

**OCW**  
**POWER SYSTEM-I**  
**EE 502**

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## MECHANICAL DESIGN OF TRANSMISSION LINE

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## MODULE I

### Transmission line

#### Conductors

Commonly used conductor materials:

The most commonly used conductor materials for overhead lines are copper, aluminium, steel-cored aluminium, galvanised steel and cadmium copper. The choice of a particular material will depend upon the cost, the required electrical and mechanical properties and the local conditions. All conductors used for overhead lines are preferably stranded in order to increase the flexibility. In stranded conductors, there is generally one central wire and round this, successive layers of wires containing 6, 12, 18, 24 ..... wires. Thus, if there are  $n$  layers, the total number of individual wires is  $3n(n + 1) + 1$ . In the manufacture of stranded conductors, the consecutive layers of wires are twisted or spiralled in opposite directions so that layers are bound together.

#### Types of Conductors

1. **Copper.** Copper is an ideal material for overhead lines owing to its high electrical conductivity and greater tensile strength. It is always used in the hard drawn form as stranded conductor. Although hard drawing decreases the electrical conductivity slightly yet it increases the tensile strength considerably.

Copper has high current density i.e., the current carrying capacity of copper per unit of X-sectional area is quite large. This leads to two advantages. Firstly, smaller X-sectional area of conductor is required and secondly, the area offered by the conductor to wind loads is reduced. Moreover, this metal is quite homogeneous, durable and has high scrap value. There is hardly any doubt that copper is an ideal material for transmission and distribution of electric power. However, due to its higher cost and non-availability, it is rarely used for these purposes. Now-a-days the trend is to use aluminium in place of copper.

2. **Aluminium.** Aluminium is cheap and light as compared to copper but it has much smaller conductivity and tensile strength. The relative comparison of the two materials is briefed below:

(i) The conductivity of aluminium is 60% that of copper. The smaller conductivity of aluminium means that for any particular transmission efficiency, the X-sectional area of conductor must be larger in aluminium than in copper. For the same resistance, the diameter of aluminium

conductor is about 1.26 times the diameter of copper conductor. The increased X-section of aluminium exposes a greater surface to wind pressure and, therefore, supporting towers must be designed for greater transverse strength. This often requires the use of higher towers with consequence of greater sag.

(ii) The specific gravity of aluminium (2.71 gm/cc) is lower than that of copper (8.9 gm/cc). Therefore, an aluminium conductor has almost one-half the weight of equivalent copper conductor. For this reason, the supporting structures for aluminium need not be made so strong as that of copper conductor.

(iii) Aluminium conductor being light, is liable to greater swings and hence larger cross-arms are required.

(iv) Due to lower tensile strength and higher coefficient of linear expansion of aluminium, the sag is greater in aluminium conductors. Considering the combined properties of cost, conductivity, tensile strength, weight etc., aluminium has an edge over copper. Therefore, it is being widely used as a conductor material. It is particularly profitable to use aluminium for heavy-current transmission where the conductor size is large and its cost forms a major proportion of the total cost of complete installation.

3. **Steel cored aluminium.** Due to low tensile strength, aluminium conductors produce greater sag. This prohibits their use for larger spans and makes them unsuitable for long distance transmission. In order to increase the tensile strength, the aluminium conductor is reinforced with a core of galvanised steel wires. The composite conductor thus obtained is known as steel cored aluminium and is abbreviated as A.C.S.R. (aluminium conductor steel reinforced).

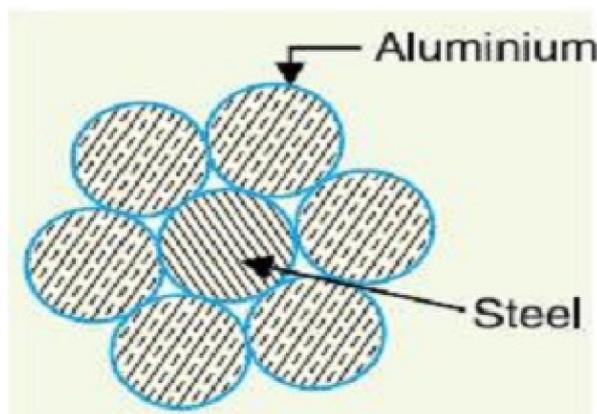


Fig 1.1: ACSR Conductor

Steel-cored aluminium conductor consists of central core of galvanized steel wires surrounded by a number of aluminium strands. Usually, diameter of both steel and aluminium wires is the same. The X-section of the two metals are generally in the ratio of 1 : 6 but can be modified to 1 : 4 in order to get more tensile strength for the conductor. Fig. shows steel cored aluminium conductor having one steel wire surrounded by six wires of aluminium. The result of this composite conductor is that steel core takes greater percentage of mechanical strength while aluminium strands carry the bulk of current. The steel cored aluminium conductors have the following advantages :

- (i) The reinforcement with steel increases the tensile strength but at the same time keeps the composite conductor light. Therefore, steel cored aluminium conductors will produce smaller sag and hence longer spans can be used.
- (ii) Due to smaller sag with steel cored aluminium conductors, towers of smaller heights can be used.

### **TRANSMISSION LINE PARAMETER**

An electric transmission line has four parameters, namely resistance, inductance, capacitance and shunt conductance. These four parameters are uniformly distributed along the whole line. Each line element has its own value, and it is not possible to concentrate or lumped them at discrete points on the line. For this reason the line parameters are known as distributed parameter, but can be lumped for the purpose of analysis on approximate basis. However, the validity of assumption for the analysis on lumped basis may fail if the line is very long.

#### **Line Inductance:**

When an alternating current flows through a conductor, a changing flux is set up which links the conductor. Due to these flux linkages, the conductor possesses inductance.

Mathematically, inductance is defined as the flux linkages per ampere i.e.

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

where  $\psi$  = flux linkage in weber-turns

I = current in turns

Which shows that the self inductance of an electric circuit is numerically equal to the flux linkage of the circuit per unit of current.

### Flux Linkages:

As stated earlier, the inductance of a circuit is defined as the flux linkages per unit current. Therefore, in order to find the inductance of a circuit, the determination of flux linkages is of primary importance. We shall discuss two important cases of flux linkages.

1. Flux linkages due to a single current carrying conductor. Consider a long straight cylindrical conductor of radius  $r$  metres and carrying a current  $I$  amperes (rms) as shown in Fig.1.2(i). This current will set up magnetic field. The magnetic lines of force will exist inside the conductor as well as outside the conductor. Both these fluxes will contribute to the inductance of the conductor.

**(i) Flux linkages due to internal flux.** Refer to Fig.1.2 (ii) where the X-section of the conductor is shown magnified for clarity. The magnetic field intensity at a point  $x$  metres from the centre is given by;

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

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

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

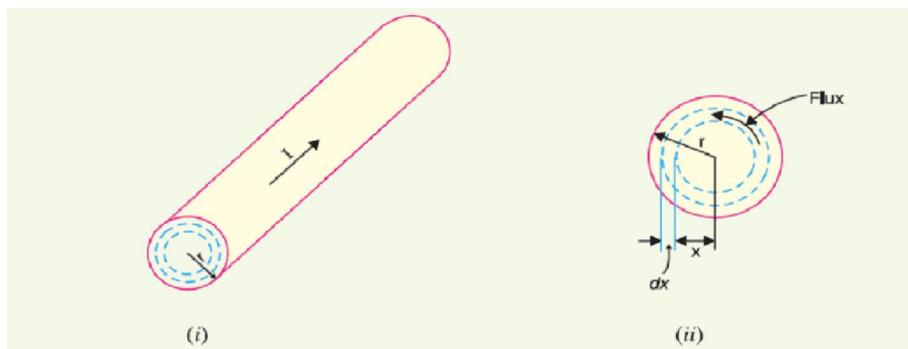


Fig 1.2: Internal flux linkage in a cylindrical conductor

If  $\mu$  ( $=\mu_0\mu_r$ ) is the permeability of the conductor, then flux density at the considered point is given by

$$B_x = \mu_0\mu_r H_x$$

$$= \frac{\mu_0 x I}{2\pi r^2} \text{ wb/m}^2 \quad (\mu_r=1 \text{ for non magnetic material})$$

Now, flux  $d\phi$  through a cylindrical shell of radial thickness  $dx$  and axial length 1 m is given by

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

This flux links with the current  $I_x$  only. Therefore the flux linkages per unit length of the conductor is

$$d\psi = \frac{\pi x^2}{\pi r^2} d\phi = \frac{\mu_0 I x^3}{2\pi r^4} dx \text{ weber-turns}$$

Total flux linkages from centre upto the conductor surface is

$$\begin{aligned} \psi_{\text{int}} &= \int_0^r \frac{\mu_0 x I^3}{2\pi r^4} dx \\ &= \frac{\mu_0 I}{8\pi} \text{ weber-turns per meter length} \end{aligned}$$

**(ii) Flux linkages due to external flux.** Now let us calculate the flux linkages of the conductor due to external flux. The external flux extends from the surface of the conductor to infinity. Referring to Fig. 4.5, the field intensity at a distance  $x$  metres (from centre) outside the conductor is given by ;

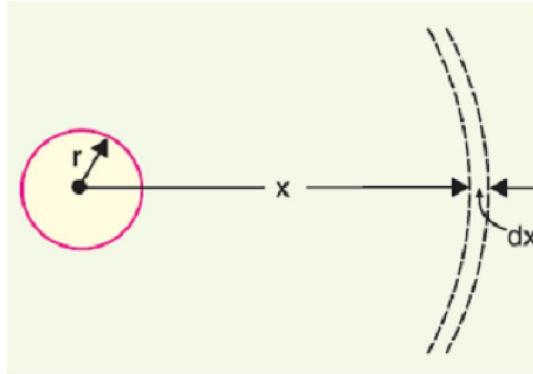


Fig 1.3: External flux linkage in a conductor

$$H_x = \frac{I}{2\pi x} \text{ AT/m}$$

$$\text{Flux density, } B_x = \mu_0 H_x = \frac{\mu_0 I}{2\pi X} \text{ wb/m}^2$$

Now, flux  $d\phi$  through a cylindrical shell of radial thickness  $dx$  and axial length 1 m is given by

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

The flux  $d\phi$  links all the current in the conductor once and only once.

$$d\psi = d\phi = \frac{\mu_0 I}{2\pi x} dx \quad \text{Weber-turns}$$

Total flux linkage of the conductor from surface to infinity

$$\psi_{ext} = \int_r^{\infty} \frac{\mu_0 I}{2\pi x} dx \quad \text{Weber-turns}$$

$$\text{Over all flux linkage } \psi = \psi_{int} + \psi_{ext} = \frac{\mu_0 I}{8\pi} + \int_r^{\infty} \frac{\mu_0 I}{2\pi x} dx$$

$$= \frac{\mu_0 I}{2\pi} \left[ \frac{1}{4} + \int_r^{\infty} \frac{dx}{x} \right] \quad \text{weber-turns/m length}$$

### Inductance of Single Phase Two Wire Line

A single phase line consists of two parallel conductors which form a rectangular loop of one turn. When an alternating current flows through such a loop, a changing magnetic flux is set up. The changing flux links the loop and hence the loop possesses inductance. It may appear that inductance of a single phase line is negligible because it consists of a loop of one turn and the flux path is through air of high reluctance. But as the X-sectional area of the loop is very large, even for a small flux density, the total flux linking the loop is quite large and hence the line has appreciable inductance.

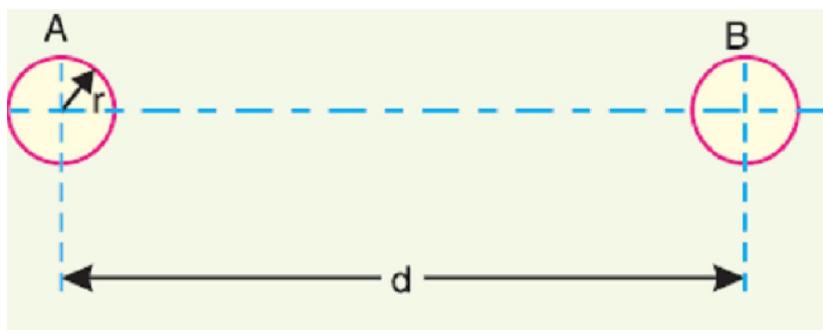


Fig 1.4: Single phase two wire transmission line

Consider a single phase overhead line consisting of two parallel conductors A and B spaced  $d$  metres apart as shown in Fig. 4.7. Conductors A and B carry the same amount of current (i.e.  $I_A = I_B$ ), but in the opposite direction because one forms the return circuit of the other.

$$I_A + I_B = 0$$

In order to find the inductance of conductor A (or conductor B), we shall have to consider the flux linkages with it. There will be flux linkages with conductor A due to its own current  $I_A$  and also due to the mutual inductance effect of current  $I_B$  in the conductor B. Flux linkages with conductor A due to its own current

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

Flux linkages with conductor A due to current  $I_B$

$$= \frac{\mu_0 I_B}{2\pi} \left[ \int_d^\infty \frac{dx}{x} \right]$$

Total flux linkage with the with conductor A is

$$\begin{aligned} \psi_A &= \frac{\mu_0 I_A}{2\pi} \left( \frac{1}{4} + \int_r^\infty \frac{dx}{x} \right) + \frac{\mu_0 I_B}{2\pi} \int_d^\infty \frac{dx}{x} \\ &= \frac{\mu_0}{2\pi} \left[ \left( \frac{1}{4} + \ln \infty - \ln r \right) I_A + (\ln \infty - \ln d) I_B \right] \\ &= \frac{\mu_0}{2\pi} \left[ \frac{I_A}{4} - I_A \ln r - I_B \ln d \right] \\ &= \frac{\mu_0}{2\pi} \left[ \frac{I_A}{4} + I_A \ln d - I_A \ln r \right] \\ &= \frac{\mu_0}{2\pi} \left[ \frac{I_A}{4} + I_A \ln \frac{d}{r} \right] \\ &= \frac{\mu_0 I_A}{2\pi} \left[ \frac{1}{4} + \ln \frac{d}{r} \right] \end{aligned}$$

Inductance of conductor A,

$$\begin{aligned} L_A &= \frac{\psi_A}{I_A} \\ &= \frac{\mu_0}{2\pi} \left[ \frac{1}{4} + \ln \frac{d}{r} \right] \text{ H/m} \\ &= 2 \times 10^{-7} \left[ \ln e^{\frac{1}{4}} + \ln \frac{d}{r} \right] \end{aligned}$$

$$= 2 \times 10^{-7} \left[ \ln \frac{d}{r e^{-1/4}} \right]$$

$$= 2 \times 10^{-7} \ln \frac{d}{r'} \text{ H/m}$$

The radius  $r'$  is that of a fictitious conductor assumed to have no internal flux but with the same inductance as the actual conductor of radius  $r$ . The quantity  $e^{-1/4} = 0.7788$  so that  $r' = r e^{-1/4} = 0.7788 r$

The term  $r' (= r e^{-1/4})$  is called geometric mean radius (GMR) of the conductor.

Loop inductance  $= 2 L_A = 2 \times 2 \times 10^{-7} \log d/r' \text{ H/m}$

Note that  $r' = 0.7788 r$  is applicable to only solid round conductor.

### Inductance of Three phase Overhead line:

Fig. 1.4 shows the three conductors A, B and C of a 3-phase line carrying currents  $I_A$ ,  $I_B$  and  $I_C$  respectively. Let  $d_1$ ,  $d_2$  and  $d_3$  be the spacing between the conductors as shown. Let us further assume that the loads are balanced i.e.  $I_A + I_B + I_C = 0$ . Consider the flux linkages with conductor A. There will be flux linkages with conductor A due to its own current and also due to the mutual inductance effects of  $I_B$  and  $I_C$ .

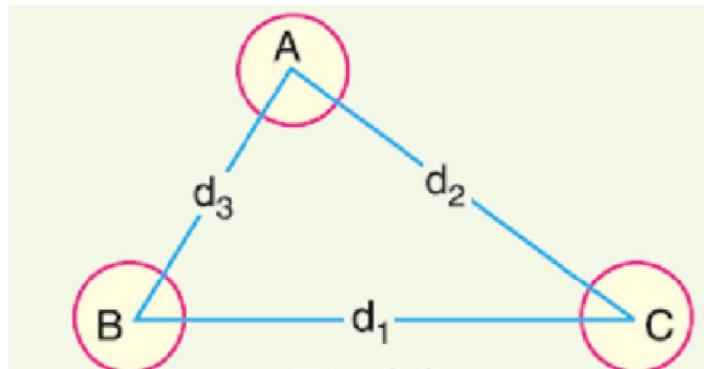


Fig 1.4 Three phase Overhead line

Flux linkages with conductor A due to its own current

$$= \frac{\mu_0 I_A}{2\pi} \left( \frac{1}{4} + \int_r^\infty \frac{dx}{x} \right)$$

Flux linkages with conductor A due to current  $I_B$

$$= \frac{\mu_0 I_B}{2\pi} \left( \frac{1}{4} + \int_{d_1}^\infty \frac{dx}{x} \right)$$

Flux linkages with conductor A due to current  $I_C$

$$= \frac{\mu_0 I_C}{2\pi} \left( \frac{1}{4} + \int_{d_2}^{\infty} \frac{dx}{x} \right)$$

The total flux linkage with the conductor A is

$$\psi_A = \frac{\mu_0 I_A}{2\pi} \left( \frac{1}{4} + \int_r^{\infty} \frac{dx}{x} \right) + \frac{\mu_0 I_B}{2\pi} \left( \frac{1}{4} + \int_{d_1}^{\infty} \frac{dx}{x} \right) + \frac{\mu_0 I_C}{2\pi} \left( \frac{1}{4} + \int_{d_2}^{\infty} \frac{dx}{x} \right)$$

As  $I_A + I_B + I_C = 0$

$$\psi_A = \frac{\mu_0}{2\pi} \left[ \left( \frac{1}{4} - \ln r \right) I_A + I_B \ln d_3 + I_C \ln d_2 \right]$$

**(i) Symmetrical Spacing:**

If the three conductors A, B and C are placed symmetrically at the corners of an equilateral triangle of side  $d$ , then,  $d_1 = d_2 = d_3 = d$ . Under such conditions, the flux linkages with conductor A become:

$$\psi_A = \frac{\mu_0}{2\pi} \left[ \left( \frac{1}{4} - \ln r \right) I_A - (I_B + I_C) \ln d \right]$$

$$\psi_A = \frac{\mu_0}{2\pi} \left[ \left( \frac{1}{4} - \ln r \right) I_A + I_A \ln d \right]$$

$$\psi_A = \frac{\mu_0 I_A}{2\pi} \left[ \left( \frac{1}{4} + \ln \frac{d}{r} \right) \right]$$

Inductance of conductor A,  $L_A = \frac{\psi_A}{I_A} = \frac{\mu_0}{2\pi} \left[ \left( \frac{1}{4} + \ln \frac{d}{r} \right) \right]$  H/m

putting the value of  $\mu_0 = 4\pi \times 10^{-7}$  in the above equation

$$L_A = 2 \times 10^{-7} \left[ \left( \ln \frac{d}{r} \right) \right] \text{ H/m}$$

**(ii) Unsymmetrical spacing**

When 3-phase line conductors are not equidistant from each other, the conductor spacing is said to be unsymmetrical. Under such conditions, the flux linkages and inductance of each phase are not the same. A different inductance in each phase results in unequal voltage drops in the three phases even if the currents in the conductors are balanced. Therefore, the voltage at the receiving end will not be the same for all phases. In order that voltage drops are equal in all

conductors, we generally interchange the positions of the conductors at regular intervals along the line so that each conductor occupies the original position of every other conductor over an equal distance. Such an exchange of positions is known as transposition. Fig. 1.5 shows the transposed line. The phase conductors are designated as A, B and C and the positions occupied are numbered 1, 2 and 3. The effect of transposition is that each conductor has the same average inductance.

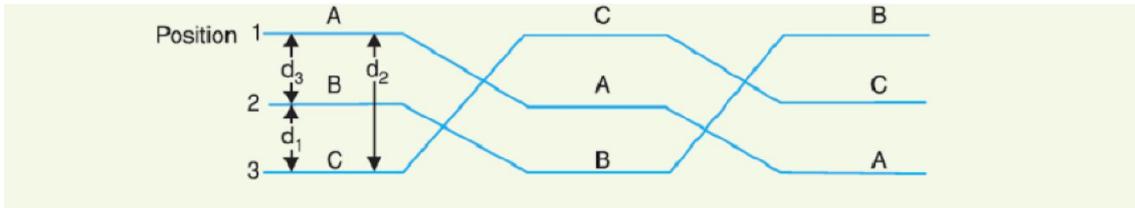


Fig 1.5: Transposition of three phase conductor

Above fig.1.5 shows a 3-phase transposed line having unsymmetrical spacing. Let us assume that each of the three sections is 1 m in length. Let us further assume balanced conditions i.e.,  $I_A + I_B + I_C = 0$ .

The inductance per phase can be

$$L_A = 2 \times 10^{-7} \left[ \ln \frac{\sqrt[3]{d_1 d_2 d_3}}{r'} \right] \text{ H/m}$$

### Electric potential

The electric potential at a point due to a charge is the work done in bringing a unit positive charge from infinity to that point. The concept of electric potential is extremely important for the determination of capacitance in a circuit since the latter is defined as the charge per unit potential. We shall now discuss in detail the electric potential due to some important conductor arrangements.

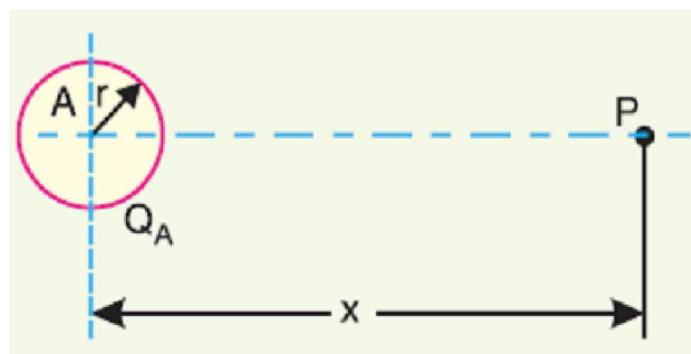


Fig 1.6 Potential of single conductor

(i) **Potential at a charged single conductor.** Consider a long straight cylindrical conductor A of radius  $r$  metres. Let the conductor operate at such a potential ( $V_A$ ) that charge  $Q_A$  coulombs per metre exists on the conductor. It is desired to find the expression for  $V_A$ . The electric intensity  $E$  at a distance  $x$  from the centre of the conductor in air is given by

$$E = \frac{Q_A}{2\pi\epsilon_0 x} \text{ volts/m}$$

As  $x$  approaches infinity, the value of  $E$  approaches zero. Therefore, the potential difference between conductor A and infinity distant neutral plane is given by:

$$V_A = \frac{Q_A}{2\pi\epsilon_0} \int_r^\infty \frac{dx}{x}$$

### Capacitance of Single Phase Two Wire Line

Consider a single phase overhead transmission line consisting of two parallel conductors A and B spaced  $d$  metres apart in air. Suppose that radius of each conductor is  $r$  metres. Let their respective charge be  $+Q$  and  $-Q$  coulombs per metre length.

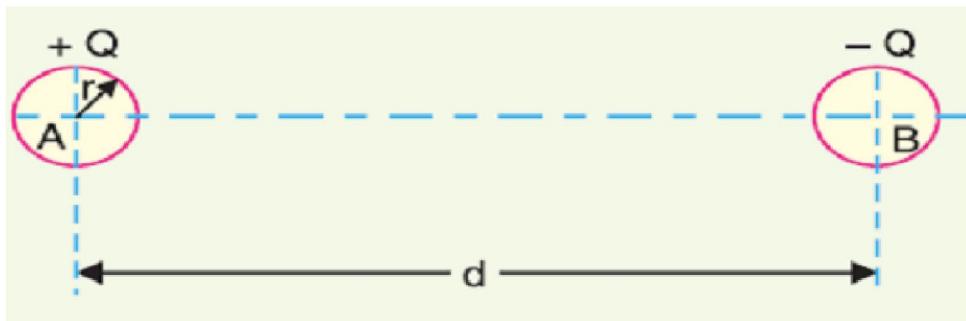


Fig 1.7: Single phase two wire transmission line

The total p.d. between conductor A and neutral “infinite” plane is

$$\begin{aligned} V_A &= \frac{Q}{2\pi\epsilon_0} \int_r^\infty \frac{dx}{x} - \frac{Q}{2\pi\epsilon_0} \int_d^\infty \frac{dx}{x} \\ &= \frac{Q}{2\pi\epsilon_0} \ln \frac{d}{r} \text{ Volts} \end{aligned}$$

Similarly, p.d. between conductor B and neutral “infinite” plane is

$$V_B = \frac{-Q}{2\pi\epsilon_0} \int_r^\infty \frac{dx}{x} + \frac{Q}{2\pi\epsilon_0} \int_d^\infty \frac{dx}{x}$$

$$= \frac{-Q}{2\pi\epsilon_0} \ln \frac{d}{r} \text{ Volts}$$

Both these potentials are w.r.t. the same neutral plane. Since the unlike charges attract each other, the potential difference between the conductors is

$$V_{AB} = 2V_A = \frac{2Q}{2\pi\epsilon_0} \ln \frac{d}{r}$$

$$C_{AB} = \frac{Q}{V_{AB}} = \frac{\pi\epsilon_0}{\ln \frac{d}{r}} \text{ F/m}$$

**Capacitance to neutral:** Above equation gives the capacitance between the conductors of a two wire line. Often it is desired to know the capacitance between one of the conductors and a neutral point between them. Since potential of the mid-point between the conductors is zero, the potential difference between each conductor and the ground or neutral is half the potential difference between the conductors. Thus the capacitance to ground or capacitance to neutral for the two wire line is twice the line-to-line capacitance.

$$C_N = C_{AN} = C_{BN} = 2C_{AB} = \frac{2\pi\epsilon_0}{\ln \frac{d}{r}}$$

### Capacitance of a 3-Phase Overhead Line

In a 3-phase transmission line, the capacitance of each conductor is considered instead of capacitance from conductor to conductor. Here, again two cases arise viz., symmetrical spacing and unsymmetrical spacing.

(i) **Symmetrical Spacing.** Fig. 1.8 shows the three conductors A, B and C of the 3-phase overhead transmission line having charges  $Q_A$ ,  $Q_B$  and  $Q_C$  per metre length respectively. Let the Conductors be equidistant ( $d$  metres) from each other. We shall find the capacitance from line conductor to neutral in this symmetrically spaced line. Referring to Fig.1.8 overall potential difference between conductor A and infinite neutral plane is given by

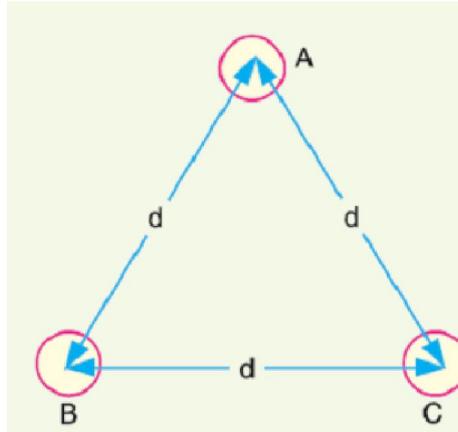


Fig 1.8 Three phase symmetrically spaced transmission line

$$V_A = \int_r^{\infty} \frac{Q_A}{2\pi\epsilon_0 x} dx + \int_d^{\infty} \frac{Q_B}{2\pi\epsilon_0 x} dx + \int_d^{\infty} \frac{Q_C}{2\pi\epsilon_0 x} dx$$

Assuming  $Q_A + Q_B + Q_C = 0$

$$V_A = \frac{Q_A}{2\pi\epsilon_0} \ln \frac{d}{r}$$

Capacitance of conductor A with respect to neutral

$$C_A = \frac{Q_A}{V_A} = \frac{2\pi\epsilon_0}{\ln \frac{d}{r}} \text{ F/m}$$

Note that this equation is identical to capacitance to neutral for two-wire line. Derived in a similar manner, the expressions for capacitance are the same for conductors B and C.

**(ii) Unsymmetrical spacing.** Fig.1.9 shows a 3-phase transposed line having unsymmetrical spacing. Let us assume balanced conditions i.e.  $Q_A + Q_B + Q_C = 0$ .

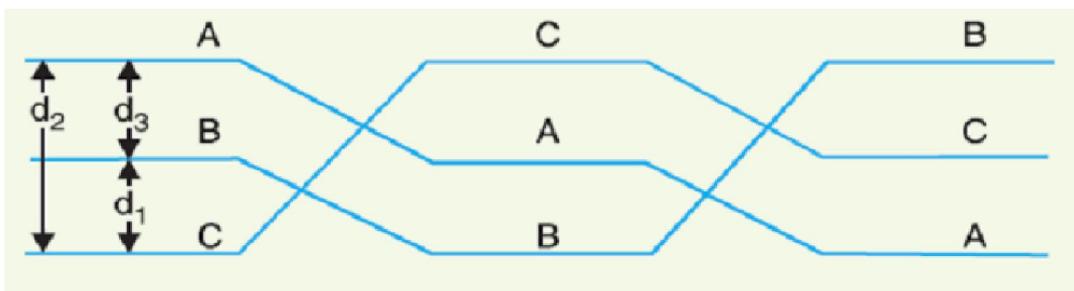


Fig 1.9: Unsymmetrically spaced transposed three phase line

$$V_A = \frac{Q_A}{2\pi\epsilon} \ln \frac{\sqrt[3]{d_1 d_2 d_3}}{r}$$

Capacitance from conductor to neutral is

$$C_A = \frac{Q_A}{V_A} = \frac{2\pi\epsilon_0}{\ln \frac{\sqrt[3]{d_1 d_2 d_3}}{r}}$$

### Performance of Transmission Line

The transmission lines are categorized as three types-

- 1) Short transmission line– the line length is up to 80 km and the operating voltage is < 20 kV.
- 2) Medium transmission line– the line length is between 80 km to 160 km and the operating voltage is > 20 kV and < 100kV
- 3) Long transmission line – the line length is more than 160 km and the operating voltage is > 100 kV

Whatever may be the category of transmission line, the main aim is to transmit power from one end to another. Like other electrical system, the transmission network also will have some power loss and voltage drop during transmitting power from sending end to receiving end. Hence, performance of transmission line can be determined by its efficiency and voltage regulation.

$$\text{Efficiency of transmission line} = \frac{\text{Power delivered at receiving end}}{\text{Power sent from sending end}} \times 100\%$$

Power sent from sending end – line losses = Power delivered at receiving end.

Voltage regulation of transmission line is measure of change of receiving end voltage from no-load to full load condition.

$$\% \text{ regulation} = \frac{\text{no load receiving end voltage} - \text{full load receiving end voltage}}{\text{full load voltage}} \times 100\%$$

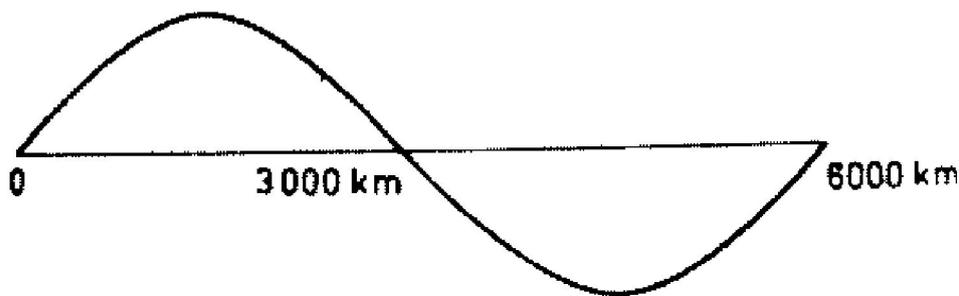
Every transmission line will have three basic electrical parameters. The conductors of the line will have electrical resistance, inductance, and capacitance. As the transmission line is a set of conductors being run from one place to another supported by transmission towers, the parameters are distributed uniformly along the line.

The electrical power is transmitted over a transmission line with a speed of light that is  $3 \times 10^8$  m/sec. Frequency of the power is 50 Hz. The wave length of the voltage and current of the power can be determined by the equation given below,

$f\lambda = v$  where  $f$  is power frequency, &  $\lambda$  is wave length and  $v$  is the speed of light.

$$\text{Therefore } \lambda = \frac{v}{f} = \frac{3 \times 10^8}{50} = 6 \times 10^6 \text{ meter} = 6000 \text{ km}$$

Hence the wave length of the transmitting power is quite long compared to the generally used line length of transmission line.



**Voltage distribution of 50 Hz supply**

For this reason, the transmission line, with length less than 160 km, the parameters are assumed to be lumped and not distributed. Such lines are known as electrically short transmission line. This electrically short transmission lines are again categorized as short transmission line (length up to 80 km) and medium transmission line (length between 80 and 160 km). The capacitive parameter of short transmission line is ignored whereas in case of medium length line the , capacitance is assumed to be lumped at the middle of the line or half of the capacitance may be considered to be lumped at each ends of the transmission line. Lines with length more than 160 km, the parameters are considered to be distributed over the line. This is called long transmission line.

## **TWO PORT NETWORK**

A major section of power system engineering deals in the transmission of electrical power from one particular place (e.g. generating station) to another like substations or distribution units with maximum efficiency. So it is of substantial importance for power system engineers to be thorough with its mathematical modeling. Thus the entire transmission system can be simplified to a **two port network** for the sake of easier calculations.

The circuit of a 2 port network is shown in the diagram below. As the name suggests, a 2 port network consists of an input port PQ and an output port RS. Each port has 2 terminals to connect itself to the external circuit. Thus it is essentially a 2 port or a 4 terminal circuit, having

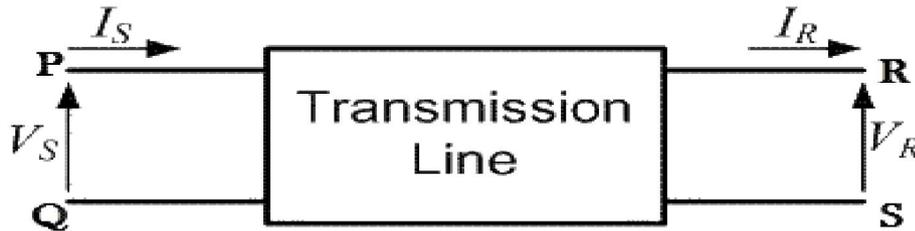


Fig 1.10: Representation of Two port network

Supply end voltage= $V_s$

Supply end current= $I_s$

Given to the input port P Q.

Receiving end voltage= $V_R$

Receiving end current= $I_R$

Given to the output port R S.

Now the **ABCD parameters** or the transmission line parameters provide the link between the supply and receiving end voltages and currents, considering the circuit elements to be linear in nature.

Thus the relation between the sending and receiving end specifications are given using **ABCD parameters** by the equations below.

$$V_s = AV_R + BI_R \quad (1)$$

$$I_s = CV_R + DI_R \quad (2)$$

Now in order to determine the ABCD parameters of transmission line let us impose the required circuit conditions in different cases.

### **ABCD Parameters (When Receiving End is Open Circuited)**

The receiving end is open circuited meaning receiving end current  $I_R = 0$ .

Applying this condition to equation (1) we get,

$$V_s = AV_R + B0$$

$$V_s = AV_R + 0$$

$$A = \frac{V_s}{V_R} (I_R = 0)$$

Thus it implies that on applying open circuit condition to ABCD parameters, we get parameter A as the ratio of sending end voltage to the open circuit receiving end voltage. Since dimension wise A is a ratio of voltage to voltage, A is a dimension less parameter.

Applying the same open circuit condition i.e.  $I_R = 0$  to equation (2)

$$I_s = CV_R + D0$$

$$I_s = CV_R + 0$$

$$C = \frac{I_s}{V_R} (I_R = 0)$$

Thus its implies that on applying open circuit condition to ABCD parameters of transmission line, we get parameter C as the ratio of sending end current to the open circuit receiving end voltage. Since dimension wise C is a ratio of current to voltage, its unit is mho.

Thus C is the open circuit conductance and is given by  $C = I_s/V_R$  mho.

### **ABCD Parameters (When Receiving End is Short Circuited)**

Receiving end is short circuited meaning receiving end voltage  $V_R = 0$

Applying this condition to equation (1) we get,

$$V_s = A0 + BI_R$$

$$V_s = 0 + BI_R$$

$$B = \frac{V_s}{I_R} (V_R = 0)$$

Thus its implies that on applying short circuit condition to ABCD parameters, we get parameter B as the ratio of sending end voltage to the short circuit receiving end current. Since dimension wise B is a ratio of voltage to current, its unit is  $\Omega$ . Thus B is the short circuit resistance and is given by

$$B = V_s/I_R \Omega.$$

Applying the same short circuit condition i.e.  $V_R = 0$  to equation (2) we get

$$I_s = C0 + DI_R$$

$$I_s = 0 + DI_R$$

$$D = \frac{I_s}{I_R} (V_R = 0)$$

Thus it implies that on applying short circuit condition to ABCD parameters, we get parameter D as the ratio of sending end current to the short circuit receiving end current. Since dimension wise D is a ratio of current to current, it's a dimension less parameter.

### Short Transmission Line

The transmission lines which have length less than 80 km are generally referred as **short transmission lines**.

For short length, the shunt capacitance of this type of line is neglected and other parameters like electrical resistance and inductor of these short lines are lumped, hence the equivalent circuit is represented as given below, Let's draw the vector diagram for this equivalent circuit, taking receiving end current  $I_r$  as reference. The sending end and receiving end voltages make angle with that reference receiving end current, of  $\phi_s$  and  $\phi_r$ , respectively.

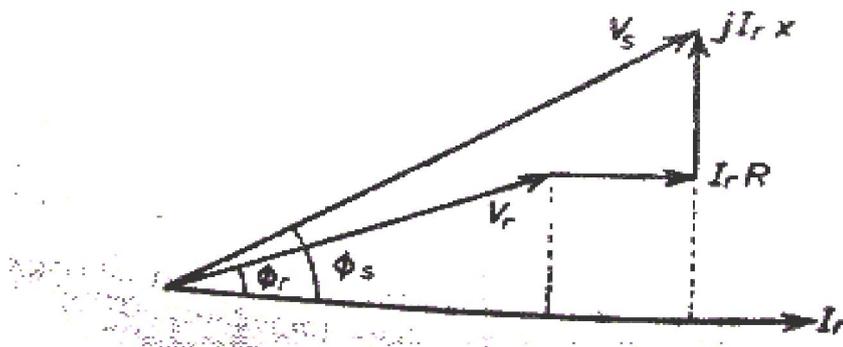
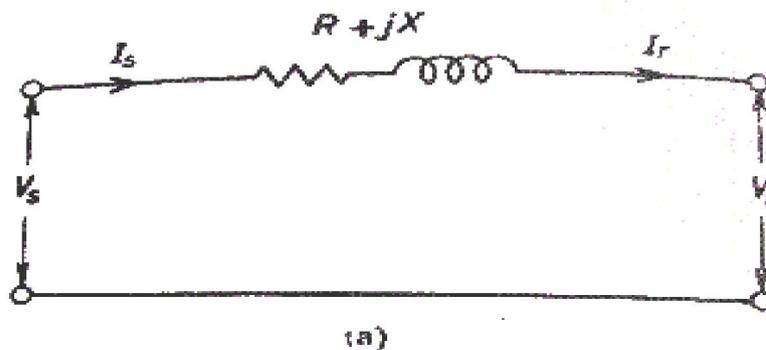


Fig.1.11 Representation of a short transmission line

As the shunt capacitance of the line is neglected, hence sending end current and receiving end current is same, i.e.

$$I_s = I_R.$$

Now if we observe the vector diagram carefully, we will get,

$V_s$  is approximately equal to

$$V_R + I_R \cdot R \cdot \cos\phi_R + I_R \cdot X \cdot \sin\phi_R$$

That means,

$$V_s \cong V_R + I_R \cdot R \cdot \cos\phi_R + I_R \cdot X \cdot \sin\phi_R \quad \text{as it is assumed that } \phi_s \cong \phi_R$$

As there is no capacitance, during no load condition the current through the line is considered as zero, hence at no load condition, receiving end voltage is the same as sending end voltage.

As per definition of voltage regulation of power transmission line,

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

$$= \frac{I_R R \cos\Phi_R + I_R X \sin\Phi_R}{V_R} \times 100\%$$

Any electrical network generally has two input terminals and two output terminals. If we consider any complex electrical network in a black box, it will have two input terminals and output terminals. This network is called two – port network. Two port model of a network simplifies the network solving technique. Mathematically a two port network can be solved by 2 by 2 matrix.

A transmission as it is also an electrical network; line can be represented as two port network.

Hence two port network of transmission line can be represented as 2 by 2 matrixes. Here the concept of ABCD parameters comes. Voltage and currents of the network can be represented as,

$$V_s = AV_R + BI_R$$

$$I_s = CV_R + DI_R$$

Where A, B, C and D are different constant of the network.

If we put  $I_R = 0$  at equation (1), we get,

$$A = \left( \frac{V_S}{V_R} \right)_{I_R=0}$$

Hence, A is the voltage impressed at the sending end per volt at the receiving end when receiving end is open. It is dimension less.

If we put  $V_R = 0$  at equation (1), we get

$$B = \left( \frac{V_S}{I_R} \right)_{V_R=0}$$

That indicates it is impedance of the transmission line when the receiving terminals are short circuited. This parameter is referred as transfer impedance.

$$C = \left( \frac{I_S}{V_R} \right)_{I_R=0}$$

C is the current in amperes into the sending end per volt on open circuited receiving end. It has the dimension of admittance.

$$D = \left( \frac{I_S}{I_R} \right)_{V_R=0}$$

D is the current in amperes into the sending end per amp on short circuited receiving end. It is dimensionless.

Now from equivalent circuit, it is found that,

$$V_S = V_R + I_R Z \text{ and } I_S = I_R$$

Comparing these equations with equation (1) and (2) we get,

$A = 1, B = Z, C = 0$  and  $D = 1$ . As we know that the constant  $A, B, C$  and  $D$  are related for passive network as,

$$AD - BC = 1.$$

Here,  $A = 1, B = Z, C = 0$  and  $D = 1$

$$\Rightarrow 1.1 - Z.0 = 1$$

So the values calculated are correct for short transmission line

From above equation (1),

$$V_s = AV_R + BI_R$$

When  $I_R = 0$  that means receiving end terminals is open circuited and then from the equation (1), we get receiving end voltage at no load.

$$V'_R = \frac{V_s}{A}$$

and as per definition of voltage regulation of power transmission line,

$$\% \text{ voltage regulation} = \frac{V_s / A - V_r}{V_r} \times 100 \%$$

### **Efficiency of Short Transmission Line**

The efficiency of short line as simple as efficiency equation of any other electrical equipment, that means

$$\% \text{ efficiency} = \frac{\text{Power received at receiving end}}{\text{Power received at receiving end} + 3I_R^2 R} \times 100$$

$R$  is per phase electrical resistance of the transmission line.

### Medium Transmission Line

The transmission line having its effective length more than 80 km but less than 250 km, is generally referred to as a **medium transmission line**. Due to the line length being considerably high, admittance  $Y$  of the network does play a role in calculating the effective circuit parameters, unlike in the case of short transmission lines. For this reason the modeling of a **medium length transmission line** is done using lumped shunt admittance along with the lumped impedance in series to the circuit.

These lumped parameters of a medium length transmission line can be represented using two different models, namely-

- 1) Nominal  $\Pi$  representation.
- 2) Nominal  $T$  representation.

Let's now go into the detailed discussion of these above mentioned models.

### Nominal $\Pi$ Representation of a Medium Transmission Line

In case of a nominal  $\Pi$  representation, the lumped series impedance is placed at the middle of the circuit where as the shunt admittances are at the ends. As we can see from the diagram of the  $\Pi$  network below, the total lumped shunt admittance is divided into 2 equal halves, and each half with value  $Y/2$  is placed at both the sending and the receiving end while the entire circuit impedance is between the two. The shape of the circuit so formed resembles that of a symbol  $\Pi$ , and for this reason it is known as the nominal  $\Pi$  representation of a medium transmission line. It is mainly used for determining the general circuit parameters and performing load flow analysis.

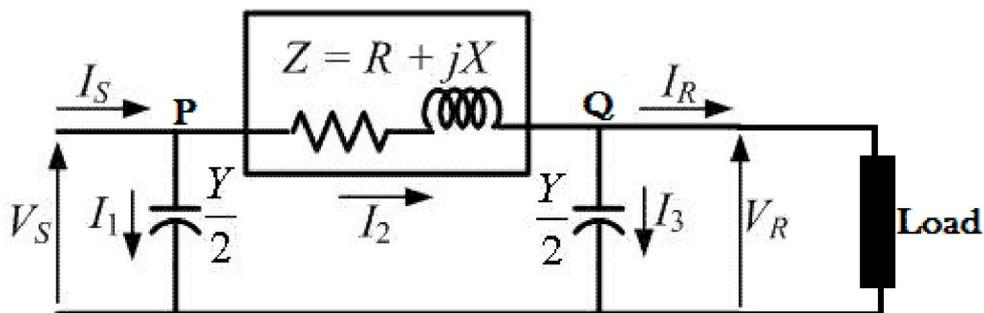


Fig.1.12: Nominal  $\Pi$  Representation of a Medium Transmission Line

As we can see here,  $V_S$  and  $V_R$  is the supply and receiving end voltages respectively, and  $I_S$  is the current flowing through the supply end.

$I_R$  is the current flowing through the receiving end of the circuit.

$I_1$  and  $I_3$  are the values of currents flowing through the admittances. And

$I_2$  is the current through the impedance  $Z$ .

Now applying KCL, at node P, we get

$$I_S = I_1 + I_2 \quad (1)$$

Similarly applying KCL, to node Q.

$$I_2 = I_3 + I_R \quad (2)$$

Now substituting equation (2) to equation (1)

$$\begin{aligned} I_S &= I_1 + I_3 + I_R \\ &= \frac{Y}{2}V_S + \frac{Y}{2}V_R + I_R \end{aligned} \quad (3)$$

Now by applying KVL to the circuit,

$$\begin{aligned} V_S &= V_R + ZI_2 \\ &= V_R + Z\left(V_R \frac{Y}{2} + I_R\right) \\ &= \left(Z \frac{Y}{2} + 1\right)V_R + ZI_R \end{aligned} \quad (4)$$

Now substituting equation (4) to equation (3), we get

$$\begin{aligned} I_S &= \frac{Y}{2} \left[ \left( \frac{Y}{2}Z + 1 \right) V_R + ZI_R \right] + \frac{Y}{2}V_R + I_R \\ &= Y \left( \frac{Y}{4}Z + 1 \right) V_R + \left( \frac{Y}{2}Z + 1 \right) I_R \end{aligned} \quad (5)$$

Comparing equation (4) and (5) with the standard ABCD parameter equations we derive the parameters of a medium transmission line as:

$$A = \left( \frac{Y}{2}Z + 1 \right)$$

$$B = Z$$

$$C = Y \left( \frac{Y}{4}Z + 1 \right)$$

$$D = \left( \frac{Y}{2}Z + 1 \right)$$

### Nominal T Representation of a Medium Transmission Line

In the **nominal T** model of a medium transmission line the lumped shunt admittance is placed in the middle, while the net series impedance is divided into two equal halves and placed on either side of the shunt admittance. The circuit so formed resembles the symbol of a capital **T**, and hence is known as the nominal T network of a medium length transmission line and is shown in the diagram below.

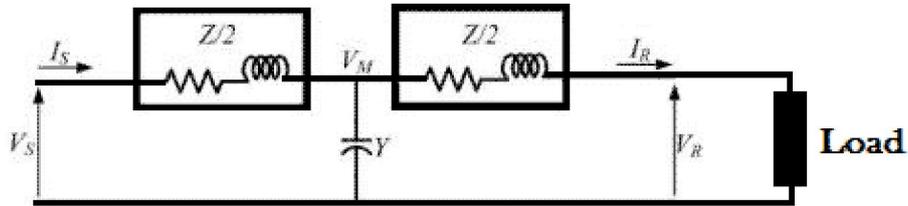


Fig.1.13: Nominal T representation of medium transmission line

Here also  $V_S$  and  $V_R$  is the supply and receiving end voltages respectively, and  $I_S$  is the current flowing through the supply end.

$I_R$  is the current flowing through the receiving end of the circuit.

Let M be a node at the midpoint of the circuit, and the drop at M, be given by  $V_M$ .

Applying KVL to the above network we get,

$$\frac{V_S - V_M}{Z/2} = YV_M + \frac{V_M - V_R}{Z/2} \quad (6)$$

$$V_M = \frac{2(V_S + V_R)}{YZ + 4}$$

And the receiving end current

$$I_R = \frac{2(V_M - V_R)}{Z/2} \quad (7)$$

Now substituting  $V_M$  from equation (6) to (7) we get

$$V_S = \left(\frac{Y}{2}Z + 1\right)V_R + Z\left(\frac{Y}{4}Z + 1\right)I_R \quad (8)$$

Now the sending end current is,

$$I_S = YV_M + I_R \quad (9)$$

Substituting the value of  $V_M$  to equation (9) we get,

$$I_S = YV_R + \left(\frac{Y}{2}Z + 1\right)I_R \quad (10)$$

Again comparing equation (8) and (10) with the standard ABCD parameter equations, the parameters of the **T** network of a medium transmission line are

$$A = \left(\frac{Y}{2}Z + 1\right)$$

$$B = Z\left(\frac{Y}{4}Z + 1\right)$$

$$C = Y$$

$$D = \left(\frac{Y}{2}Z + 1\right)$$

### **Long Transmission Line**

A power transmission line with its effective length of around 250 ms or above is referred to as a **long transmission line**. Calculations related to circuit parameters (ABCD parameters) of such a power transmission is not that simple, as was the case for a short transmission line or medium transmission line. The reason being that, the effective circuit length in this case is much higher than what it was for the former models (long and medium line) and, thus ruling out the approximations considered there like.

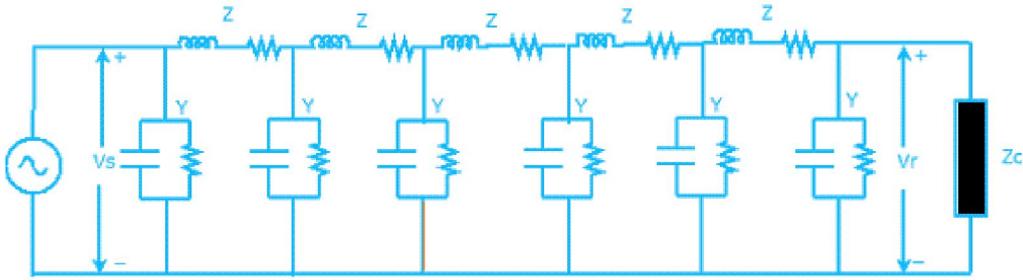


Fig.1.14: Long line model

- a) Ignoring the shunt admittance of the network, like in a small transmission line model.
- b) Considering the circuit impedance and admittance to be lumped and concentrated at a point as was the case for the medium line model.

Rather, for all practical reasons we should consider the circuit impedance and admittance to be distributed over the entire circuit length as shown in the figure below.

The calculations of circuit parameters for this reason are going to be slightly more rigorous as we will see here. For accurate modeling to determine circuit parameters let us consider the circuit of the **long transmission line** as shown in the diagram below.

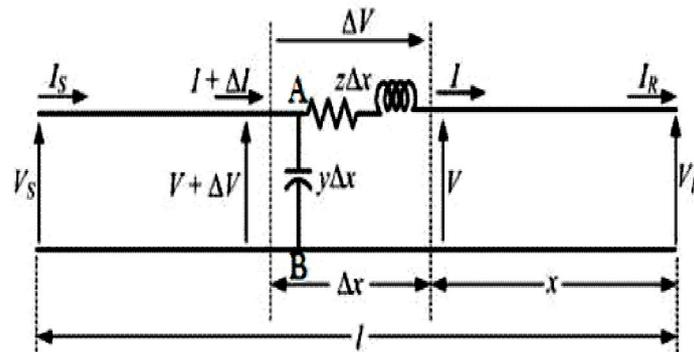


Fig.1.15: Modeling of long transmission line

Here a line of length  $l > 250\text{km}$  is supplied with a sending end voltage and current of  $V_s$  and  $I_s$  respectively, where as the  $V_r$  and  $I_r$  are the values of voltage and current obtained from the receiving end. Lets us now consider an element of infinitely small length  $\Delta x$  at a distance  $x$  from the receiving end as shown in the figure 1.15 where.

$V$  = value of voltage just before entering the element  $\Delta x$ .

$I$  = value of current just before entering the element  $\Delta x$ .

$V + \Delta V$  = voltage leaving the element  $\Delta x$ .

$I + \Delta I$  = current leaving the element  $\Delta x$ .

$\Delta V$  = voltage drop across element  $\Delta x$ .

$z\Delta x$  = series impedance of element  $\Delta x$

$y\Delta x$  = shunt admittance of element  $\Delta x$

Where  $Z = z l$  and  $Y = y l$  are the values of total impedance and admittance of the long transmission line.

Therefore, the voltage drop across the infinitely small element  $\Delta x$  is given by

$$\Delta V = I z \Delta x$$

Now to determine the current  $\Delta I$ , we apply KCL to node A.

$$\Delta I = (V + \Delta V) y \Delta x = V y \Delta x + \Delta V y \Delta x \quad (1)$$

Since the term  $\Delta V y \Delta x$  is the product of 2 infinitely small values, we can ignore it for the sake of easier calculation.

$$\text{Therefore, we can write } dI/dx = V y \quad (2)$$

Now derivating both sides of eqn (1) with respect to  $x$ ,

$$d^2 V/dx^2 = z dI/dx$$

Now substituting  $dI/dx = V y$  from equation (2)

$$d^2 V/dx^2 = zyV$$

$$\text{or } d^2 V/dx^2 - zyV = 0 \quad (3)$$

The solution of the above second order differential equation is given by.

$$V = A_1 e^{x\sqrt{yz}} + A_2 e^{-x\sqrt{yz}} \quad (4)$$

Derivating equation (4) w.r.to  $x$ .

$$dV/dx = \sqrt{(yz)} A_1 e^{x\sqrt{yz}} - \sqrt{(yz)} A_2 e^{-x\sqrt{yz}} \quad (5)$$

Now comparing equation (1) with equation (5)

$$I = \frac{dV}{dX} = \sqrt{\frac{y}{z}} A_1 e^{-X\sqrt{YZ}} \quad (6)$$

Now to go further let us define the characteristic impedance  $Z_c$  and propagation constant  $\delta$  of a long transmission line as

$$Z_c = \sqrt{(z/y)} \Omega$$

$$\delta = \sqrt{(yz)}$$

Then the voltage and current equation can be expressed in terms of characteristic impedance and propagation constant as

$$V = A_1 e^{\delta x} + A_2 e^{-\delta x} \quad (7)$$

$$I = A_1 / Z_c e^{\delta x} + A_2 / Z_c e^{-\delta x} \quad (8)$$

Now at  $x=0$ ,  $V = V_R$  and  $I = I_R$ . Substituting these conditions to equation (7) and (8) respectively.

$$V_R = A_1 + A_2 \quad (9)$$

$$I_R = A_1 / Z_c + A_2 / Z_c \quad (10)$$

Solving equation (9) and (10),

We get values of  $A_1$  and  $A_2$  as,

$$A_1 = (V_R + Z_c I_R) / 2$$

$$\text{And } A_2 = (V_R - Z_c I_R) / 2$$

Now applying another extreme condition at  $x=l$ , we have  $V = V_S$  and  $I = I_S$ .

Now to determine  $V_S$  and  $I_S$  we substitute  $x$  by  $l$  and put the values of  $A_1$  and

$A_2$  in equation (7) and (8) we get

$$V_S = (V_R + Z_c I_R) e^{\delta l} / 2 + (V_R - Z_c I_R) e^{-\delta l} / 2 \quad (11)$$

$$I_S = (V_R / Z_c + I_R) e^{\delta l} / 2 - (V_R / Z_c - I_R) e^{-\delta l} / 2 \quad (12)$$

By trigonometric and exponential operators we know

$$\sinh \delta l = (e^{\delta l} - e^{-\delta l}) / 2$$

$$\text{And } \cosh \delta l = (e^{\delta l} + e^{-\delta l}) / 2$$

Therefore, equation(11) and (12) can be re-written as

$$V_S = V_R \cosh \delta l + Z_c I_R \sinh \delta l$$

$$I_S = (V_R \sinh \delta l) / Z_c + I_R \cosh \delta l$$

Thus comparing with the general circuit parameters equation, we get the ABCD parameters of a long transmission line as,

$$A = \cosh \delta l$$

$$B = Z_c \sinh \delta l$$

$$C = \sinh \delta l / Z_C$$

$$D = \cosh \delta l$$

## **Skin Effect**

The phenomena arising due to unequal distribution of current over the entire cross section of the conductor being used for long distance power transmission is referred as the skin effect in transmission lines. Such a phenomena does not have much role to play in case of a very short line, but with increase in the effective length of the conductors, skin effect increases considerably. So the modifications in line calculation needs to be done accordingly. The distribution of current over the entire cross section of the conductor is quite uniform in case of a DC system. But what we are using in the present era of power system engineering is predominantly an alternating current system, where the current tends to flow with higher density through the surface of the conductors (i.e. skin of the conductor), leaving the core deprived of necessary number of electrons. In fact there even arises a condition when absolutely no current flows through the core, and concentrating the entire amount on the surface region, thus resulting in an increase in the effective electrical resistance of the conductor. This particular trend of an AC transmission system to take the surface path for the flow of current depriving the core is referred to as the skin effect in transmission lines.

## **Why Skin Effect Occurs in Transmission Lines?**

Having understood the phenomena of **skin effect** let us now see why this arises in case of an AC system. To have a clear understanding of that look into the cross sectional view of the conductor during the flow of alternating current given in the diagram below.

Let us initially consider the solid conductor to be split up into a number of annular filaments spaced infinitely small distance apart, such that each filament carries an infinitely small fraction of the total current.

Like if the total current = I

Let us consider the conductor to be split up into  $n$  filament carrying current ' $i$ ' such that  $I = ni$  .

Now during the flow of an alternating current, the current carrying filaments lying on the core has a flux linkage with the entire conductor cross section including the filaments of the surface as well as those in the core. Whereas the flux set up by the outer filaments is restricted only to the surface itself and is unable to link with the inner filaments. Thus the flux linkage of the conductor increases as we move closer towards the core and at the same rate increases the inductor as it has a direct proportionality relationship with flux linkage. This results in a larger inductive reactance being induced into the core as compared to the outer sections of the conductor. The high value of reactance in the inner section results in the current being distributed in an un-uniform manner and forcing the bulk of the current to flow through the outer surface or skin giving rise to the phenomena called **skin effect in transmission lines**.

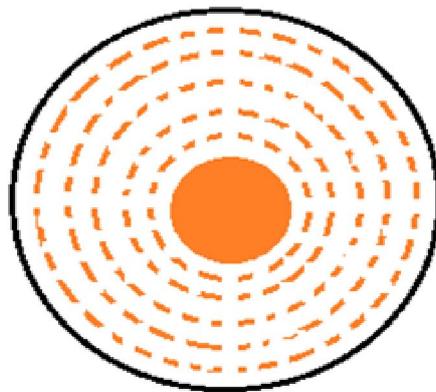


Fig.1.16: Current distribution in a conductor

### **Factors Affecting Skin Effect in Transmission Lines**

The skin effect in an ac system depends on a number of factors like:-

- 1) Shape of conductor.
- 2) Type of material.
- 3) Diameter of the conductors.
- 4) Operational frequency.

**Proximity Effect:**

Proximity means nearness in space or time, so as the name suggests, proximity effect in transmission lines indicates the effect in one conductor for other neighbouring conductors. When the alternating current is flowing through a conductor, alternating magnetic flux is generated surrounding the conductor. This magnetic flux associates with the neighbouring wires and generates a circulating current (it can be termed as 'eddy current' also). This circulating current increases the resistance of the conductor and push away the flowing current through the conductor, which causes the crowding effect.

When the gaps between two wires are greater the proximity effect is less and it rises when the gap reduces. The flux due to central conductor links with right side conductor. In a two wire system more lines of flux link elements farther apart than the elements nearest to each other as shown above. Therefore, the inductance of the elements farther apart is more as compared to the elements near to each other and hence the current density is less in the elements farther apart than the current density in the element near to each other. As a result the effective resistance of the conductor is increased due to non uniform distribution of current. This phenomenon is actually referred as proximity effect. This effect is pronounced in the case of cables where the distance between the conductor is small whereas proximity effect in transmission lines in the case of overhead system, with usual spacing is negligibly small.

**Series and shunt compensation:**

The demand of active power is expressing Kilo watt (kw) or mega watt (mw). This power should be supplied from electrical generating station. All the arrangements in electrical pomes system are done to meet up this basic requirement. Although in alternating power system, reactive power always comes in to picture. This reactive power is expressed in Kilo VAR or Mega VAR. The demand of this reactive power is mainly originated from inductive load connected to the system. These inductive loads are generally electromagnetic circuit of electric motors, electrical transformers, inductance of transmission and distribution networks, induction furnaces, fluorescent lightings etc. This reactive power should be properly compensated otherwise, the

ratio of actual power consumed by the load, to the total power i.e. vector sum of active and reactive power, of the system becomes quite less. This ratio is alternatively known as electrical power factor, and fewer ratios indicates poor power factor of the system. If the power factor of the system is poor, the ampere burden of the transmission, distribution network, transformers, alternators and other equipments connected to the system, becomes high for required active power. And hence reactive power compensation becomes so important. This is commonly done by capacitor bank.

Let's explain in details,

we know that active power is expressed  $=VI\cos\theta$

where,  $\cos\theta$  is the power factor of the system. Hence, if this power factor has got less value, the corresponding current (I) increases for same active power P.

As the current of the system increases, the ohmic loss of the system increases. Ohmic loss means, generated electrical power is lost as unwanted heat originated in the system. The cross-section of the conducting parts of the system may also have to be increased for carrying extra ampere burden, which is also not economical in the commercial point of view. Another major disadvantage, is poor voltage regulation of the system, which mainly caused due to poor power factor.

The equipments used to compensate reactive power.

There are mainly two equipments used for this purpose.

**(1)** Synchronous condensers

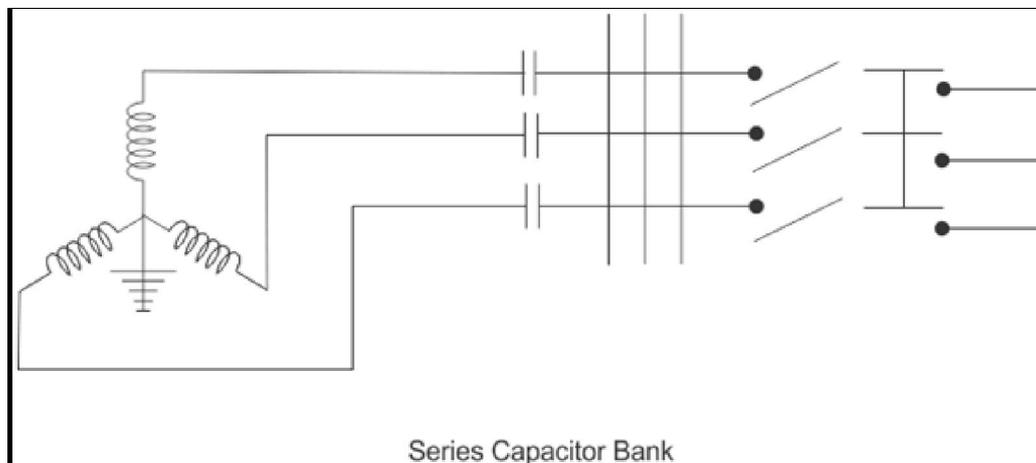
**(2)** Static capacitors or Capacitor Bank

Synchronous condensers, can produce reactive power and the production of reactive power can be regulated. Due to this regulating advantage, the synchronous condensers are very suitable for correcting power factor of the system, but this equipment is quite expensive compared to static capacitors. That is why synchronous condensers, are justified to use only for voltage regulation of very high voltage transmission system. The regulation in static capacitors can also be achieved to some extent by split the total capacitor bank in 3 sectors of ratio 1: 2:2. This division enables

the capacitor to run in 1, 2, 1+2=3, 2+2=4, 1+2+2=5 steps. If still further steps are required, the division may be made in the ratio 1:2:3 or 1:2:4. These divisions make the static capacitor bank more expensive but still the cost is much lower than synchronous condensers. It is found that maximum benefit from compensating equipments can be achieved when they are connected to the individual load side. This is practically and economically possible only by using small rated capacitors with individual load not by using synchronous condensers. Static capacitor Bank.

Static capacitor can further be subdivided into two categories,

- (a) Shunt capacitors
- (b) Series capacitor



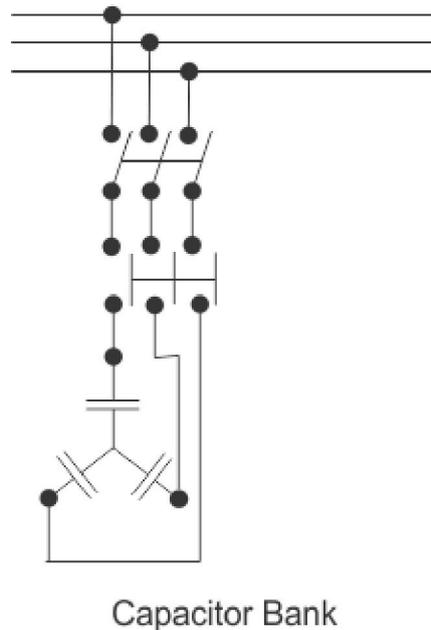


Fig.1.17: Series and Shunt Capacitor bank

These categories are mainly based on the methods of connecting capacitor bank with the system. Among these two categories, shunt capacitors are more commonly used in the power system of all voltage levels. There are some specific advantages of using shunt capacitors such as,

- a) It reduces line current of the system.
- b) It improves voltage level of the load.
- c) It also reduces system Losses.
- d) It improves power factor of the source current.
- e) It reduces load of the alternator.
- f) It reduces capital investment per mega watt of the Load.

All the above mentioned benefits come from the fact, that the effect of capacitor reduces reactive current flowing through the whole system. Shunt capacitor draws almost fixed amount of leading current which is superimposed on the load current and consequently reduces reactive components of the load and hence improves the power factor of the system. series capacitor on the other hand has no control over flow of current. As these are connected in series with load , the load current always passes through the series capacitor bank. Actually, the

capacitive reactance of series capacitor neutralizes the inductive reactance of the line hence, reduces, effective reactance of the line. Thereby, voltage regulation of the system is improved. But series capacitor bank has a major disadvantage. During faulty condition, the voltage across the capacitor maybe raised up to 15 times more than its rated value. Thus series capacitor must have sophisticated and elaborate protective equipments. Because of this, use of-series capacitor is confined in the extra high voltage system only.

## MODULE II

### Corona

When an alternating potential difference is applied across two conductors whose spacing is large as compared to their diameters, there is no apparent change in the condition of atmospheric air surrounding the wires if the applied voltage is low. However, when the applied voltage exceeds a certain value, called critical disruptive voltage, the conductors are surrounded by a faint violet glow called corona.

The phenomenon of corona is accompanied by a hissing sound, production of ozone, power loss and radio interference. Electric power transmission practically deals in the bulk transfer of electrical energy, from generating stations situated many kilometers away from the main consumption centers or the cities. For this reason the long distance transmission cables are of utmost necessity for effective power transfer, which in-evidently results in huge losses across the system. Minimizing those has been a major challenge for power engineers of late and to do that one should have a clear understanding of the type and nature of losses. One of them being the **corona effect in power system**, which has a predominant role in reducing the efficiency of EHV(extra high voltage lines) which we are going to concentrate on, in this article. When an alternating current is made to flow across two conductors of the transmission line whose spacing is large compared to their diameters, then air surrounding the conductors (composed of ions) is subjected to dielectric stress. At low values of supply end voltage, nothing really occurs as the stress is too less to ionize the air outside. But when the potential difference is made to increase beyond some threshold value of around 30 kV known as the **critical disruptive voltage**, then the field strength increases and then the air surrounding it experiences stress high enough to be dissociated into ions making the atmosphere conducting. This results in electric discharge around the conductors due to the flow of these ions, giving rise to a faint luminescent glow, along with the hissing sound accompanied by the liberation of ozone, which is readily identified due to its characteristic odor. This phenomenon of electrical discharge occurring in transmission line for high values of voltage is known as the **corona effect in power system**. If the voltage across the lines is still increased the glow becomes more and more intense along with hissing noise, inducing very high power loss into the system which must be accounted for.

## **Factors Affecting Corona Effect in Power System**

As mentioned earlier, the line voltage of the conductor is the main determining factor for corona in transmission lines, at low values of voltage (lesser than critical disruptive voltage) the stress on the air is too less to dissociate them, and hence no electrical discharge occurs. Since with increasing voltage corona effect in a transmission line occurs due to the ionization of atmospheric air surrounding the cables, it is mainly affected by the conditions of the cable as well as the physical state of the atmosphere. Let us look into these criterion now with greater details :

### **Atmospheric Conditions for Corona in Transmission Lines**

It has been physically proven that the voltage gradient for di-electric breakdown of air is directly proportional to the density of air. Hence in a stormy day, due to continuous air flow the number of ions present surrounding the conductor is far more than normal, and hence its more likely to have electrical discharge in transmission lines on such a day, compared to a day with fairly clear weather. The system has to designed taking those extreme situations into consideration.

### **Condition of Cables for Corona in Transmission Line.**

This particular phenomena depends highly on the conductors and its physical condition. It has an inverse proportionality relationship with the diameter of the conductors. i.e. with the increase in diameter, the effect of corona in power system reduces considerably.

Also the presence of dirt or roughness of the conductor reduces the critical breakdown voltage, making the conductors more prone to corona losses. Hence in most cities and industrial areas having high pollution, this factor is of reasonable importance to counter the ill effects it has on the system.

### **Spacing between Conductors**

As already mentioned, for corona to occur effectively the spacing between the lines should be much higher compared to its diameter, but if the length is increased beyond a certain limit, the

dielectric stress on the air reduces and consequently the effect of corona reduces as well. If the spacing is made too large then corona for that region of the transmission line might not occur at all.

**Important Terms:**

The phenomenon of corona plays an important role in the design of an overhead transmission line. Therefore, it is profitable to consider the following terms much used in the analysis of corona effects:

**(i) Critical Disruptive Voltage:** It is the minimum phase-neutral voltage at which corona occurs. Consider two conductors of radii  $r$  cm and spaced  $d$  cm apart. If  $V$  is the phase-neutral potential, then potential gradient at the conductor surface is given by:

$$g = \frac{V}{r \ln \frac{d}{r}} \text{ Volts/cm}$$

In order that corona is formed, the value of  $g$  must be made equal to the breakdown strength of air. The breakdown strength of air at 76 cm pressure and temperature of 25°C is 30 kV/cm (max) or 21.2 kV/cm (r.m.s.) and is denoted by  $g_0$ . If  $V_c$  is the phase-neutral potential required under these conditions, then,

$$g_0 = \frac{V_c}{r \ln \frac{d}{r}}$$

where  $g_0$  = breakdown strength of air at 76 cm of mercury and 25°C  
 = 30 kV/cm (max) or 21.2 kV/cm (r.m.s.)

∴ Critical disruptive voltage,  $V_c = g_0 r \ln \frac{d}{r}$

The above expression for disruptive voltage is under standard conditions i.e. at 76 cm of Hg and 25°C. However, if these conditions vary, the air density also changes, thus altering the value

of  $g_0$ . The value of  $g_0$  is directly proportional to air density. Thus the breakdown strength of air at a barometric pressure of  $b$  cm of mercury and temperature of  $t^\circ\text{C}$  becomes  $\delta g_0$  where

$$\delta = \text{air density factor} = \frac{3.92}{273 + t}$$

Under standard conditions, the value of  $\delta = 1$ .

$$\text{Critical disruptive voltage, } V_c = g_0 \delta r \ln \frac{d}{r}$$

Correction must also be made for the surface condition of the conductor. This is accounted for by multiplying the above expression by irregularity factor  $m_0$ .

$$\text{Critical disruptive voltage, } V_c = g_0 \delta m_0 r \ln \frac{d}{r} \text{ kV/phase}$$

where

$m_0 = 1$  for polished conductors

$= 0.98$  to  $0.92$  for dirty conductors

$= 0.87$  to  $0.8$  for stranded conductors

### (ii) Visual critical voltage

It is the minimum phase-neutral voltage at which corona glow appears all along the line conductors.

It has been seen that in case of parallel conductors, the corona glow does not begin at the disruptive voltage  $V_c$  but at a higher voltage  $V_v$ , called **visual critical voltage**. The phase-neutral effective value of visual critical voltage is given by the following empirical formula

$$V_v = m_v g_0 \delta r \left(1 + \frac{0.3}{\sqrt{\delta r}}\right) \ln \frac{d}{r} \text{ kV/phase}$$

where  $m_v$  is another irregularity factor having a value of  $1.0$  for polished conductors and  $0.72$  to  $0.82$  for rough conductors.

**(iii) Power loss due to corona** Formation of corona is always accompanied by energy loss which is dissipated in the form of light, heat, sound and chemical action. When disruptive voltage is exceeded, the power loss due to corona is given by:

$$P = 241 \times 10^{-5} \left(\frac{f + 25}{\delta}\right) \sqrt{\frac{r}{d}} (V - V_c)^2 \text{ kw/km/phase}$$

## **Advantages and Disadvantages of Corona**

Corona has many advantages and disadvantages. In the correct design of a high voltage overheadline, a balance should be struck between the advantages and disadvantages.

Below are the Advantages and disadvantages of Corona.

### **Advantages**

- Due to corona formation, the air surrounding the conductor becomes conducting and hence virtual diameter of the conductor is increased. The increased diameter reduces the electrostatic stresses between the conductors.
- Corona reduces the effects of transients produced by surges.

### **Disadvantages**

- Corona is accompanied by a loss of energy. This affects the transmission efficiency of the line.
- Ozone is produced by corona and may cause corrosion of the conductor due to chemical action.
- The current drawn by the line due to corona is non-sinusoidal and hence non-sinusoidal Voltage drop occurs in the line. This may cause inductive interference with neighboring Communication lines.

## **Methods to reduce Corona Discharge Effect**

Corona can be avoided

1. **By minimizing the voltage stress and electric field gradient.:** This is accomplished by using utilizing good high voltage design practices, i.e., maximizing the distance between conductors that have large voltage differentials, using conductors with large radii, and avoiding parts that have sharp points or sharp edges.
2. **Surface Treatments:** Corona inception voltage can sometimes be increased by using a surface treatment, such as a semiconductor layer, high voltage putty or corona dope.
3. **Homogenous Insulators:** Use a good, homogeneous insulator. Void free solids, such as properly prepared silicone and epoxy potting materials work well.

4. **If you are limited to using air as your insulator**, then you are left with geometry as the critical parameter. Finally, ensure that steps are taken to reduce or eliminate unwanted voltage transients, which can cause corona to start.
5. **Using Bundled Conductors:** on our 345 kV lines, we have installed multiple conductors per phase. This is a common way of increasing the effective diameter of the conductor, which in turn results in less resistance, which in turn reduces losses.
6. **Elimination of sharp points:** electric charges tend to form on sharp points; therefore when practicable we strive to eliminate sharp points on transmission line components.
7. **Using Corona rings:** On certain new 345 kV structures, we are now installing corona rings. These rings have smooth round surfaces which are designed to distribute charge across a wider area, thereby reducing the electric field and the resulting corona discharges.
8. **Whether:** Corona phenomena much worse in foul weather, high altitude
9. **New Conductor:** New conductors can lead to poor corona performance for a while.
10. **By increasing the spacing between the conductors:** Corona Discharge Effect can be reduced by increasing the clearance spacing between the phases of the transmission lines. However increase in the phase's results in heavier metal supports. Cost and Space requirement increases.
11. **By increasing the diameter of the conductor:** Diameter of the conductor can be increased to reduce the corona discharge effect. By using hollow conductors corona discharge effect can be improved.

## **Insulators**

**Electrical Insulator** must be used in electrical system to prevent unwanted flow of current to the earth from its supporting points. The **insulator** plays a vital role in electrical system. **Electrical Insulator** is a very high resistive path through which practically no current can flow. In transmission and distribution system, the overhead conductors are generally supported by supporting towers or poles. The towers and poles both are properly grounded. So there must be **insulator** between tower or pole body and current carrying conductors to prevent the flow of current from conductor to earth through the grounded supporting towers or poles.

## **Insulating Material**

The main cause of failure of overhead line insulator, is flash over, occurs in between line and earth during abnormal over voltage in the system. During this flash over, the huge heat produced by arcing, causes puncher in insulator body. Viewing this phenomenon the materials used for electrical insulator, has to possess some specific properties.

### **Properties of Insulating Material**

The materials generally used for insulating purpose is called **insulating material**. For successful utilization, this material should have some specific properties as listed below-

1. It must be mechanically strong enough to carry tension and weight of conductors.
2. It must have very high dielectric strength to withstand the voltage stresses in High Voltage system.
3. It must possess high Insulation Resistance to prevent leakage current to the earth.
4. The **insulating material** must be free from unwanted impurities.
5. It should not be porous.
6. There must not be any entrance on the surface of electrical insulator so that the moisture or gases can enter in it.
7. There physical as well as electrical properties must be less affected by changing temperature.

There are mainly three **types of insulator** used as **overhead insulator** likewise

1. **Pin Insulator**
2. **Suspension Insulator**
3. **Strain Insulator**

In addition to that there are other two **types of electrical insulator** available mainly for low voltage application i.e. **Stray Insulator** and **Shackle Insulator**.

#### **Pin Insulator**

**Pin Insulator** is earliest developed **overhead insulator**, but still popularly used in power network up to 33KV system. Pin type insulator can be one part, two parts or three parts type, depending upon application voltage. In 11KV system we generally use one part type insulator where whole pin insulator is one piece of properly shaped porcelain or glass. As the leakage path

of insulator is through its surface, it is desirable to increase the vertical length of the insulator surface area for lengthening leakage path. In order to obtain lengthy leakage path, one, tower or more rain sheds or petticoats are provided on the insulator body. In addition to that rain shed or petticoats on an insulator serve another purpose. These rain sheds or petticoats are so designed, that during raining the outer surface of the rain shed becomes wet but the inner surface remains dry and non-conductive. So there will be discontinuations of conducting path through the wet pin insulator surface.

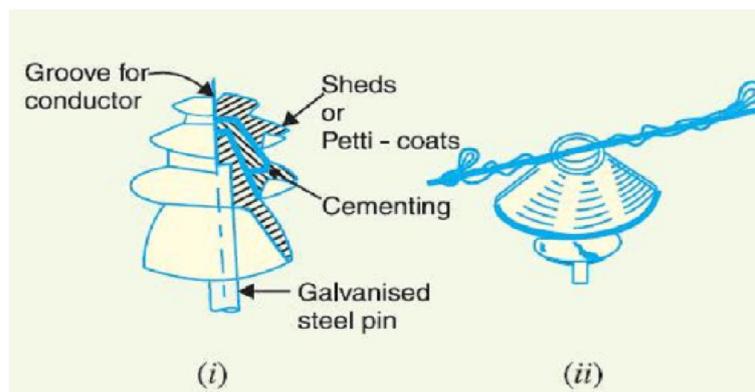


Fig 2.1- Pin Insulator

In higher **voltage** like 33KV and 66KV manufacturing of one part porcelain pin insulator becomes difficult. Because in higher voltage, the thickness of the insulator become more and a quite thick single piece porcelain insulator cannot manufactured practically. In this case we use multiple part pin insulator, where a number of properly designed porcelain shells are fixed together by Portland cement to form one complete insulator unit. For 33KV tow parts and for 66KV three parts pin insulator are generally used.

### Designing Consideration of Electrical Insulator

The live conductor attached to the top of the pin insulator is at a potential and bottom of the insulator fixed to supporting structure of earth potential. The insulator has to withstand the potential stresses between conductor and earth. The shortest distance between conductor and earth, surrounding the insulator body, along which electrical discharge may take place through air, is known as flash over distance.

1. When insulator is wet, its outer surface becomes almost conducting. Hence the flash over distance of insulator is decreased. The design of an electrical insulator should be such that the decrease of flash over distance is minimum when the insulator is wet. That is why the upper most petticoat of a pin insulator has umbrella type designed so that it can protect, the rest lower part of the insulator from rain. The upper surface of top most petticoat is inclined as less as possible to maintain maximum flash over voltage during raining.

2. To keep the inner side of the insulator dry, the rain sheds are made in order that these rain sheds should not disturb the voltage distribution they are so designed that their subsurface at right angle to the electromagnetic lines of force.

### **Suspension Insulator**

In higher voltage, beyond 33KV, it becomes uneconomical to use pin insulator because size, weight of the insulator become more. Handling and replacing bigger size single unit insulator are quite difficult task. For overcoming these difficulties, **suspension insulator** was developed. In **suspension insulator** numbers of insulators are connected in series to form a string and the line conductor is carried by the bottom most insulator. Each insulator of a suspension string is called disc insulator because of their disc like shape.

### **Advantages of Suspension Insulator**

- (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 any one 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.

### **Disadvantages of Suspension Insulator**

1. Suspension insulator string costlier than pin and post type insulator.
2. Suspension string requires more height of supporting structure than that for pin or post insulator to maintain same ground clearance of current conductor.
3. The amplitude of free swing of conductors is larger in suspension insulator system, hence, more spacing between conductors should be provided.

### **Strain Insulator**

When suspension string is used to sustain extraordinary tensile load of conductor it is referred as **string insulator**. When there is a dead end or there is a sharp corner in transmission line, the line has to sustain a great tensile load of conductor or strain. A **strain insulator** must have considerable mechanical strength as well as the necessary electrical insulating properties.

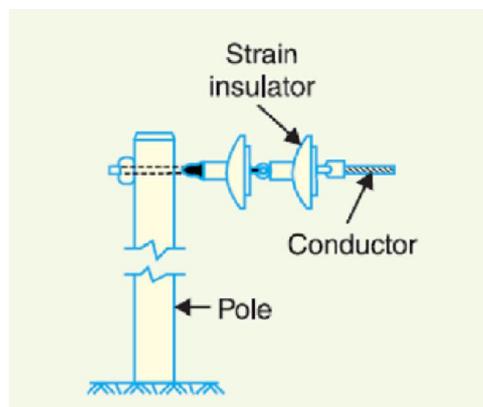


Fig 2.2- Strain Insulator

### **Shackle Insulator or Spool Insulator**

The **shackle insulator** or **spool insulator** is usually used in low voltage distribution network. It can be used both in horizontal and vertical position. The use of such insulator has decreased recently after increasing the using of underground cable for distribution purpose. The tapered hole of the **spool insulator** distributes the load more evenly and minimizes the possibility of breakage when heavily loaded. The conductor in the groove of **shackle insulator** is fixed with the help of soft binding wire.

### **POTENTIAL DISTRIBUTION OVER A STRING OF SUSPENSION INSULATORS:**

A string of suspension insulators consists of a number of porcelain discs connected in series through metallic links. Fig. 2.3(i) shows 3-disc string of suspension insulators. The porcelain portion of each disc is in between two metal links. Therefore, each disc forms a capacitor  $C$  as shown in Fig.2.3(ii). This is known as mutual capacitance or self-capacitance. If there were mutual capacitance alone, then charging current would have been the same through all the discs and consequently voltage across each unit would have been the same i.e.,  $V/3$  as shown in Fig. 2.3(ii). However, in actual practice, capacitance also exists between metal fitting of each disc and tower or earth. This is known as shunt capacitance  $C_1$ . Due to shunt capacitance, charging current is not the same through all the discs of the string [See Fig 2.3(iii)]. Therefore, voltage across each disc will be different. Obviously, the disc nearest to the line conductor will have the maximum voltage. Thus referring to Fig 2.3(iii),  $V_3$  will be much more than  $V_2$  or  $V_1$ .

The following points may be noted regarding the potential distribution over a string of suspension insulators:

- (i) The voltage impressed on a string of suspension insulators does not distribute itself uniformly across the individual discs due to the presence of shunt capacitance.
- (ii) The disc nearest to the conductor has maximum voltage across it. As we move towards the cross-arm, the voltage across each disc goes on decreasing.
- (iii) The unit nearest to the conductor is under maximum electrical stress and is likely to be punctured. Therefore, means must be provided to equalize the potential across each unit.

(iv) The presence of stray capacitance causes unequal potential distribution over the string. The end unit of the string (which is the closest to the line) takes maximum potential difference and the upper units have a gradually decreased potential difference until the uppermost unit which has the lowest potential difference. The next proof illustrates this concept.

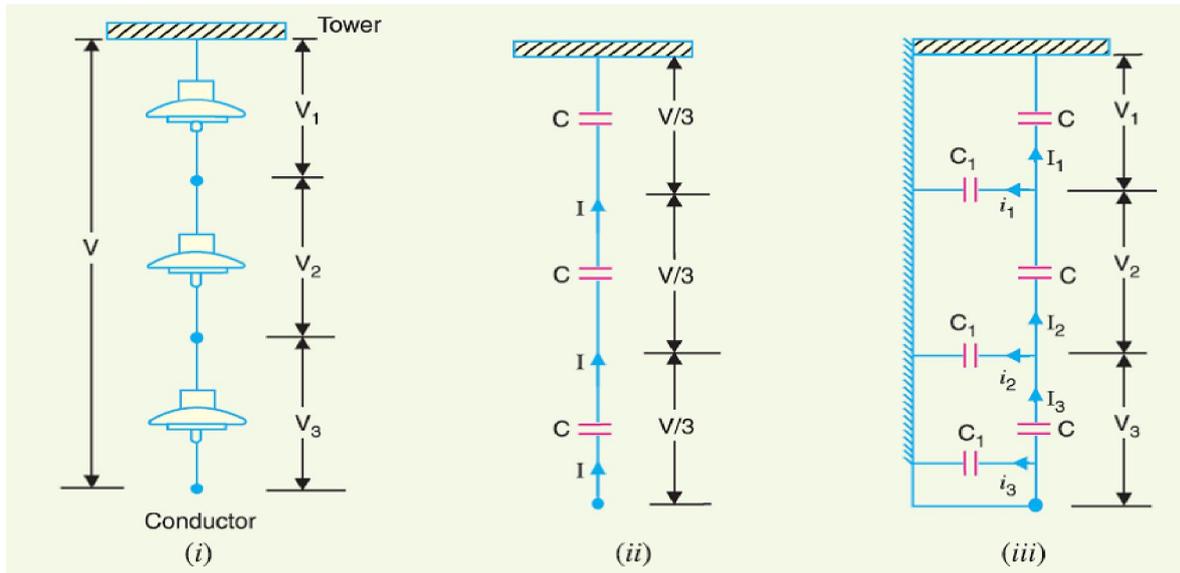


Fig 2.3- Suspension Insulator string

**String Efficiency:**

As stated above, 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 i.e.

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

Where n is the no. 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.** Fig. 2.3(iii) 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  $C_1$  is some fraction  $K$  of self capacitance i.e.,  $C_1 = KC$ . Starting from the cross-arm or tower, the voltage across each unit is  $V_1, V_2$  and  $V_3$  respectively as shown.

Applying kirchoff's current law to node A

$$I_2 = I_1 + i_1$$

$$V_2 \omega C = V_1 \omega C + V_1 \omega C_1$$

$$V_2 \omega C = V_1 \omega C + V_1 \omega KC$$

$$V_2 = V_1(1 + K)$$

Applying kirchoff's current law to node B

$$I_3 = I_2 + i_2$$

$$V_3 \omega C = V_2 \omega C + (V_1 + V_2) \omega C_1$$

$$V_3 \omega C = V_2 \omega C + (V_1 + V_2) \omega KC$$

$$V_3 = KV_1 + V_2(1 + K)$$

$$V_3 = V_1(1 + 3K + K^2)$$

$$\%string\ efficiency = \frac{V}{3 \times V_3} \times 100$$

The following points may be noted from the above mathematical analysis:

- (i) If  $K = 0.2$  (Say), then we get,  $V_2 = 1.2 V_1$  and  $V_3 = 1.64 V_1$ . 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  $K (= C_1/C)$ , 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

### **String Efficiency and methods to improve 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 i.e.,

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

where  $n$  = 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.

### **Methods of Improving String Efficiency**

The maximum voltage appears across the insulator nearest to the line conductor and decreases equalise the potential across the various units of the string i.e. to improve the string efficiency 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.

The various methods for improving the string efficiency are:

1. **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.
2. **By grading the 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 equalise 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.

3. **By using a guard ring.** The potential across each unit in a string can be equalised by using a guard ring which is a metal ring electrically connected to the conductor and surrounding the bottom insulator. The guard ring introduces capacitance between metal fittings and the line conductor. The guard ring is contoured in such a way that shunt capacitance currents  $i_1$ ,  $i_2$  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.

### **Conductor Material**

The most common conductor in use for transmission today is aluminum conductor steel reinforced (ACSR). Also seeing much use is all-aluminum-alloy conductor (AAAC). Aluminum is used because it has about half the weight of a comparable resistance copper cable (though larger diameter due to lower fundamental conductivity), as well as being cheaper. Copper was more popular in the past and is still in use, especially at lower voltages and for grounding. Bare copper conductors are light green.

While larger conductors may lose less energy due to lower electrical resistance, they are more costly than smaller conductors. An optimization rule called *Kelvin's Law* states that the optimum size of conductor for a line is found when the cost of the energy wasted in the conductor is equal to the annual interest paid on that portion of the line construction cost due to the size of the conductors. The optimization problem is made more complex by additional factors such as varying annual load, varying cost of installation, and the discrete sizes of cable that are commonly made.

Since a conductor is a flexible object with uniform weight per unit length, the geometric shape of a conductor strung on towers approximates that of a catenary. The sag of the conductor (vertical distance between the highest and lowest point of the curve) varies depending on the temperature and additional load such as ice cover. A minimum overhead clearance must be maintained for safety. Since the temperature of the conductor increases with increasing heat produced by the current through it, it is sometimes possible to increase the power handling capacity (uprate) by changing the conductors for a type with a lower coefficient of thermal expansion or a higher allowable operating temperature.

### **BUNDLE CONDUCTORS**

For higher amounts of current, **bundle conductors** are used for several reasons. Due to the skin effect, for larger conductors, the current capacity does not increase proportional to the cross-sectional area; instead, it is only with the linear dimension. Also, reactance decreases only slowly with size. But the cost and weight do increase with area. Due to this, several conductors in parallel become more economical.

Bundle conductors consist of several parallel cables connected at intervals by spacers, often in a cylindrical configuration. The optimum number of conductors depends on the current rating, but typically higher-voltage lines also have higher current. There is also some advantage due to lower corona loss. American Electric Power is building 765 kV lines using six conductors per phase in a bundle. Spacers must resist the forces due to wind, and magnetic forces during a short-circuit.

#### **Advantages**

At extra high voltage, the electric field gradient at the surface of a single conductor is high enough to ionize air, which loses power and generates both audible noise and interference with communication systems. The field surrounding a bundle of conductors is similar to the field that would surround a single, very large conductor—this produces lower gradients which mitigates issues associated with high field strength. When transmitting alternating current, bundle conductors also avoid the reduction in capacity of a single large conductor due to the skin effect. A bundle conductor also has lower reactance, compared to a single conductor. Additionally, bundled conductors cool themselves more efficiently due to the increased surface area of the conductors, further reducing line losses.

## MECHANICAL DESIGN OF TRANSMISSION LINE

### Sag in Overhead Transmission Line:

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. Following Fig. 8.1 shows a conductor suspended between two equal level supports A and B. The conductor is not fully stretched but is allowed to have a dip. The lowest point on the conductor is O and the sag is S.

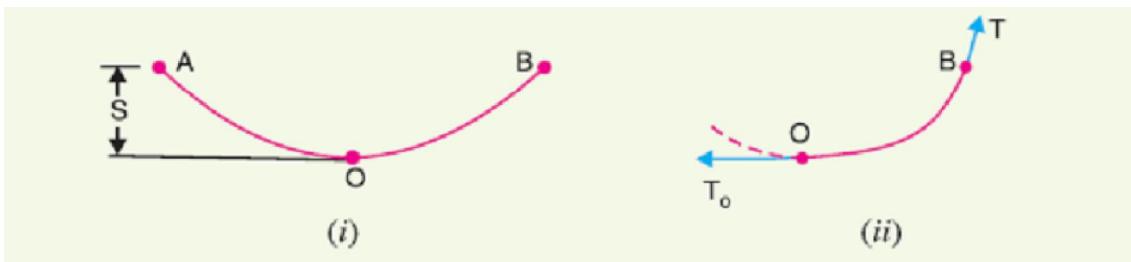


Fig 2.4- Sag in a transmission line

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  $T_0$  at the lowest Point O acts horizontally as shown in Fig. (ii).
- (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  $T = T_0$ .

**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 is made between the two.

**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. It is a standard practice to keep conductor tension less than 50% of its ultimate tensile strength i.e., minimum factor of safety in respect of conductor tension should be 2. We shall now calculate sag and tension of a conductor when (i) supports are at equal levels and (ii) supports are at unequal levels.

**When supports are at equal levels.** Consider a conductor between two equilevel supports A and B with O as the lowest point as shown in Fig.2.5. It can be proved that lowest point will be at a conductor between two equilevel supports A and B with O as the lowest point as shown in Fig. 2.5. It can be proved that lowest point will be at the mid-span.

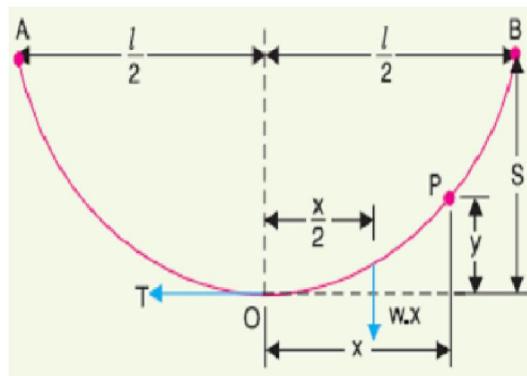


Fig 2.5- Sag Clculation

A conductor between two equilevel supports A and B with O as the lowest point as shown in Fig. 2. 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 co-ordinates 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  $w_x$  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 & B.

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

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

**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

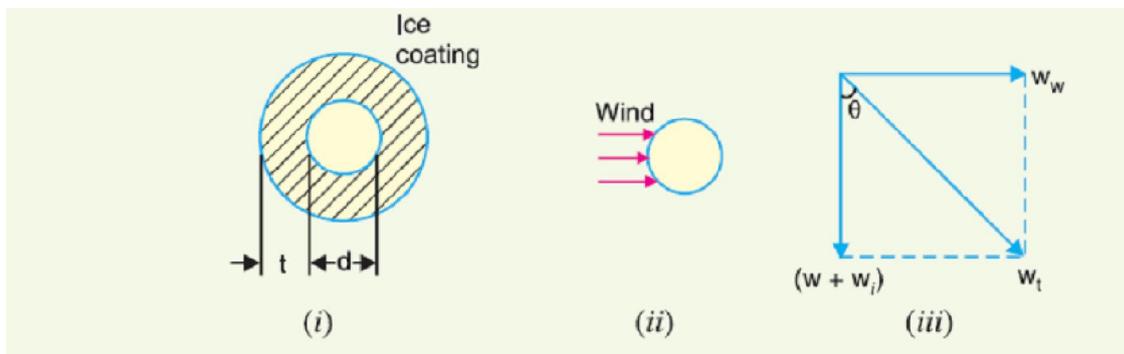


Fig 2.6- Effect of Ice and Wind

Total weight of conductor per unit length is

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

Where  $w$  = 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 \* volume of ice per unit length

= density of ice x  $\frac{\pi}{4} [(d + 2t)^2 - d^2] \times 1$

$w_w$  = wind force per unit length

= wind pressure per unit area  $\times$  projected area per unit length

= wind pressure x  $[(d + 2t) \times 1]$

### **Vibration Damper**

Aeolian vibrations mostly occur at steady wind velocities from 1 to 7 m/s. With increasing wind turbulences the wind power input to the conductor will decrease. The intensity to induce vibrations depends on several parameters such as type of conductors and clamps, tension, span length, topography in the surrounding, height and direction of the line as well as the frequency of occurrence of the vibration induced wind streams.

In the wake of wind power plants (up to 3 x diameter of the rotor behind the plant) the wind velocity will be reduced up to 0,5 of the velocity of the free wind stream, so that lower wind velocities could be expected more frequently here. That's why the probability of a higher stresses for the conductors caused by wind-induced vibrations will be greater than without wind power plants.

On the other hand the intensity of turbulences will increase which will hinder the arising of vibrations. The both important parameters for inducing vibrations, wind velocity and turbulence intensity, depends on the distance to the rotor and the height of it.

The investigations showed an increasing of damage probability on OHTL due to the wake of wind power plants of the factor 2,5 to 3,5 between one and three rotor diameters behind the plant which will cause an equivalent decreasing of lifetime of conductors and earth wires.

**Stringing chart:** 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. These charts are very helpful while stringing overhead lines.

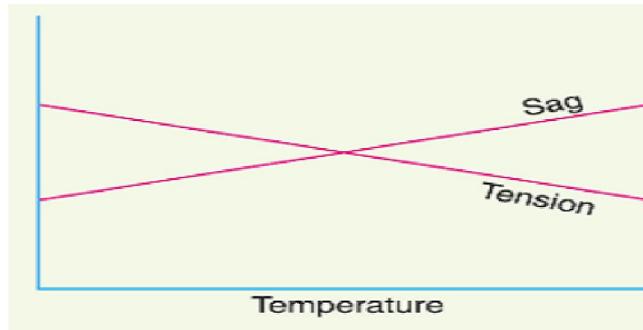


Fig 2.7- Stringing Chart

**Sag Template:** A Sag Template is a very important tool with the help of which the position of towers on the Profile is decided so that they conform to the limitations of vertical and wind loads on any particular tower, and minimum clearances, as per I.E. Rules, required to be maintained between the line conductor to ground, telephone lines, buildings, streets, navigable canals, power lines, or any other object coming under or near the line.

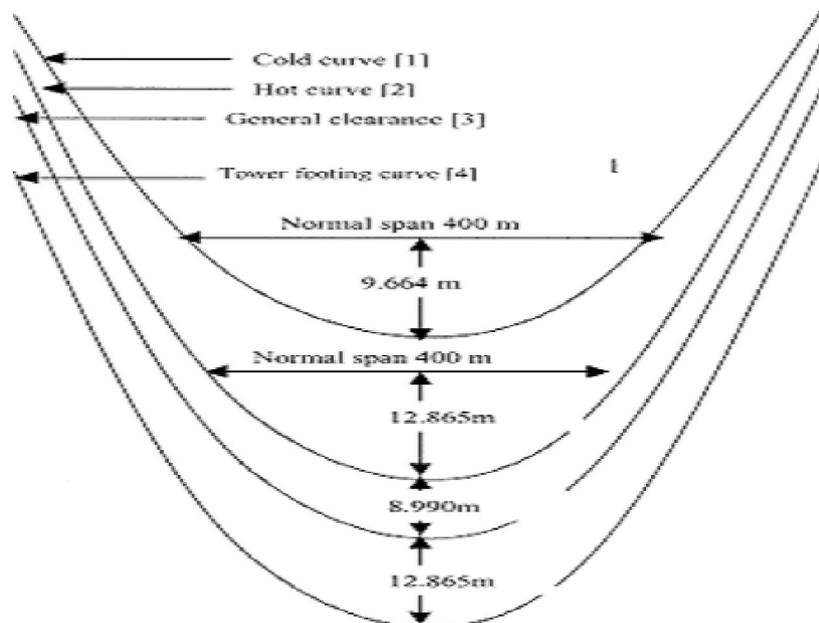


Fig 2.8- Sag Template

A Sag Template is specific for the particular line voltage, the conductor used and the applicable design conditions. Therefore, the correct applicable Sag Template should be used. A Sag Template consists of a set of parabolic curves drawn on a transparent celluloid or a crylic clear sheet duly cut in over the maximum conductor sag curve to allow the conductor curve to be drawn and the lowest points of the conductor sag to be marked on the profile when the profile is placed underneath it.

The set of curves in the sag template consists of:

- a) Cold or Uplift Curve' showing sag of conductor at minimum temperature (minus 2.5°C) and still wind.
- b) Hot or Maximum Sag Curve' showing maximum sag of conductor at maximum temperature and still wind including sag tolerances allowed (normally 4%), if any, and under maximum ice condition wherever applicable.
- c) Ground Clearance Curve' which is drawn parallel to the 'Hot or Maximum Sag Curve' and at a distance equal to the specified minimum ground clearance for the relevant voltage.
- d) 'Tower Footing Curve' which is drawn parallel to the 'Ground Clearance Curve' and separated by a minimum distance equal to the maximum sag at the basic design span.

## INSULATED CABLES

Electric power can be transmitted or distributed either by overhead system or by underground cables. The underground cables have several advantages such as less liable to damage through storms or lightning, low maintenance cost, less chance of faults, smaller voltage drop and better general appearance. However, their major drawback is that they have greater installation cost and introduce insulation problems at high voltages compared with the equivalent overhead system. For this reason, underground cables are employed where it is impracticable to use overhead lines. Such locations may be thickly populated areas where municipal authorities prohibit overhead lines for reasons of safety, or around plants and substations or where maintenance conditions do not permit the use of overhead construction. The chief use of underground cables for many years has been for distribution of electric power in congested urban areas at comparatively low or moderate voltages. However, recent improvements in the design and manufacture have led to the development of cables suitable for use at high voltages. This has made it possible to employ underground cables for transmission of electric power for short or moderate distances. In this chapter, we shall focus our attention on the various aspects of underground cables and their increasing use in power system.

**Underground Cables:-**An underground cable essentially consists of one or more conductors covered with suitable insulation and surrounded by a protecting cover. Although several types of cables are available, the type of cable to be used will depend upon the working voltage and service requirements. In general, a cable must fulfill the following necessary requirements:

- (i) The conductor used in cables should be tinned stranded copper or aluminum of high conductivity. Stranding is done so that conductor may become flexible and carry more current.
- (ii) The conductor size should be such that the cable carries the desired load current without overheating and causes voltage drop within permissible limits.
- (iii) The cable must have proper thickness of insulation in order to give high degree of safety and reliability at the voltage for which it is designed.
- (iv) The cable must be provided with suitable mechanical protection so that it may withstand the rough use in laying it.
- (v) The materials used in the manufacture of cables should be such that there is complete chemical and physical stability throughout.

**Construction of Cables:**-Figure shows the general construction of a 3-conductor cable. The various parts are

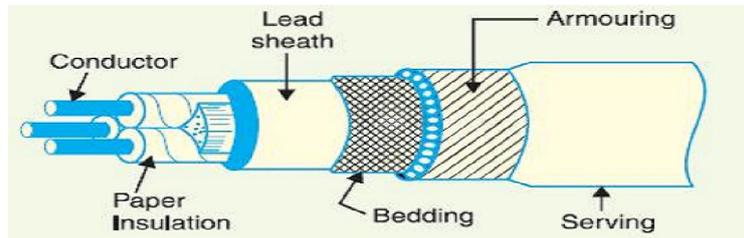


Fig 2.9- Cable

**Cores or Conductors.** A cable may have one or more than one core (conductor) depending upon the type of service for which it is intended. For instance, the 3 conductor cable shown in Figure is used for 3-phase service. The conductors are made of tinned copper or aluminum and are usually stranded in order to provide flexibility to the cable.

(ii) **Insulation.** Each core or conductor is provided with a suitable thickness of insulation, the thickness of layer depending upon the voltage to be withstood by the cable. The commonly used materials for insulation are impregnated paper, varnished cambric or rubber mineral compound.

(iii) **Metallic sheath.** In order to protect the cable from moisture, gases or other damaging liquids (acids or alkalis) in the soil and atmosphere, a metallic sheath of lead or aluminum is provided over the insulation as shown in Fig.

(iv) **Bedding.** Over the metallic sheath is applied a layer of bedding which consists of a fibrous material like jute or hessian tape. The purpose of bedding is to protect the metallic sheath against corrosion and from mechanical injury due to armoring.

(v) **Armouring.** Over the bedding, armoring is provided which consists of one or two layers of galvanized steel wire or steel tape. Its purpose is to protect the cable from mechanical injury while laying it and during the course of handling. Armouring may not be done in the case of some cables.

(vi) **Serving.** In order to protect armoring from atmospheric conditions, a layer of fibrous material (like jute) similar to bedding is provided over the armoring. This is known as serving.

It may not be out of place to mention here that bedding, armouring and serving are only applied to the cables for the protection of conductor insulation and to protect the metallic sheath from mechanical injury.

**Insulating Materials for Cables:**-The satisfactory operation of a cable depends to a great extent upon the characteristics of insulation used. Therefore, the proper choice of insulating material for cables is of considerable importance. In general, the insulating materials used in cables should have the following properties:

- (i) High insulation resistance to avoid leakage current.
- (ii) High dielectric strength to avoid electrical breakdown of the cable.
- (iii) High mechanical strength to withstand the mechanical handling of cables.
- (iv) Non-hygroscopic i.e., it should not absorb moisture from air or soil. The moisture tends to decrease the insulation resistance and hastens the breakdown of the cable. In case the insulating material is hygroscopic, it must be enclosed in a waterproof covering like lead sheath.
- (v) Non-inflammable.
- (vi) Low cost so as to make the underground system a viable proposition.
- (vii) Unaffected by acids and alkalies to avoid any chemical action. No one insulating material possesses all the above mentioned properties. Therefore, the type of insulating material to be used depends upon the purpose for which the cable is required and the quality of insulation to be aimed at.

The principal insulating materials used in cables are rubber, vulcanized rubber, impregnated paper and polyvinyl chloride.

**1. Rubber:** Rubber may be obtained from milky sap of tropical trees or it may be produced from oil products. It has relative permittivity varying between 2 and 3, dielectric strength is about 30 kV/mm and resistivity of insulation is  $10^{17}$  cm. Although pure rubber has reasonably high insulating properties, it suffers from some major drawbacks viz., readily absorbs moisture, maximum safe temperature is low (about 38°C), soft and liable to damage due to rough handling and ages when exposed to light. Therefore, pure rubber cannot be used as an insulating material.

**2. Vulcanised India Rubber (V.I.R.).** It is prepared by mixing pure rubber with mineral matter such as zinc oxide, red lead etc., and 3 to 5% of sulphur. The compound so formed is rolled into thin sheets and cut into strips. The rubber compound is then applied to the conductor and

is heated to a temperature of about 150°C. The whole process is called vulcanisation and the product obtained is known as vulcanised India rubber. Vulcanised India rubber has greater mechanical strength, durability and wear resistant property than pure rubber. Its main drawback is that sulphur reacts very quickly with copper and for this reason, cables using VIR insulation have tinned copper conductor. The VIR insulation is generally used for low and moderate voltage cables.

**3. Impregnated paper.** It consists of chemically pulped paper made from wood chippings and impregnated with some compound such as paraffinic or naphthenic material. This type of insulation has almost superseded the rubber insulation. It is because it has the advantages of low cost, low capacitance, high dielectric strength and high insulation resistance. The only disadvantage is that paper is hygroscopic and even if it is impregnated with suitable compound, it absorbs moisture and thus lowers the insulation resistance of the cable.

**4. Polyvinyl chloride (PVC).** This insulating material is a synthetic compound. It is obtained from the polymerization of acetylene and is in the form of white powder. For obtaining this material as a cable insulation, it is compounded with certain materials known as plasticizers which are liquids with high boiling point. The plasticizer forms a gell and renders the material plastic over the desired range of temperature. Polyvinyl chloride has high insulation resistance, good dielectric strength and mechanical toughness over a wide range of temperatures. It is inert to oxygen and almost inert to many alkalies and acids. Therefore, this type of insulation is preferred over VIR in extreme environmental conditions such as in cement factory or chemical factory. As the mechanical properties (i.e., elasticity etc.) of PVC are not so good as those of rubber, therefore, PVC insulated cables are generally used for low and medium domestic lights and power installations.

**Classification of Cables:** -Cables for underground service may be classified in two ways according to (i) the type of insulating material used in their manufacture (ii) the voltage for which they are manufactured. However, the latter method of classification is generally preferred, according to which cables can be divided into the following groups:

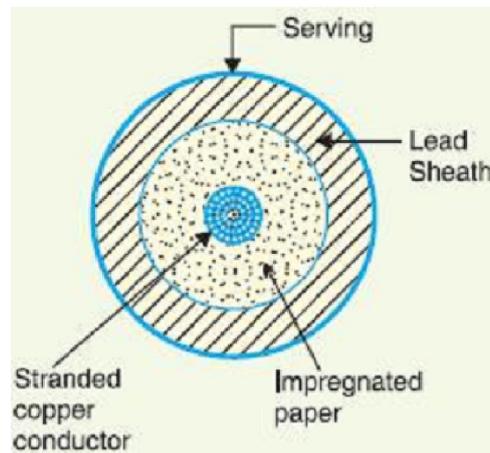


Fig 2.10- Cross section of Cables

- (i) Low-tension (L.T.) cables — upto 1000 V
- (ii) High-tension (H.T.) cables — upto 11,000 V
- (iii) Super-tension (S.T.) cables — from 22 kV to 33 kV
- (iv) Extra high-tension (E.H.T.) cables — from 33 kV to 66 kV
- (iv) Extra super voltage cables — beyond 132 kV

A cable may have one or more than one core depending upon the type of service for which it is intended. It may be (i) single-core (ii) two-core (iii) three-core (iv) four-core etc. For a 3-phase service, either 3-single-core cables or three-core cable can be used depending upon the operating voltage and load demand. Fig. 11.2 shows the constructional details of a single-core low tension cable. The cable has ordinary construction because the stresses developed in the cable for low voltages (up to 6600 V) are generally small. It consists of one circular core of tinned stranded copper (or aluminium) insulated by layers of impregnated paper. The insulation is surrounded by a lead sheath which prevents the entry of moisture into the inner parts. In order to protect the lead sheath from corrosion, an overall serving of compounded fibrous material (jute etc.) is provided. Single-core cables are not usually armoured in order to avoid excessive sheath losses. The principal advantages of single-core cables are simple construction and availability of larger copper section.

### Cable for 3-phase

In practice, underground cables are generally required to deliver 3-phase power. For the purpose, either three-core cable or three single core cables may be used. For voltages upto 66 kV, 3-core cable (i.e., multi-core construction) is preferred due to economic reasons. However, for voltages beyond 66 kV, 3-core-cables become too large and unwieldy and, therefore, single-core cables are used. The following types of cables are generally used for 3-phase service:

1. Belted cables — upto 11 kV
2. Screened cables — from 22 kV to 66 kV
3. Pressure cables — beyond 66 kV

### Dielectric Stress in Cable

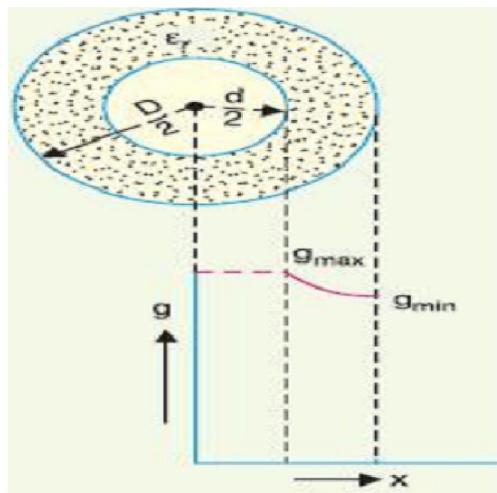


Fig 2.11- Dielectric Stress in Cable

Under operating conditions, the insulation of a cable is subjected to electrostatic forces. This is known as dielectric stress. The dielectric stress at any point in a cable is in fact the potential gradient (or electric intensity) at that point. Consider a single core cable with core diameter  $d$  and internal sheath diameter  $D$ . The electric intensity at a point  $x$  metres from the centre of the cable is

$$E_x = \frac{Q}{2\pi\epsilon_0\epsilon_r x} \text{ volts/m}$$

By definition, electric intensity is equal to potential gradient. Therefore, potential gradient  $g$  at a

point  $x$  meters from the Centre of cable is

$$g = E_x$$

$$g = \frac{E}{2\pi\epsilon_0\epsilon_r x} \text{ volts/m}$$

Potential difference  $V$  between conductor and sheath is

$$V = \frac{Q}{2\pi\epsilon_0\epsilon_r} \ln \frac{D}{d} \text{ volts}$$

$$Q = \frac{2\pi\epsilon_0\epsilon_r V}{\ln \frac{D}{d}}$$

Substituting the value of  $Q$ , we get

$$g = \frac{V}{x \ln \frac{D}{d}} \text{ volts/m}$$

It is clear from the above equation that potential gradient varies inversely as the distance  $x$ .

Therefore, potential gradient will be maximum when  $x$  is minimum i.e., when  $x = d/2$  or at the surface of the conductor. On the other hand, potential gradient will be minimum at  $x = D/2$  or at sheath surface.

Maximum potential gradient is

$$g_{\max} = \frac{2V}{d \ln \frac{D}{d}} \text{ volts/m}$$

Minimum potential gradient is

$$g_{\min} = \frac{2V}{D \ln \frac{D}{d}} \text{ volts/m}$$

$$\frac{g_{\max}}{g_{\min}} = \frac{D}{d}$$

The variation of stress in the dielectric is shown in Fig.14. It is clear that dielectric stress is maximum at the conductor surface and its value goes on decreasing as we move away from the conductor. It may be noted that maximum stress is an important consideration in the design of a

cable. For instance, if a cable is to be operated at such a voltage that maximum stress is 5 kV/mm, then the insulation used must have a dielectric strength of at least 5 kV/mm, otherwise breakdown of the cable will become inevitable.

### **Most Economical Size of Conductor**

It has already been shown that maximum stress in a cable occurs at the surface of the conductor. For safe working of the cable, dielectric strength of the insulation should be more than the maximum stress. Rewriting the expression for maximum stress, we get,

$$g_{\max} = \frac{2V}{d \ln \frac{D}{d}} \text{ volts/m}$$

The values of working voltage  $V$  and internal sheath diameter  $D$  have to be kept fixed at certain values due to design considerations. This leaves conductor diameter  $d$  to be the only variable.

For given values of  $V$  and  $D$ , the most economical conductor diameter will be one for which  $g_{\max}$  has a minimum value. The value of  $g_{\max}$  will be minimum when  $d \ln D/d$  is maximum i.e.

$$\frac{d}{dd} \left[ d \ln \frac{D}{d} \right] = 0$$

$$\frac{D}{d} = e = 2.718$$

Most economical conductor diameter is

$$d = \frac{D}{2.718}$$

and the value of  $g_{\max}$  under this condition is

$$g_{\max} = \frac{2V}{d} \text{ volts/m}$$

### **Grading of Cables**

The process of achieving uniform electrostatic stress in the dielectric of cables is known as grading of cables. It has already been shown that electrostatic stress in a single core cable has a maximum value ( $g_{\max}$ ) at the conductor surface and goes on decreasing as we move towards the sheath. The maximum voltage that can be safely applied to a cable depends upon  $g_{\max}$  i.e., electrostatic stress at the conductor surface. For safe working of a cable having homogeneous dielectric, the strength of dielectric must be more than  $g_{\max}$ . If a dielectric of high

strength is used for a cable, it is useful only near the conductor where stress is maximum. But as we move away from the conductor, the electrostatic stress decreases, so the dielectric will be unnecessarily over strong. The unequal stress distribution in a cable is undesirable for two reasons. Firstly, insulation of greater thickness is required which increases the cable size. Secondly, it may lead to the breakdown of insulation. In order to overcome above disadvantages, it is necessary to have a uniform stress distribution in cables. This can be achieved by distributing the stress in such a way that its value is increased in the outer layers of dielectric. This is known as grading of cables. The following are the two main methods of grading of cables:

- (i) Capacitance grading (ii) Intersheath grading

**Capacitance Grading:**

The process of achieving uniformity in the dielectric stress by using layers of different dielectrics is known as capacitance grading.

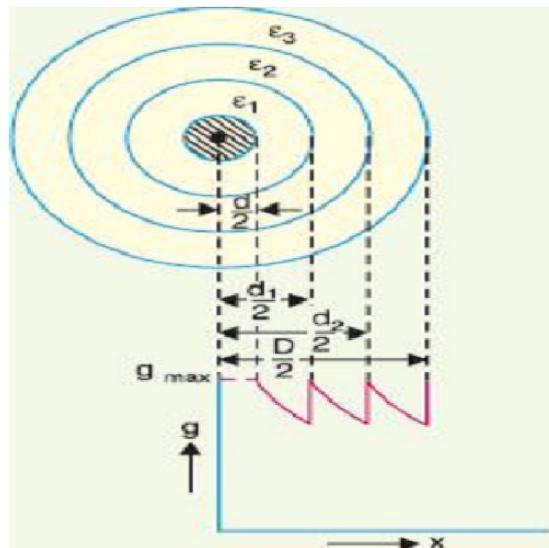


Fig 2.12- Capacitance grading

In capacitance grading, the homogeneous dielectric is replaced by a composite dielectric. The composite dielectric consists of various layers of different dielectrics in such a manner that relative permittivity  $\epsilon_r$  of any layer is inversely proportional to its distance from the center. Under such conditions, the value of potential gradient any point in the dielectric is constant and is independent of its distance from the center. In other words, the dielectric stress in the cable is same everywhere and the grading is ideal one. However, ideal

grading requires the use of an infinite number of dielectrics which is an impossible task. In practice, two or three dielectrics are used in the decreasing order of permittivity, the dielectric of highest permittivity being used near the core. The capacitance grading can be explained beautifully by referring to the above Figure. There are three dielectrics of outer diameter  $d_1$ ,  $d_2$  and  $D$  and of relative permittivity  $>1$ ,  $>2$  and  $>3$  respectively. If the permittivity are such that  $>1 > 2 > 3$  and the three dielectrics are worked at the same maximum stress, then

$$\epsilon_1 d = \epsilon_2 d_1 = \epsilon_3 d_2$$

$$V_1 = \frac{g_{\max}}{2} d \ln \frac{d_1}{d}$$

$$V_2 = \frac{g_{\max}}{2} d_1 \ln \frac{d_2}{d_1}$$

$$V_3 = \frac{g_{\max}}{2} d_2 \ln \frac{D}{d_2}$$

Total p.d. between core and earthed sheath is

$$V = V_1 + V_2 + V_3$$

$$V = \frac{g_{\max}}{2} \left[ d \ln \frac{d_1}{d} + d_1 \ln \frac{d_2}{d_1} + d_2 \ln \frac{D}{d_2} \right]$$

**Intersheath Grading:** In this method of cable grading, a homogeneous dielectric is used, but it is divided into various layers by placing metallic intersheaths between the core and lead sheath. The intersheaths are held at suitable potentials which are in between the core potential and earth potential. This arrangement improves voltage distribution in the dielectric of the cable and consequently more uniform potential gradient is obtained.

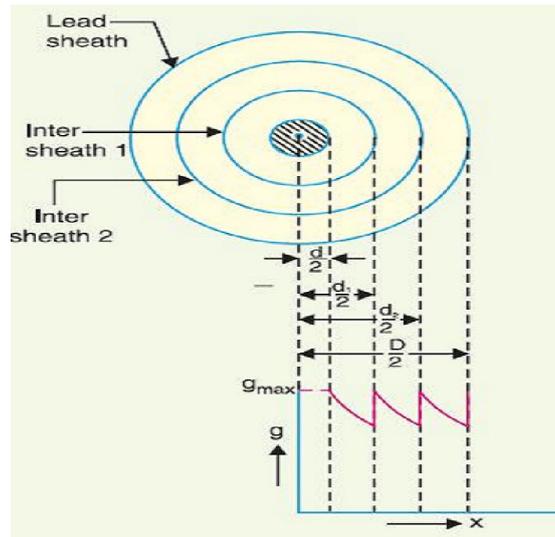


Fig 2.13- Intersheath grading

Consider a cable of core diameter  $d$  and outer lead sheath of diameter  $D$ . Suppose that two intersheaths of diameters  $d_1$  and  $d_2$  are inserted into the homogeneous dielectric and maintained at some fixed potentials. Let  $V_1$ ,  $V_2$  and  $V_3$  respectively be the voltage between core and inter sheath 1, between inter sheath 1 and 2 and between inter sheath 2 and outer lead sheath. As there is a definite potential difference between the inner and outer layers of each inter sheath, therefore, each sheath can be treated like a homogeneous single core cable. Maximum stress between core and inter sheath 1 is

$$g_{1max} = \frac{V_1}{\frac{d}{2} \log_e \frac{d_1}{d}}$$

$$g_{2max} = \frac{V_2}{\frac{d_1}{2} \log_e \frac{d_2}{d_1}}$$

$$g_{3max} = \frac{V_3}{\frac{d_2}{2} \log_e \frac{D}{d_2}}$$

Since the dielectric is homogeneous, the maximum stress in each layer is the same i.e.,

$$g_{1max} = g_{2max} = g_{3max} = g_{max}$$

$$\frac{V_1}{\frac{d}{2} \ln \frac{d_1}{d}} = \frac{V_2}{\frac{d_1}{2} \ln \frac{d_2}{d_1}} = \frac{V_3}{\frac{d_2}{2} \ln \frac{D}{d_2}}$$

As the cable behaves like three capacitors in series, therefore, all the potentials are in phase i.e.

Voltage between conductor and earthed lead sheath is

$$V = V_1 + V_2 + V_3$$

Inter sheath grading has three principal disadvantages. Firstly, there are complications in fixing the sheath potentials. Secondly, the inter sheaths are likely to be damaged during transportation and installation which might result in local concentrations of potential gradient. Thirdly, there are considerable losses in the inter sheaths due to charging currents. For these reasons, inter sheath grading is rarely used.

### Measurement of capacitance of 3-core cables

In three-core cables, capacitance does not have a single value, but can be lumped as shown in below figure.

Capacitance between each core and sheath =  $C_s$

Capacitance between cores =  $C$

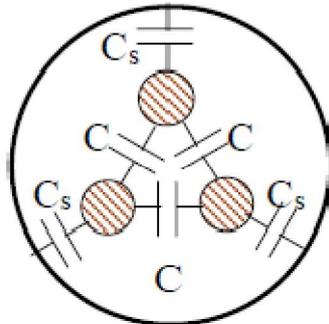


Fig 2.14- Cable Capacitance

These can be separated from measurements as described in the following section.

(a) Strap the 3 cores together and measure the capacitance between this bundle and the sheath as shown in figure.

Measured value =  $C_{m1} = 3 C_s$

This gives the capacitance to the sheath as  $C_s = \frac{C_{m1}}{3}$

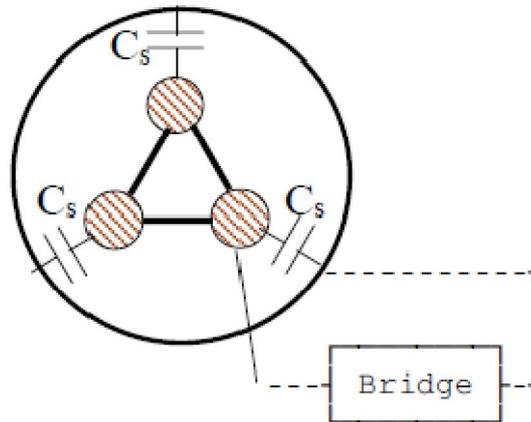


Fig 2.15- Capacitance Measurement

(b) Connect 2 of the cores to the sheath and measure between the remaining core and the sheath.

Measured value  $C_{m2} = 2C + C_s$

i.e.  $C = (C_{m2} - C_s)/2 = (3C_{m2} - C_{m1})/6$

Which gives the capacitance between the conductors.

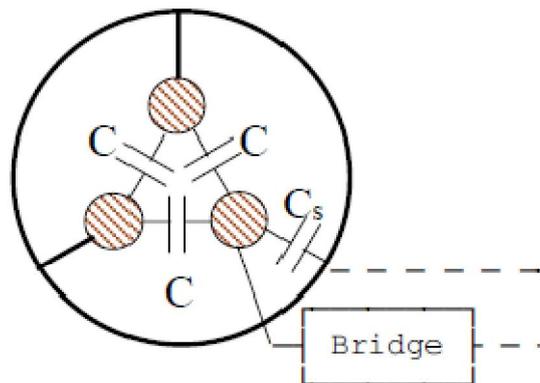


Fig 2.16- Capacitance Measurement

The effective capacitance to neutral  $C_0$  of any of the cores may be obtained by considering the star equivalent. This gives

$$C_0 = C_s + 3C = \frac{1}{3}C_{m1} + 3 \frac{3C_m^2 - C_m^1}{6}$$

$$C_0 = \frac{3}{2}C_m^2 - \frac{1}{6}C_m^1$$

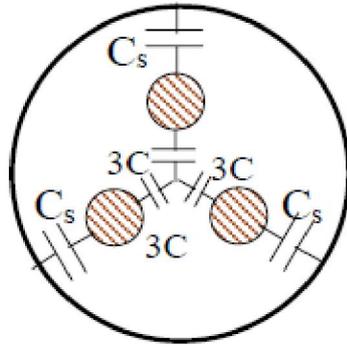


Fig 2.17-Calculation of  $C_0$

In the breakdown of actual 3-core belted cables, it is generally observed that charring occurs at those places where the stress is tangential to the layers of paper. Thus for the insulation to be effective, the tangential stresses in paper insulation should be preferably avoided. This can usually be accomplished only screening each core separately (or by having individual lead sheaths for each of the cores), so that the cable in effect becomes 3 individual cables laid within the same protective covering.