission and interconnecting two systems of different nominal frequencies, the choice of DC is obvious. In other cases, the choice is to be based on detailed techno-economic comparison. The considerations in the planning for DC depend on the application. Two applications can be considered as representative. These are:

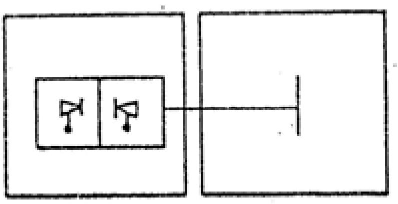
Long distance bulk power transmission.

Interconnection between two adjacent systems.

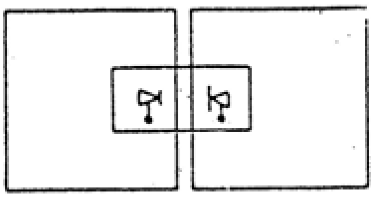
In the first application, the DC and AC alternatives for the same level of system security and reliability are likely to have the same power carrying capability. Thus the cost comparisons would form the basis for the selection of the DC (or AC) alternative, if the requirements regarding technical performance are not critical.



(a) Two terminal DC link



(b) Back to back DC link along with AC feeder



(c) Back to back DC link at border Different configuration for asynchronous interconnection

In the second application, AC interconnection poses several problems in certain cases. For the same level of system security (and reliability), the required capacity or AC interconnection will be much more than that for DC (even ignoring the beneficial aspects of DC power modulation). Thus the choice for DC interconnection will be based on the following considerations.

- Small fluctuations in the voltage and frequency do not affect the power flow which can be set at any desired value.
- The system security can be enhanced by fast control of DC power. Having settled on the DC link for interconnection there are three possible configurations for interconnection. These are:
- A two terminal transmission where each terminal is located at a suitable place somewhere within the network and connected by a DC overhead line or cable.
- A back to back HVDC station (also called HVDC coupling station) located somewhere within one of the network and an AC line from the other network to the common station.
- A back to back station located close to the border between the two systems. This is a special case of the above. These are illustrated in above figure In the choice between the first and second configuration, it is to be noted that converter costs are less for the common coupling station and the AC 1inecosts are greater than the DC line costs.1f the distances involved are less than 200 km, the second configuration is to be preferred. If the short circuit ratio (SCR) is acceptable, then the third alternative will be the most economic. The specifications and design of DC system require an understanding of the various interactions between the DC and AC systems. The interruption (or reduction) of power in a DC link can occur due to DC line faults

AC system faults The speed of recovery from transient DC lines faults is of concern in maintaining the integrity of the overall System. The power flow and stability studies are used in this context. The recovery of Dc link from AC system faults is more complex. The depression of AC voltage at the inverter bus can lead to commutation failure and loss of DC power. The DC power is ramped up on the clearing of the fault. Too fast an increase in DC power output can lead to the reduction of AC voltage and failure of commutation (due to corresponding increase in the VAR demand). An optimum rate of increase in DC power can be determined from stability study. This is influenced by control strategy and system characteristics. The following aspects also require a detailed study of the system interactions: VAR requirements of converter stations

- Dynamic over voltages
- Harmonic generation and design of filters
- Damping of low frequency and sub synchronous torsional oscillations
- Carrier frequency interference caused by spiky currents in valves (at the beginning of conduction) due to the discharge of stray capacitances and snubber circuits. The converter control plays a major role in these interactions and the control strategy should be such as to improve the overall system performance.

Choice of voltage level:

For long distance bulk power transmission, the voltage level is chosen to minimize the total costs for a given power level (P). The total costs include investment (Cl) and cost of losses (C2). The costs per unit length are modeled as

$$C_1 = A_c + A_1 nV + A_2 nQ \qquad (1)$$

Where,

V is the voltage level with respect to ground n is the number of conductors

q is the total cross-section of each conductor

A0. A1 and A2 are constants.

The cost of losses per unit length is given by

$$C_2 = \left[n\left(\frac{P}{nV}\right)^2 \rho T L p\right]/q \qquad (2)$$

Where,

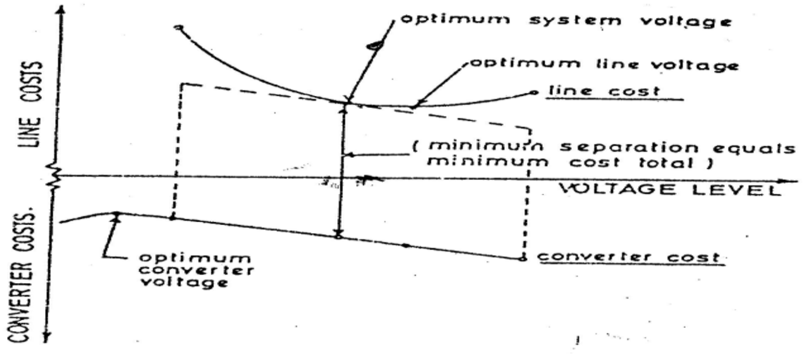
ρ = conductor resistivity

T = total operation time in a year

L = loss load, factor

p = cost per unit energy C2 can be simplified as

$$C_2 = \frac{\left(A_3\left(\frac{P}{V}\right)^2 \rho\right)}{nq} \qquad (3)$$



Selection of optimum system voltage for a fixed power transfer.

By minimizing the sum *of* C2 and the third term in C1, We have,

$$nq = \sqrt{(A_3/A_2)\rho}(P/V) \qquad (4)$$

$$J = P\Big/(nqV) = \sqrt{\frac{A_2}{A_3\rho}} \qquad (5)$$

Where J is the current density. The total costs, using 5 can be written as

$$C = C_1 + C_2 = A_0 + A_1 nV + 2\sqrt{A_2 A_3 \rho}\left(\frac{P}{V}\right) \qquad (6)$$

The voltage level Vis chosen to minimize C. The equation (6) ignores the variation of terminal costs with the voltage. The above figure shows the selection of optimum system voltage to minimize the sum of convener and line costs.

In case of back to back DC ties, the line costs are absent. Hence the voltage level is chosen to minimize converter costs. This level is generally much lower than that in the presence of an overhead line.

8) Discuss the possible HVDC links for the interconnection of HVDC transmission line AC systems (APRIL/2014) (NOV/2012) (APRIL/2012)

INTERCONNECTION OF HVDC TRANSMISSION INTO A.C SYSTEMS:

Based on interconnection, the following HVDC links are possible.

1.***HVDC bipolar transmission system, where bulk power is transmitted from one point to another point over long distance:***

A two terminal D.C link using overhead links is used to transmit large blocks of relatively cheap power from remote sources to load centers situated far away from the generating stations. This enables the development of remote power generation sites.

Cable transmission with A.C systems is possible for a distance of not more than 40 km due to problem of the charging current. For longer distances HVDC is opted. Sometimes the power transmission in congested urban areas is done with underground cables.

e.g. For two terminal D.C link

Rihand - Delhi line

Length - 810 km

Voltage - ± 400 kV

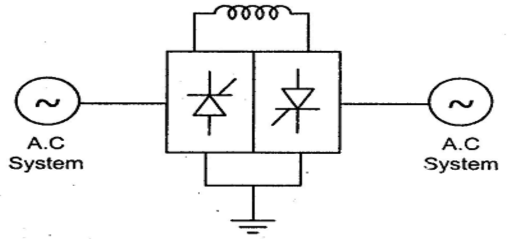
Power - 1000 - 1500 MW

2.**Back to back D.C link,** where rectification and inversion is carried out in the same converter station with very small or no D.C lines as shown in below figure.

Advantages:

To control the power and stabilize the system.

To connect two different frequencies of A.C system.

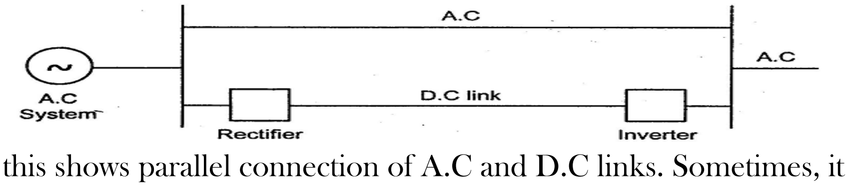


A back to back link consists of sending and receiving end converter stations situated close to each other and the Q.C line is of zero or negligible length. They are used to couple A.C systems of different frequencies. eg. Back to Back HVDC systems are located at

- Vindyachal
- Chandrapur .
- Sasaram
- Gazuwaka

3. Parallel connection of A.C and D.C links, where both A.C and D.C lines run parallel. It is mainly used to modulate the power of A.C line.

Due to its fast control, the D.C line can improve transient stability of the system.



this shows parallel connection of A.C and D.C links. Sometimes, it is necessary to put a D.C link in parallel with an existing A.C link. This scheme is used to reinforce the A.C link to improve its stability.

A D.C link has an extremely rapid speed of response and hence, it can change its transmitted power much more rapidly than a turbine-generator can adjust its output.

In an A.C system, several modes of electromechanical oscillations may involve single machine or a number of machines in a system or a number of areas connected by tie lines. To avoid such oscillations, a D.C link may be used.

The maximum transmitted power capability of an A.C link may be set by its steady state stability limit. By connecting a D.C link in parallel with the A.C link raises the steady state and transient stability limits of the A.C link

e.g. Pacific inter tie (USA) D.C link,

Length - 1362 Km

Capacity - 1440 MW

Set in parallel with an A.C link to increase the power capability of A.C link from 2100 MW - 2500 MW

4. Multi-terminal D.C links: All large A.C power systems are effectively of multi-terminal variety. However, almost all D.C links set up are two terminal links. A multi-terminal D.C network of rectifier and inverter stations is theoretically possible. One of the essential requirements in a multi-terminal D.C scheme is the use of large D.C circuit breakers.

The two terminal D.C link does not need to be equipped with A.C circuit breakers because faults on the link can be clear

ed by the converter control action. However, a multiterminal scheme needs D. C circuit breakers.

9) State the applications of HVDC transmission

APPLICATIONS OF HVDC SYSTEMS:

The following are the areas of application for D.C transmission.

Long Distance Bulk Power Transmission

The cost of D.C transmission line is less than that of A.C line while the cost of the terminal equipment in case of D.C is high. In case of long distance transmission lines, D.C at high voltage becomes economical.

2. Power Transmission through Underground or Submarine Cables.

D.C cables are easier for construction and laying. Large submarine A.C cables are oil or gas-filled under pressure. D.C cables can have simple paper insulation impregnated with a high viscosity compound. Thus it is practically economical for distances of 50 km.

3. Asynchronous Interconnection of A.C Systems Operating at Different Frequencies or Where Independent Control of Systems is desired

HVDC transmission is used for interconnecting two A.C systems even of different frequencies. This becomes economical when there is diversity between the two systems. The interconnection also reduces the reserve capacity of the plant required in the systems. It has an advantage that when the two A.C systems remain independent in their voltage and frequency control. A D.C link does not increase the short circuit capacity of interconnected power systems. This is a great advantage in the use of D.C link for interconnection. The efficiency of operation also increases.

4. A.C and D.C Lines in Parallel High voltage A.C line and HVDC line can be used in parallel as an A.C - D.C system. The D.C link can be used with advantage for control of power, thereby increasing the transien1 stability.

5. D.C Transmission with A.C Distribution Systems

The high voltage A.C systems can be connected to a distribution system or secondary transmission system through a relatively-short D.C link. The main advantage of a D.C link consist of ease of control of power flow and a reduced short-circuit level.

6. Back to Back HVDC Coupling Stations

Back to Back D.C links have the advantage of reducing the overall conversion cost and improving the reliability of D.C systems because the rectification and inversion are carried out in the same converter stations with no D.C lines.

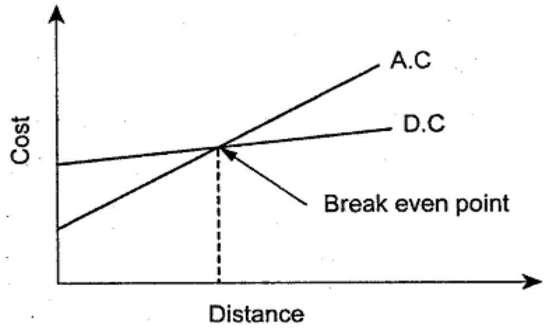
7. Control and Stabilization of Power Flow in A.C Ties in an Integrated Power Systems

9) Explain about the limitations, advantages and disadvantages of HVDC transmission systems.

LIMITATIONS OF HVDC TRANSMISSION:

(a) High Cost of Conversion Equipments.

The cost of terminal equipment is high. The voltage and the power to be transmitted should be high to justify the choice economically. The cost curve of D.C transmission intersects the cost curve of A.C transmission at one distance that is known as breakeven distance. This distance is about 500 - 600 km. Cost curve is as shown in below figure.



Generation of Harmonics which require A.C and D.C filters, adding to the cost of converter station

There is a possibility of considerable distortion in the waveform of the A.C voltages by the use of HVDC link. Special filters will be necessary in the terminal equipment on either side of HVDC. The Harmonics also interfere with communication system.

Blocks the reactive power

Reactive power = VI sin Ø = 0 D. C line blocks the flow of reactive power from one end to another end. These reactive powers are required by some load that must be fulfilled by the inverters.

(d) Complexity of control

D.C line is restricted to point to point transmission. It is not possible to tap D.C power at several locations in the line. Wherever power is to be tapped, a control station is required and coordinated with other terminals. This increases the complexity and cost of the system. However there is no problem in A.C line, when the power is controlled at both ends of the line, it is called two terminal D.C system or line. If there is more than two control stations in line, it is known as multi terminal HVDC system.

(f) Inability to use transformers to change voltage level

(g) The difficulty of breaking D.C currents which results in high cost of D.C breakers.

ADVANTAGES OF HVDC TRANSMISSION:

- HVDC can carry more power with two conductors.
- Corona loss and radio interference is less.
- Dielectric loss is less.
- Absence of skin effect reduces power losses.
- Ground can be used as return conductor
- Economical for long distance transmission.
- No charging current.
- No transmission of short circuit power in case of any fault
- Fault clearing time is small.
- Don't require line compensation.
- Asynchronous interconnection of A.C systems operating at different frequencies.
- Control and stabilization of power flows in A.C ties in an integrated power systems.
- No reactive power loss.

DISADVANTAGES OF HVDC TRANSMISSION:

- Terminal equipment cost is high due to the presence of converters and filters.
- Maintenance cost is high.

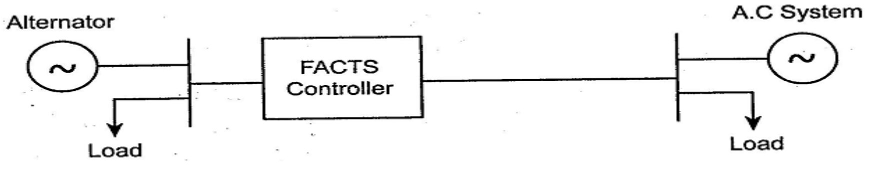
- Costs of D.C breakers are high.
- Inability to use transformers to change voltage levels.
- Converters generate harmonics both on A.C and D.C sides These harmonics may interfere with communication systems.
- D.C lines block the flow of reactive power from one end to another end. But these are required by some load that must be fulfilled by the inverters.
- Point to point transmission is not possible by HVDC.

10) Write short notes on FACTS. (NOV/2012) (NOV/2013)

FLEXIBLE ALTERNATING CURRENT TRANSMISSION SYSTEM (FACTS)

INTRODUCTION

A FACT is an acronym for a group of devices known as *Flexible Alternating Current Transmission Systems*. Dr. Narain G. Hingorani is considered the father of the FACTS Concept, for it was his innovative ideas that fueled the inception of this family of power electronic devices. The term 'flexible' in the acronym stems from the fact that these devices provide controllability; stability and power transfer capability of A.C transmission systems. Flexible A.C transmission system is as shown in figure.



For years, capacitor banks have been used to overcome problems originating due to an insufficiency of reactive power in A.C transmission lines. However controlling capacitor switching in a manner that will optimally switching transient has been a problem facing electrical power engineers for years.

PURPOSE OF FACTS:

The main purpose of FACTS device is to provide controllable compensation to a power system, enabling an increase in the system's power transmission capability. There is an increasing demand for power from various present and future load centers, and there is also a surplus of electric power generation in America. This surplus power generation is not uniformly distributed throughout the United States. Therefore, one can see that an increase in transmission capability is vital to meet increasing generation demands.

The basic idea behind FACTS is that it is possible to continuously vary the apparent impedance of specific transmission lines so as to force power to flow along a desired path. With the precise control of impedance of transmission lines using FACTS devices, it is possible to maintain constant power flow of a desired quantum in a desired path, in the presence of continuous changes of load levels in the external A.C network and to react in a planned way to contingencies.

OBJECTIVES OF FACTS:

FACTS use controllable series and shunt compensations located at intermediate substations with the following objectives.

- Rapid control of reactive power flow and voltage profile using series and shunt connected controllers. Secure loading of lines close to their thermal limits.
- Improve power transferability, transient stability and dynamic stability during fault switching, etc. **ADVANTAGES:**

The main advantages of FACTS technology are as follows.

- Improved steady state system performance.
- Improvements in system transient or dynamic stability
- Reduced financial costs and/or environmental impacts.
- FACTS controllers require minimal maintenance.
- Increase the system security.
- Reduces power system oscillations.

FACTS CONTROLLER

11) What is the significance of SVC in power system? (5) (APRIL/2015)

Static VAR Compensator (SVC)

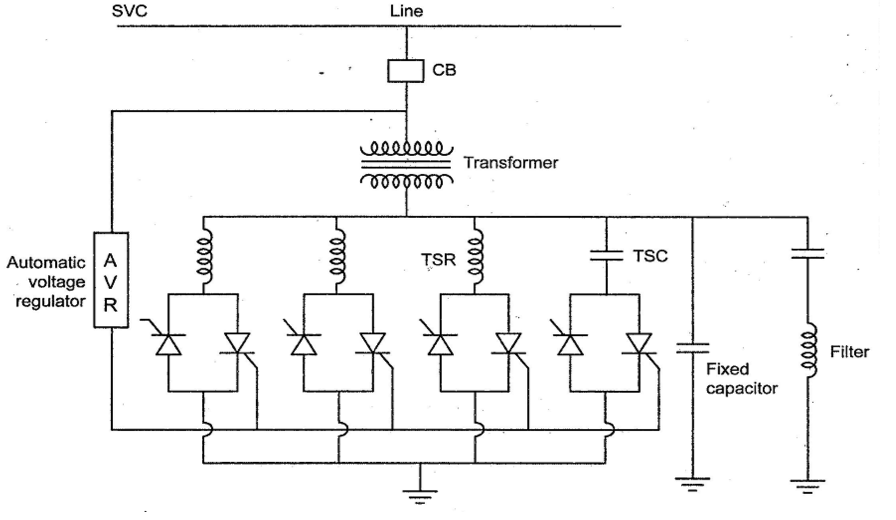
SVC is a shunt connected static VAR generator or absorber whose output is adjusted to control capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (bus voltage).

An SVC is based on thyristor-controlled reactors (TCR), thyristor controlled capacitors (TSC) and fixed capacitors (FC) tuned to filters. A TCR consists of a fixed reactor in series with a bi-directional thyristor valve. A TSC consists of a capacitor bank in series with a bi-directional thyristor valve and damping reactor, which also serves to re-tune the circuit to avoid parallel resonance with the network. Two very common design types, both having each their specific merits are as shown in figure.

Advantages of SVC:

The transient ability and steady state power handling capacity can be increased by using SVC at intermediate buses of long lines.

- Dynamic stability is increased due to the increased damping provided.
- Steady state and temporary over voltages can be controlled.
- Load power factor is improved and hence system efficiency is improved.
- SVC is faster in response than synchronous condensers.



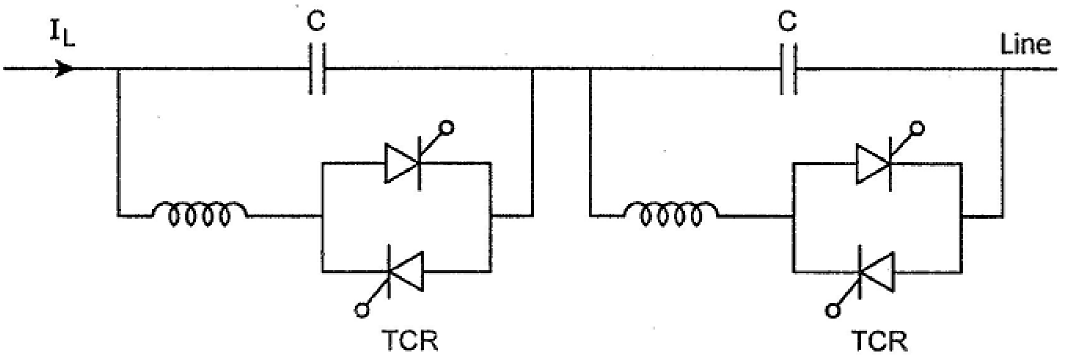
Static VAR compensator

Thyristor Controlled Series Compensator (TCSC)

TCSC is a capacitive reactance compensator, which is used to control the effective line .reactance by connecting a TCR combination with mechanically switched capacitor section in series. TCSR is based on thyristors without the gate turn off capability. Series compensation is used with long lines for providing compensation of reactive powers and giving higher power transferability. Fig.5.15 shows thyristor controlled series compensator.

When TCR firing angle = 180°, the reactor becomes non-conducting and the series capacitor has its normal impedance. If 90° <TCR firing angle <180°, Capacitive impedance increases.

If TCR firing angle = 90°, the reactor becomes fully conducting and the total impedance becomes inductive. So TCSC helps in limiting fault currents.



TCSC

It is preferred to the shunt compensation as the rating required for the series compensations are comparatively smaller. However the series compensated lines suffer from the drawback of producing series resonance at frequencies lower than power frequencies, which is called sub-synchronous reactance. Sub-synchronous reactance results in damage to rotor shafts of turbo alternators producing torsion torque.

3. STATCOM (Static Condensers)

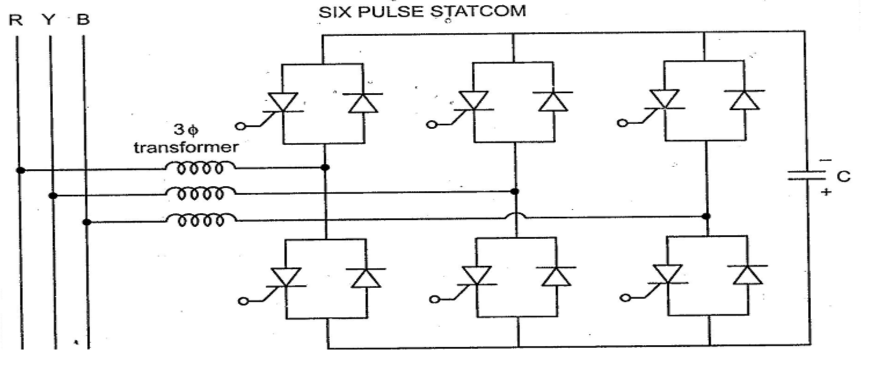
STATCOM is actually a shunt compensation device. STATCOM is a static synchronous generator operated as a shunt-connected static VAR compensator (SVC) whose capacitive or inductive output current can be controlled independently of the A.C system voltage. Below figure shows STATCOM based on voltage sourced converter.

The major differences between a SVC and STATCOM are:

- Use of Gate Turn-Off Switch (GTO) in STATCOM compared to use of conventional thyristors in SVC.
- SVC is a voltage regulator and variable susceptance controller whereas ST ATCOM is based on voltage source converter (VSC).
- Performance of STATCOM is superior to SVC because
- Reactive power delivered in STATCOM = Voltage x Current.

$$\text{Reactive power delivered in SVC} = \frac{\text{Voltage}^2}{\text{Impedance}}$$

The operating principle is like a synchronous condenser. It is a 3Ø inverter that is driven from the voltage across a D.C capacitor. VSC is coupled to circuit through a transformer, which provides the safe operating voltage and small reactance. An inverter generates three phase voltages in phase with the A.C system voltages. The current lags if the inverter voltage is less than the system voltage and leads if the inverter voltage is greater than the system voltage. The reactive power delivered by STATCOM is a function of voltage and current. This device can deliver reactive power under reduced voltage condition and has a better performance than a static VAR compensator. Except a very small loss taking place in the VSC, no real energy exchange takes place.



- The STATCOM is capable of supplying required reactive power even at small values of bus voltages where reactive power supply capability gets limited to its susceptance limit. The susceptance decreases linearly with decrease in bus voltage.
- Due to susceptance limit, SVC cannot have a short time overload capacity whereas STATCOM can have the same.
- STATCOM can serve as a real power exchanger if it has an energy source at D.C bus, conversely supply D.C power.
- STATCOM can be designed as an active filter to absorb system harmonics.

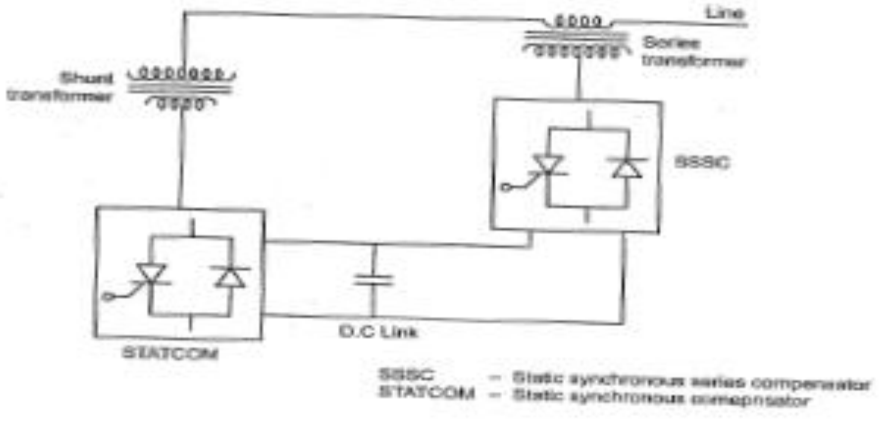
Unified Power Flow Controller (UPFC)

This is the latest in the series of FACTS controllers. UPFC is a combination of static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC) which is coupled through a D.C link to allow bi-directional flow of real power between series output of SSSC and shunt output of STATCOM. The principle is based upon injecting a variable voltage in series with the transmission line in order to control real and reactive power flow through the line and also to control voltage, impedance and angle without an external energy source.

The device has two branches:

- A series branch.
- A shunt branch.

Each branch is a GTO (gate turn off thyristor) based inverter circuit. The series branch has a voltage source inverter, which injects a voltage in series through a transformer as shown in figure. In doing so, it can exchange real power with the transmission line by injecting a voltage in series through a transformer. But this exchange of power is only possible if it has an energy source at its D.C terminal. The UPFC with only series branch functioning but exchanging its real power is called Static Synchronous Series Compensation (SSSC). It is used to control system dynamics than modulation of the power transfer within a system.



UPFC

UPFC may provide shunt reactive compensation. Super-conducting magnet connected to the D.C link is to enhance the performance of UPFC.

COMPARISON BETWEEN STATCOM AND SVC:

S.NO	STATCOM	SVC
1	It uses gate turn-off thyristors.	It uses conventional thyristors.
2	It is based on voltage source converter	It is a voltage regulator and variable susceptance controller
3	It has short time overload capability	It cannot have short time overload capability
4	It reduces system harmonics	It generates system harmonics
5	It operates both inductive and capacitive regions.	It operates mostly capacitive regions.
6	Better performance during transients.	Slow performance during transients.
7	Even with very week AC system, it maintains stable voltages.	Even with very week AC system, its operation is difficult.

CONTROL ASPECTS OF VARIOUS FACTS DEVICES:

FACTS Devices	CONTROL ASPECTS
STATCOM	Voltage control, VAR compensation, Damping oscillations and Voltage instability
SVC	Voltage control, VAR compensation, Damping oscillations and Voltage instability, Transient and Dynamic stability
TCSC	Increase power transferability, Current control, Damping oscillations, Transients and Dynamic stability, Voltage stability.
UPFC	Active and Reactive power control, Voltage control, VAR compensation, Damping oscillations, Transients and Dynamic stability, Voltage stability and limiting the fault current.

COMPARISON BETWEEN FACTS AND HVDC:

1. FACTS controllers can be retrofitted into the existing line, but not in HVDC.
2. Installation cost is less for FACTS compared to that of HVDC.
3. FACTS device provide VAR compensation.
4. FACTS device control the line impedance or inject phase shift.
5. FACTS device increases the stability margin.
6. FACTS device uses special dampers which are used to improve dynamic stability.

University 2 marks Questions:

1) What are the classification of UG cables (APRIL/2015)
2) What is the significance of FACTS devices in power system (APRIL/2015)
3) List out the terminal equipment for HVDC systems. (NOV/2014)
4) What are the advantages of HVDC transmission? (NOV/2014)
5) State the advantages of EHVDC transmission system. (APRIL/2014)
6) Give any two HVDC transmission lines in India (APRIL/2014)
7) What are the main equipment used in a converter station of a HVDC transmission system (NOV/2013)
8) Mention any two disadvantages of HVDC transmission (NOV/2013)
9) List out the types of HVDC-Link. (APRIL/2013)
10) What is break-over distance in HVDC transmission? (APRIL/2013)
11) What are the various types of HVDC systems? (NOV/2012)
12) State the objectives of FACTS technology. (NOV/2012)
13) Compare EHVDC and HVDC. (NOV/2012)
14) Write any four applications of HVDC. (NOV/2012)
15) Define "breakeven distance" in HVDC transmission. (APRIL/2012)
16) What are the various methods of voltage control in a power system? (APRIL/2012)
17) What is FACTS (APRIL/2012)
18) What is the voltage range of EHV transmission (APRIL/2012)

11 marks

1) Explain the various types of HVDC links. (APRIL/2013) (NOV/2014) (APRIL/2012)
2) Explain the terminal equipment for HVDC systems. (APRIL/2013) (NOV/2014) (APRIL/2015)
3) Explain the principle of HVDC transmission system. Also bring out the various types of HVDC systems. Draw the relevant diagram. (APRIL/2014)
4) Discuss the possible HVDC links for the interconnection of HVDC transmission line AC systems (APRIL/2014) (NOV/2012) (APRIL/2012)
5) Compare the HVDC transmission with EHVDC transmission in the following respects. (NOV/2012) i. Economics of transmission ii. Reliability iii. Technical Performance
6) Discuss in details the various equipments used in HVDC converter station. (NOV/2012)
7) Write short notes on FACTS. (NOV/2012) (NOV/2013)
8) State the advantages of HVDC transmission. Discuss the points and factors to be connected while planning a distribution system. (APRIL/2012)
9) a) Explain in details about economic distances for DC transmission. (6) (APRIL/2015) (NOV/2013) a. b) What is the significance of SVC in power system? (5) (APRIL/2015)
10) Describe the design of town electrification schemes (6) (NOV/2013)
11) Write short notes on the following: Extra high voltage AC transmission system (6) (NOV/2013) 12) Compare the EHVAC and HVDC system (11) (APRIL/2012) (APRIL/2015)