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# **UNIT-I**

## **TRANSMISSION LINE PARAMETERS**

## 2. TRANSMISSION LINES

The electric parameters of transmission lines (i.e. resistance, inductance, and capacitance) can be determined from the specifications for the conductors, and from the geometric arrangements of the conductors.

### Transmission Line Resistance

Resistance to d.c. current is given by

$$R_{dc} = \rho \frac{\ell}{A}$$

where  $\rho$  is the resistivity at 20°C

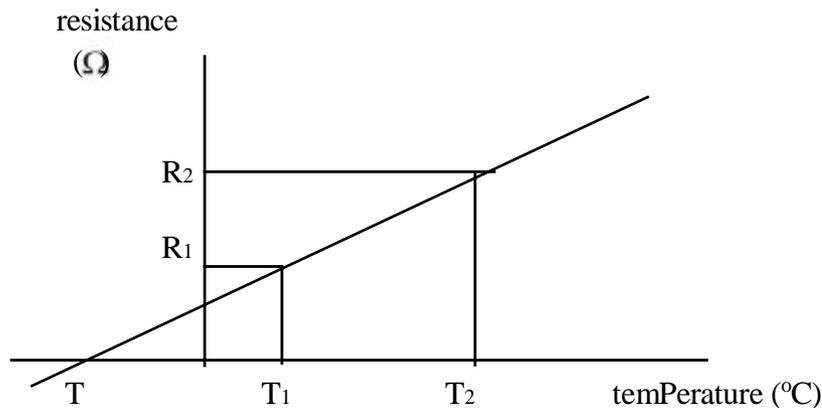
$\ell$  is the length of the conductor

$A$  is the cross sectional area of the conductor

Because of skin effect, the d.c. resistance is different from ac resistance. The ac resistance is referred to as effective resistance, and is found from power loss in the conductor

$$R = \frac{\text{power loss}}{I^2}$$

The variation of resistance with temperature is linear over the normal temperature range



**Figure 9** Graph of Resistance vs Temperature

$$\frac{(R_1 - 0)}{(T_1 - T)} = \frac{(R_2 - 0)}{(T_2 - T)}$$

$$R_2 = \frac{T_2 - T}{T_1 - T} R_1$$

### Transmission Line Inductive Reactance

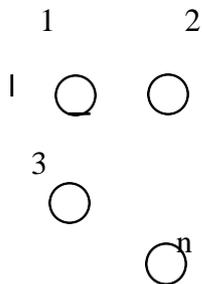
Inductance of transmission lines is calculated Per phase. It consists of self inductance of the phase conductor and mutual inductance between the conductors. It is given by:

$$L = 2 \times 10^{-7} \ln \frac{\text{GMD}}{\text{GMR}} \quad [\text{H/m}]$$

where GMR is called geometric mean radius (available from manufacturer's tables)

GMD is called geometric mean distance (must be calculated for each line configuration)

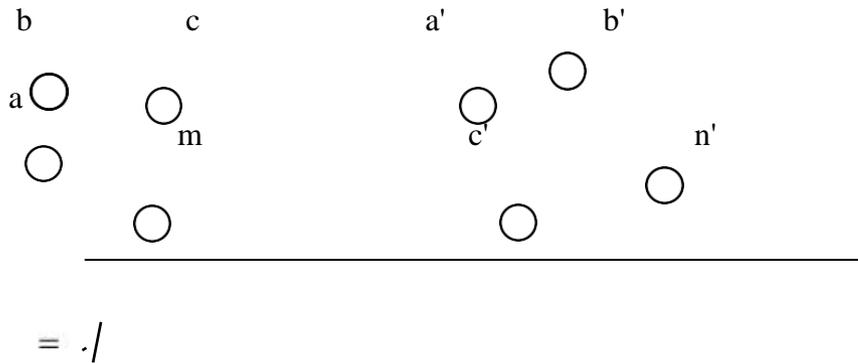
**Geometric Mean Radius:** There are magnetic flux lines not only outside of the conductor, but also inside. GMR is a hypothetical radius that replaces the actual conductor with a hollow conductor of radius equal to GMR such that the self inductance of the inductor remains the same. If each phase consists of several conductors, the GMR is given by



where  $d_{11} = \text{GMR}_1$   
 $d_{22} = \text{GMR}_2$   
 $\cdot$   
 $\cdot$   
 $\cdot$   
 $d_{nn} = \text{GMR}_n$

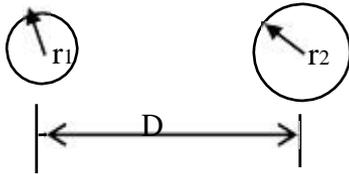
Note: for a solid conductor,  $\text{GMR} = r \cdot e^{-1/4}$ , where r is the radius of the conductor.

**Geometric Mean Distance** replaces the actual arrangement of conductors by a hypothetical mean distance such that the mutual inductance of the arrangement remains the same



where  $D_{aa'}$  is the distance between the conductors  $a, a'$  etc.

### Inductance Between Two Single Phase Conductors



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

$$L_2 = 2 \times 10^{-7} \times \ln \frac{D}{r_2'}$$

where  $r_1'$  is GMR of conductor 1

$r_2'$  is GMR of conductor 2

$D$  is the GMD between the conductors

The total inductance of the line is then

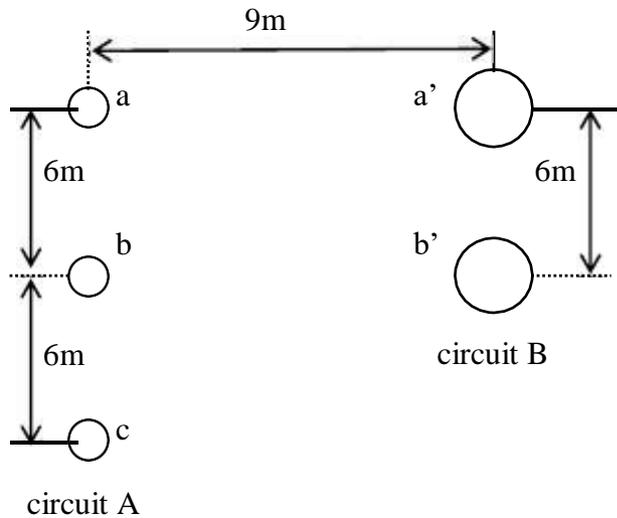
$$L_T = L_1 + L_2 = 2 \times 10^{-7} \times \left[ \ln \frac{D}{r_1'} + \ln \frac{D}{r_2'} \right] = 2 \times 10^{-7} \times \ln \frac{D^2}{r_1' r_2'} = 2 \times 10^{-7} \times 2 \times \frac{1}{2} \times \ln \frac{D^2}{r_1' r_2'}$$

$$L_T = 4 \times 10^{-7} \times \ln \left[ \frac{D^2}{r_1' r_2'} \right]^{1 \text{ per } 2} = 4 \times 10^{-7} \times \ln \frac{D}{\sqrt{r_1' r_2'}}$$

If  $r_1 = r_2$ , then

$$L_T = 4 \times 10^{-7} \times \ln \frac{D}{r_1'}$$

**Example:** Find GMD, GMR for each circuit, inductance for each circuit, and total inductance per meter for two circuits that run parallel to each other. One circuit consists of three 0.25 cm radius conductors. The second circuit consists of two 0.5 cm radius conductor



*Solution:*

$$m = 3, n' = 2, \therefore m \cdot n' = 6$$

$$GMD = \sqrt[6]{D_{aa'} D_{ab'} D_{ac'} D_{ba'} D_{bb'} D_{bc'} D_{ca'} D_{cb'}}$$

where

$$D_{aa'} = D_{bb'} = 9 \text{ m}$$

$$D_{ab'} = D_{ba'} = D_{cb'} = \sqrt{6^2 + 9^2} = \sqrt{117} \text{ m}$$

$$D_{ca'} = \sqrt{12^2 + 9^2} = 15 \text{ m}$$

$$\therefore GMD = 10.743 \text{ m}$$

Geometric Mean Radii for Circuit A:

$$GMR_A = \sqrt[3]{D_{aa} D_{bb} D_{cc}} = \sqrt[3]{(0.25 \times 10^{-2})^2 \times e^{-1/4}} \times 5^4 \times 2^2 = 0.481 \text{ m}$$

Geometric Mean Radii for Circuit B:

$$GMR_B = \sqrt[2]{D_{a'a'} D_{b'b'}} = \sqrt[4]{(0.5 \times 10^{-2} \times e^{-1/4})^2 \times 5^2} = 0.153 \text{ m}$$

Inductance of circuit A

$$L_A = 2 \times 10^{-7} \ln \frac{\text{GMD}}{\text{GMR}_A} = 2 \times 10^{-7} \ln \frac{10.743}{0.481} = 6.212 \times 10^{-7} \quad \text{H / m}$$

Inductance of circuit B

$$L_B = 2 \times 10^{-7} \ln \frac{\text{GMD}}{\text{GMR}_B} = 2 \times 10^{-7} \ln \frac{10.743}{0.153} = 3.503 \times 10^{-7} \quad \text{H / m}$$

The total inductance is then

$$L_T = L_A + L_B = 14.715 \times 10^{-7} \quad \text{H / m}$$

### The Use of Tables

Since the cables for power transmission lines are usually supplied by U.S. manufacturers, the tables of cable characteristics are in American Standard System of units and the inductive reactance is given in  $\Omega/\text{mile}$ .

$$X_L = 2\pi fL = 2\pi f \times 2 \times 10^{-7} \ln \frac{\text{GMD}}{\text{GMR}} \quad \Omega / \text{m}$$

$$X_L = 4\pi f \times 10^{-7} \ln \frac{\text{GMD}}{\text{GMR}} \quad \Omega / \text{m}$$

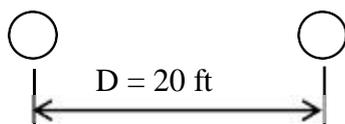
$$X_L = 4\pi f \times 10^{-7} \times 1609 \times \ln \frac{\text{GMD}}{\text{GMR}} \quad \Omega \text{ per mile}$$

$$X_L = 2.022 \times 10^{-3} \times f \times \ln \frac{\text{GMD}}{\text{GMR}} \quad \Omega \text{ per mile}$$

$$X_L = \underbrace{2.022 \times 10^{-3} \times f \times \ln \frac{1}{\text{GMR}}}_{X_a} + \underbrace{2.022 \times 10^{-3} \times f \times \ln \text{GMD}}_{X_d} \quad \Omega \text{ per mile}$$

If both, GMR and GMD are in feet, then  $X_a$  represents the inductive reactance at 1 ft spacing, and  $X_d$  is called the inductive reactance spacing factor.

**Example:** Find the inductive reactance per mile of a single phase line operating at 60 Hz. The conductor used is Partridge, with 20 ft spacings between the conductor centers.



*Solution:* From the Tables, for Partridge conductor, GMR = 0.0217 ft and inductive reactance at 1 ft spacing  $X_a = 0.465 \Omega$  per mile. The spacing factor for 20 ft spacing is  $X_d = 0.3635 \Omega$  per mile. The inductance of the line is then

$$X_L = X_a + X_d = 0.465 + 0.3635 = 0.8285 \Omega \text{ per mile}$$

### Inductance of Balanced Three Phase Line

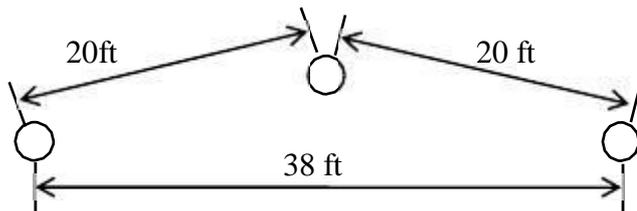
Average inductance per phase is given by:

$$L = 2 \times 10^{-7} \ln \frac{D_{eq}}{\text{GMR}}$$

where  $D_{eq}$  is the geometric mean of the three spacings of the three phase line.

$$D_{eq} = \sqrt[3]{D_{ab} D_{ac} D_{bc}}$$

**Example:** A three phase line operated at 60 Hz is arranged as shown. The conductors are ACSR Drake. Find the inductive reactance per mile.



*Solution:*

For ACSR Drake conductor, GMR = 0.0373 ft

$$D_{eq} = \sqrt[3]{20 \times 20 \times 38} = 24.8 \text{ ft}$$

$$L = 2 \times 10^{-7} \ln \frac{24.8}{0.0373} = 1.3 \times 10^{-7} \text{ H/m}$$

$$X_L = 2\pi \times 60 \times 1609 \times 1.3 \times 10^{-7} = 0.788 \Omega / \text{mile}$$

OR

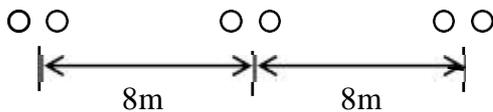
from the tables  $X_a = 0.399 \Omega / \text{mile}$

The spacing factor is calculated for spacing equal to the geometric mean distance between the conductors, that is,  $X_d = 2.022 \times 10^{-3} \times 60 \ln 24.8 = 0.389 \Omega / \text{mile}$

Then the line inductance is  $X_{line} = X_a + X_d = 0.788 \ \Omega / \text{mile} / \text{phase}$

**Example:** Each conductor of the bundled conductor line shown in the figure is 1272 MCM Pheasant. Find:

- the inductive reactance in  $\Omega/\text{km}$  and  $\Omega/\text{mile} / \text{phase}$  for  $d = 45 \text{ cm}$
- the p.u. series reactance if the length of the line is 160 km and the base is 100 MVA, 345 kV.



*Solution:*

a) The distances in ft are

$$d = \frac{0.45}{0.3048} = 1.476 \text{ ft}$$

$$D = \frac{8}{0.3048} = 26.25 \text{ ft}$$

For Pheasant conductors,  $GMR = 0.0466 \text{ ft}$ .

$GMR_b$  for a bundle of conductors is

$$GMR_b = \sqrt{GMR \times d} = \sqrt{0.0466 \times 1.476} = 0.2623 \text{ ft}$$

The geometric mean of the phase conductor spacing is

$$D_{eq} = \sqrt[3]{26.25 \times 26.25 \times 52.49} = 33.07 \text{ ft}$$

The inductance of the line is then

$$L = 2 \times 10^{-7} \ln \frac{D_{eq}}{GMR_b} = 2 \times 10^{-7} \ln \frac{33.07}{0.2623} = 9.674 \times 10^{-7} \text{ H/m}$$

The inductive reactance is

$$X_L = 2\pi fL = 2\pi \times 60 \times 9.674 \times 10^{-7} = 3.647 \times 10^4 \ \Omega / \text{m} = 0.3647 \ \Omega / \text{km} = 0.5868 \ \Omega / \text{mile}$$

b) Base impedance  $Z_b = \frac{V_b^2}{S_b} = \frac{345^2}{100} = 1190 \ \Omega$

Total impedance of the 160 km line is

$$X_L = 160 \times 0.3647 = 58.35 \ \Omega$$

$$X_{L.p.u.} = \frac{X_L}{Z_b} = \frac{58.35}{1190} = 0.049 \text{ p.u.}$$

### 2.3 Transmission Line Capacitive Reactance

Conductors of transmission lines act like plates of a capacitor. The conductors are charged, and there is a potential difference between the conductors and between the conductors and the ground. Therefore there is capacitance between the conductors and between the conductors and the ground. The basic equation for calculation of the capacitance is the definition of the capacitance as the ratio of the charge and the potential difference between the charged plates:

$$C = \frac{Q}{V} \quad \text{F}$$

where  $Q$  is the total charge on the conductors (plates)

$V$  is the potential difference between the conductors or a conductor and ground (i.e. plates)

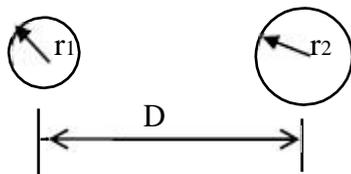
For transmission lines, we usually want the capacitance / unit length

$$C = \frac{q}{V} \quad \text{F/m}$$

where  $q$  is the charge per unit length in C/m

$V$  is the potential difference between the conductors or a conductor and ground (i.e. plates)

#### Capacitance of a Single Phase Line



For a two conductor line, the capacitance between the conductors is given by

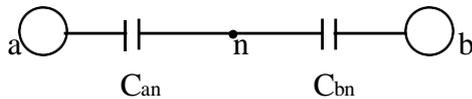
$$C = \frac{\pi \epsilon_0}{\ln \frac{D^2}{r_1 r_2}} \quad \text{F/m}$$

where  $\epsilon_0$  is the permittivity of free space and is equal to  $8.85 \times 10^{-12}$  F/m

$D$  is the distance between the conductors, center to center

Formally, this equation corresponds to the equation for inductance of a two conductor line. The equation was derived for a solid round conductor and assuming a uniform distribution of charge along the conductors. The electric field, and therefore the capacitance of stranded conductors is not the same as for solid conductors, but if the radii of the conductors are much smaller than the distance between the conductors, the error is very small and an outside radii of the stranded conductors can be used in the equation.

For most single phase lines,  $r_1 = r_2$ . In this case, half way between the conductors there is a point where  $E = 0$ . This is the neutral point  $n$



The capacitance from conductor **a** to point **n** is  $C_{an}$  and is the same as the capacitance from conductor **b** to **n**,  $C_{bn}$ .  $C_{an}$  and  $C_{bn}$  are connected in series, therefore  $C_{an} = C_{bn} = 2C_{ab}$ .<sup>1</sup> It follows that

$$C_{an} = \frac{2\pi\epsilon_0}{\ln \frac{D}{r}} \quad [\text{F/m}]$$

Since  $X_c = \frac{1}{2\pi f C}$

$$\therefore X_c = \frac{1}{2\pi f \frac{2\pi\epsilon_0}{\ln \frac{D}{r}}} = \frac{2.862 \times 10^9}{f} \ln \frac{D}{r} \quad \Omega \cdot \text{m}^{-1}$$

The capacitive reactance in  $\Omega$ -mile is

$$X_c = \frac{2.862 \times 10^9}{f} \ln \frac{D}{r} \times \frac{1.609}{1.609} = \frac{2.862 \times 10^9}{f} \ln \frac{D}{r} \quad \Omega \cdot \text{mile}^{-1}$$

Similarly as for inductive reactance, this expression can be split into two terms that are called capacitive reactance at 1 ft spacing ( $X_a'$ ) and the capacitive reactance spacing factor ( $X_d'$ ).

---


$$^1 C_{ab} = \frac{1}{\frac{1}{C_{an}} + \frac{1}{C_{bn}}} = \frac{C_{an} C_{bn}}{C_{an} + C_{bn}} \quad \text{If } C_{an} = C_{bn}, \text{ then } C_{ab} = \frac{C_{an}^2}{2C_{an}} = \frac{C_{an}}{2}$$

Therefore,  $C_{an} = 2C_{ab}$

$$X_c = \underbrace{\frac{1.779 \times 10}{f} \ln \frac{1}{r}}_{X_a'} + \underbrace{\frac{1.779 \times 10^6}{f} \ln D}_{X_d'} \quad \text{M}\Omega \cdot \text{mile}$$

$X_a'$  is given in the tables for the standard conductors,  $X_d'$  is given in the tables for the capacitive reactance spacing factor.

**Example:** Find the capacitive reactance in M  $\Omega$ -miles for a single phase line operating at 60Hz. The conductor used for the line is Partridge, and the spacing is 20 ft.



The outside radius of the Partridge conductor is  $r = \frac{0.642}{2}$  in = 0.0268 ft

The capacitive reactance is

$$X_c = \frac{1.779 \times 10}{f} \ln \frac{D}{r} = \frac{1.779 \times 10^6}{f} \ln \frac{20}{0.0268} = 0.1961 \text{ M}\Omega \cdot \text{mile}$$

OR

From tables  $X_a' = 0.1074 \text{ M}\Omega \cdot \text{mile}$

$X_d' = 0.0889 \text{ M}\Omega \cdot \text{mile}$  for 20' spacing

$$\therefore X_c = X_a' + X_d' = 0.1963 \text{ M}\Omega \cdot \text{mile}$$

This is the capacitive reactance between the conductor and the neutral. Line-to-line capacitive reactance is

$$X_{cl}^{-L} = \frac{X_c}{2} = 0.0981 \text{ M}\Omega \cdot \text{mile}$$

**Capacitance of Balanced Three Phase Line** between a phase conductor and neutral is given by

$$C_n = \frac{2\pi\epsilon_0}{\ln \frac{D_{eq}}{D_b}} \quad \text{F} / \pi$$

where  $D_{eq} = \sqrt[3]{D_{ab} D_{bc} D_{ca}}$  and  $D_{ab}$ ,  $D_{bc}$ , and  $D_{ca}$  are the distances between the centers of the phase conductors, and  $D_b$  is the geometric mean radius for the bundled conductors. (in the expression for  $D_b$  the outside radius of the conductor is used, rather than the GMR from the tables.)

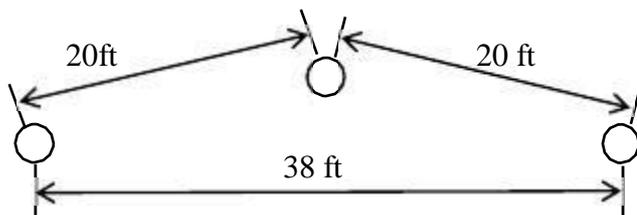
The capacitive reactance to neutral then becomes

$$X_{cn} = \frac{1.779 \times 10^6}{f} \ln \frac{D_{eq}}{D_b} \quad \Omega \text{ mile}$$

**Example:**

a) A three phase 60 Hz line is arranged as shown. The conductors are ACSR Drake. Find the capacitive reactance for 1 mile of the line.

b) If the length of the line is 175 miles and the normal operating voltage is 220 kV, find the capacitive reactance to neutral for the entire length of the line, the charging current for the line, and the charging reactive power.



*Solution:*

The outside radius for Drake conductors is  $r = \frac{1.108}{2} \text{ in} = 0.0462 \text{ ft}$

The geometric mean distance for this line is

$$D_{eq} = \sqrt[3]{20 \times 20 \times 38} = 24.8 \text{ ft}$$

From tables,  $X'_a = 0.0912 \text{ M}\Omega \text{ mile}$

$$X'_d = \frac{1.779 \times 10^6}{f} \ln D_{eq} = \frac{1.779 \times 10^6}{60} \ln 24.8 = 0.0952 \text{ M}\Omega \text{ mile}$$

$$\therefore X_{cn} = X'_a + X'_d = 0.1864 \text{ M}\Omega \text{ mile}$$

This is the capacitive reactance to neutral.

For the length of 175 miles,

$$X_{Ctotal} = \frac{X_{cn}}{175} = 1065 \text{ } \Omega$$

Charging current is

$$I_C = \frac{V_{LN}}{X_{Ctotal}} = \frac{220 \text{ k}}{1065} = 119 \text{ A}$$

Reactive power to charge the line is

$$Q_C = \sqrt{3}V_{LL}I_C = \sqrt{3} \times 220k \times 119 = 45.45 \text{ MVAr}$$

## 2.5 Transmission Line Losses and Thermal Limits

The power losses of a transmission line are proportional to the value of resistance of the line. The value of the resistance is determined by the type and length of the conductor. The current in the line is given by the power being delivered by the transmission line.

$$P_R = E_R I_{\text{equiv}} \cos \Phi_R \quad \therefore \quad I_{\text{equiv}} = \frac{P_R}{E_R \cos \Phi_R}$$

From that,

$$P_{\text{loss}} = I_{\text{equiv}}^2 R = \left( \frac{P_R}{E_R \cos \Phi_R} \right)^2 R$$

Power utilities usually strive to maintain the receiving end voltage constant. The power delivered by the transmission line is determined by the load connected to the line and cannot be changed without changing the load. The only term in the above equation that can be regulated is the power factor. If the power factor can be adjusted to be equal to 1, the power losses will be minimum.

**Efficiency** of the transmission line is given by

$$\eta_{\%} = \frac{P_R}{P_S} \cdot 100\%$$

**Thermal Limits** on equipment and conductors depend on the material of the insulation of conductors. The  $I^2R$  losses are converted into heat. The heat increases the temperature of the conductors and the insulation surrounding it. Some equipment can be cooled by introducing circulation of cooling media, other must depend on natural cooling. If the temperature exceeds the rated value, the insulation will deteriorate faster and at higher temperatures more immediate damage will occur.

The power losses increase with the load. It follows that the rated load is given by the temperature limits. The consequence of exceeding the rated load for short periods of time or by small amounts is a raised temperature that does not destroy the equipment but shortens its service life. Many utilities routinely allow short time overloads on their equipment - for example transformers are often overloaded by up to 15% during peak periods that may last only 15 or 30 minutes.

## **UNIT-II**

# **Performance of Short and Medium Length Transmission Lines**

## SHORT TRANSMISSION LINES

The transmission lines are categorized as three types

- 1) Short transmission line – the line length is up to 80 km
- 2) Medium transmission line – the line length is between 80km to 160 km
- 3) Long transmission line – the line length is more than 160 km



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 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.

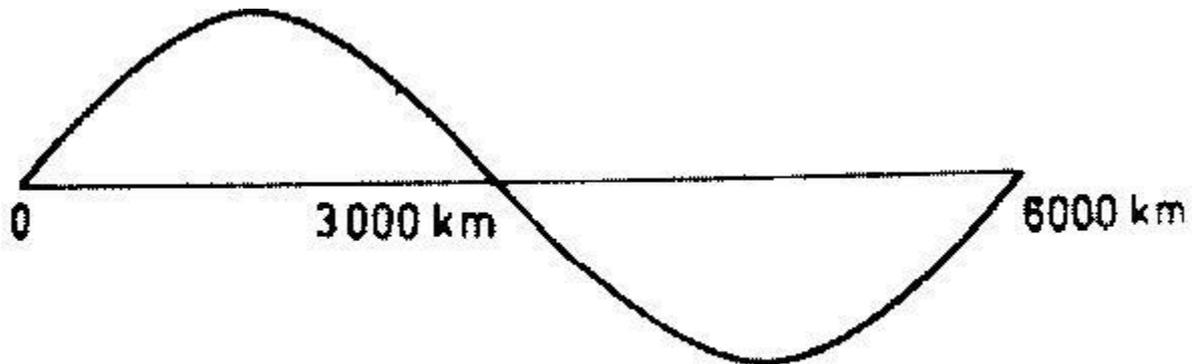
The electrical power is transmitted over a transmission line with a speed of light that is  $3 \times 10^8$  m/sec. Frequency of the power is 50Hz. The wave length of the voltage and current of the power can be determined by the equation given below,

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

Therefore,  $\lambda = \frac{v}{f}$

$$\lambda = \frac{3 \times 10^8}{50} = 6 \times 10^6 \text{ meters} = 6000 \text{ km.}$$

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



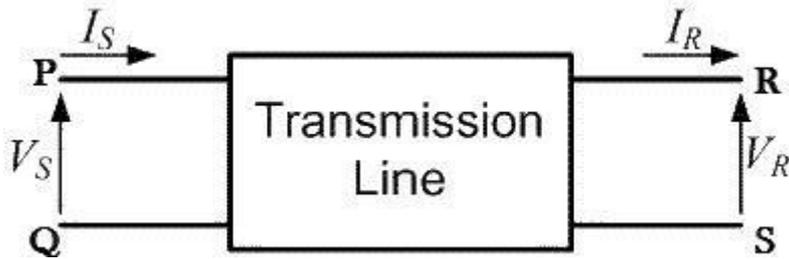
Voltage distribution of 50 Hz supply

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. These 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 end 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.

## ABCD PARAMETERS

A major section of power system engineering deals in the transmission of electrical power from one particular place (eg. 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



Supply end voltage =  $V_S$

and Supply end current =  $I_S$

Given to the input port P Q.

And there is the Receiving end Voltage =  $V_R$

and Receiving end current =  $I_R$

Given to the output port R S.

As shown in the diagram below.

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.

$$V_S = A V_R + B I_R \text{-----(1)}$$

$$I_S = C V_R + D I_R \text{-----(2)}$$

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.

$$V_S = A V_R + B \cdot 0 \Rightarrow V_S = A V_R + 0$$

$$A = \frac{V_S}{V_R} \Big|_{I_R = 0}$$

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 dimensionless parameter.

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

$$I_S = C V_R + D \cdot 0 \Rightarrow I_S = C V_R + 0$$

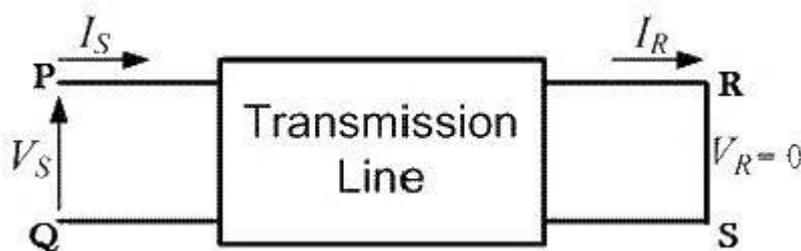
$$C = \frac{I_S}{V_R} \Big|_{I_R = 0}$$

Thus it 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

$$C = I_S / V_R \text{ mho.}$$

### 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

$$V_S = A \cdot 0 + B I_R \Rightarrow V_S = 0 + B I_R$$

$$B = \frac{V_S}{I_R} \Big|_{V_R = 0}$$

Thus it 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

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

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

$$I_S = C \cdot 0 + D I_R \Rightarrow I_S = 0 + D I_R$$

$$D = \frac{I_S}{I_R} \Big|_{V_R = 0}$$

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 dimensionless parameter.  $\therefore$  the ABCD parameters of transmission line can be tabulated as:-

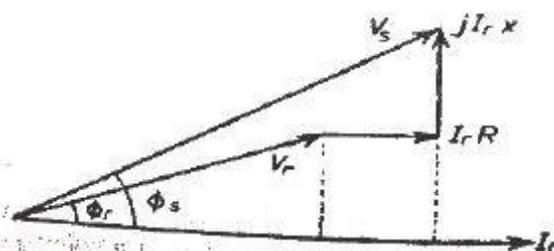
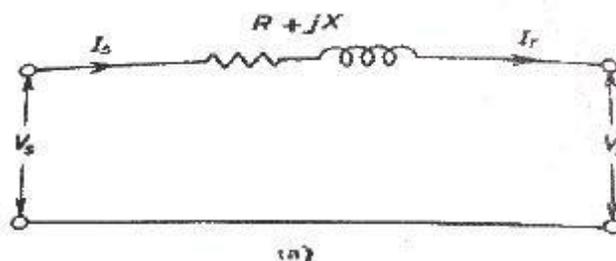
Parameter	Specification	Unit
$A = V_s / V_R$	Voltage ratio	Unit less
$B = V_s / I_R$	Short circuit resistance	$\Omega$
$C = I_s / V_R$	Open circuit conductance	mho
$D = I_s / I_R$	Current ratio	Unit less

### SHORT TRANSMISSION LINE

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

For short length, the shunt capacitance of this type of line is neglected and other parameters like resistance and inductance 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 an angle with that reference receiving end current, of  $\phi_s$  and  $\phi_r$ , respectively.



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

$$V_r + I_r R \cos \phi_r + I_r X \sin \phi_r$$

That means,

$$V_s \cong V_r + I_r R \cos \phi_r + I_r X \sin \phi_r \text{ as it is assumed that } \phi_s \cong \phi_r$$

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,

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

$$= \frac{I_r R \cos \phi_r + I_r X \sin \phi_r}{V_r} \times 100 \%$$

$$\text{per unit regulation} = \frac{I_r R}{V_r} \cos \phi_r + \frac{I_r X}{V_r} \sin \phi_r = v_r \cos \phi_r + v_x \sin \phi_r$$

Here,  $v_r$  and  $v_x$  are the per unit resistance and reactance of the short transmission line.

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 two 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 matrices.

A transmission line 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 matrices. Here the concept of ABCD parameters comes. Voltage and currents of the network can be represented as,

$$V_s = AV_r + BI_r \dots \dots \dots (1)$$

$$I_s = CV_r + DI_r \dots \dots \dots (2)$$

Where A, B, C and D are different constants 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 dimensionless.

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,

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

### Efficiency of Short Transmission Line

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

$$\% \text{ efficiency } (\mu) = \frac{\text{Power received at receiving end}}{\text{Power delivered at sending end}} \times 100 \%$$
$$\% \mu = \frac{\text{Power received at receiving end}}{\text{Power received at receiving end} + 3I_r^2 R} \times 100 \%$$

## 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 modelling of a **medium length transmission line** is done using lumped shunt admittance along with the lumped impedance in series to the circuit.

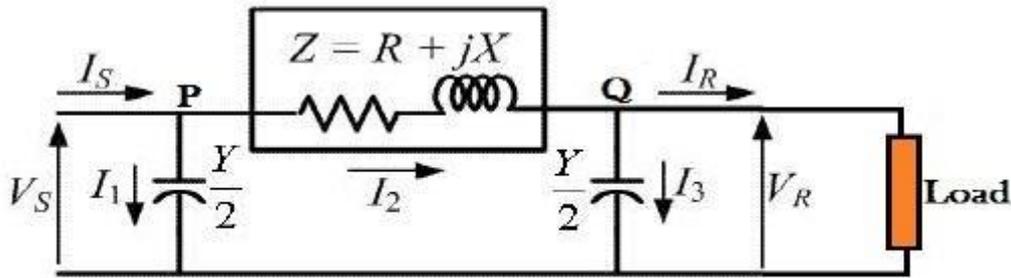
These lumped parameters of a medium length transmission line can be represented using two different models, namely.

- 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.



Nominal  $\Pi$  network of 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.

$$I_S = I_1 + I_2 \text{-----(1)}$$

Similarly applying KCL, to node Q.

$$I_2 = I_3 + I_R \text{-----(2)}$$

Now substituting equation (2) to equation (1)

$$I_S = I_1 + I_3 + I_R$$

$$= \frac{Y}{2}V_S + \frac{Y}{2}V_R + I_R \text{-----(3)}$$

Now by applying KVL to the circuit,

$$V_S = V_R + Z I_2$$

$$= V_R + Z\left(\frac{Y}{2}V_R + I_R\right)$$

$$= \left(Z\frac{Y}{2} + 1\right)V_R + ZI_R \text{-----(4)}$$

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

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

Comparing equation (4) and (5) with the standard ABCD parameter equations

$$V_S = A V_R + B I_R$$

$$I_S = C V_R + D I_R$$

We derive the parameters of a medium transmission line as:

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

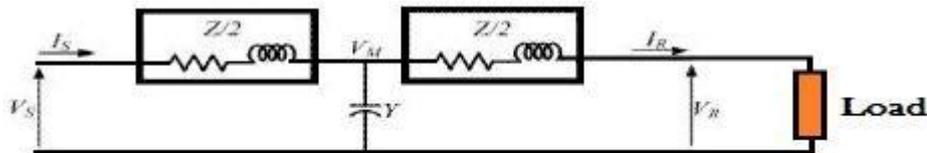
$$B = Z \Omega$$

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

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

### 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.



Nominal T representation of a 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

$$\frac{V_S - V_M}{Z/2} = Y V_M + \frac{V_M - V_R}{Z/2}$$

$$\text{Or } V_M = \frac{2(V_S + V_R)}{YZ + 4} \quad \text{-----(6)}$$

And the receiving end current

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

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

$$\text{Or } I_R = \frac{[(2V_S + V_R) / YZ + 4] - V_R}{Z/2}$$

Rearranging the above equation:

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

Now the sending end current is

$$I_S = Y V_M + I_R \text{ -----(9)}$$

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

$$\text{Or } I_S = Y V_R + \left(\frac{Y}{2}Z + 1\right)I_R \text{ -----(10)}$$

Again comparing equation (8) and (10) with the standard ABCD parameter equations

$$V_S = A V_R + B I_R$$

$$I_S = C V_R + D I_R$$

The parameters of the T network of a medium transmission line are

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

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

$$C = Y \text{ mho}$$

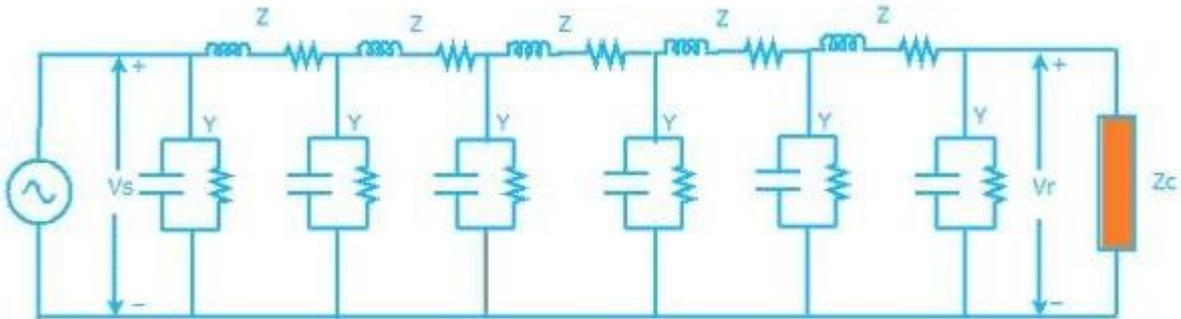
$$D = \left(\frac{Y}{2}Z + 1\right)$$

# **UNIT-III**

## **Performance of Long Transmission Lines**

## LONG TRANSMISSION LINE

A power transmission line with its effective length of around 250 Kms 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 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.

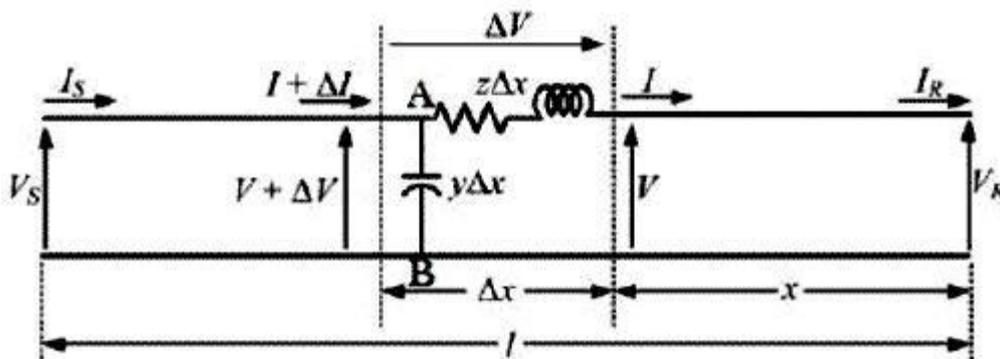


**Long Transmission Line model**

- 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 is 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.



**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. Let us now consider an element of infinitely small length  $\Delta x$  at a distance  $x$  from the receiving end as shown in the figure 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

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

$$\text{Or } I z = \Delta V / \Delta x$$

$$\text{Or } I z = dV / dx \text{ —————(1)}$$

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

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

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.

$$\therefore \text{ we can write } dI / dx = V y \text{ —————(2)}$$

Now differentiating both sides of eq (1) w.r.t  $x$ ,

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

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

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

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

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

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

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

Now comparing equation (1) with equation (5)

$$I = \frac{dV}{dx} = \frac{zA_1 e^{x\sqrt{(yz)}}}{\sqrt{(z/y)}} - \frac{zA_2 e^{-x\sqrt{(yz)}}}{\sqrt{(z/y)}} \text{ —————(6)}$$

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

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

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

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

$$V_R = A_1 + A_2 \text{ —————(9)}$$

$$I_R = A_1 / Z_c + A_2 / Z_c \text{ —————(10)}$$

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  $I = I_s$ .

$$V_S = (V_R + Z_C I_R)e^{\delta l/2} + (V_R - Z_C I_R)e^{-\delta l/2} \text{ —————(11)}$$

$$I_S = (V_R/Z_C + I_R)e^{\delta l/2} - (V_R/Z_C - I_R)e^{-\delta l/2} \text{ —————(12)}$$

By trigonometric and exponential operators we know

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

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

∴ 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,

$$C = \sinh \delta l / Z_C \quad A = \cosh \delta l \quad D = \cosh \delta l \quad B = Z_C \sinh \delta l$$

***UNIT – IV***  
***Power System Transients***

## Bewley Lattice Diagram

This is a convenient diagram devised by Bewley, which shows at a glance the position and direction of motion of every incident, reflected, and transmitted wave on the system at every instant of time. The diagram overcomes the difficulty of otherwise keeping track of the multiplicity of successive reflections at the various junctions.

Consider a transmission line having a resistance  $r$ , an inductance  $l$ , a conductance  $g$  and a capacitance  $c$ , all per unit length.

If  $\gamma$  is the propagation constant of the transmission line, and  $E$  is the magnitude of the voltage surge at the sending end,

then the magnitude and phase of the wave as it reaches any section distance  $x$  from the sending end is  $E_x$  given by.

$$E_x = E \cdot e^{-\gamma x} = E \cdot e^{-(\alpha + j\beta)x} = E e^{-\alpha x} e^{-j\beta x}$$

where

$e^{-\alpha x}$  represents the attenuation in the length of line  $x$   
 $e^{-j\beta x}$  represents the phase angle change in the length of line  $x$

Therefore,

$\alpha$  = attenuation constant of the line in nepers/km  
 $\beta$  = phase angle constant of the line in rad/km.

It is also common for an attenuation factor  $k$  to be defined corresponding to the length of a particular line. i.e.  $k = e^{-\alpha l}$  for a line of length  $l$ .

The propagation constant of a line  $\gamma$  and shunt admittance  $y$  per unit length is given by

$$\gamma = \sqrt{(r + j\omega l)(g + j\omega c)}$$

Similarly the surge impedance of the line (or characteristic impedance)  $Z_0$

$$Z_0 = \sqrt{\frac{r + j\omega l}{g + j\omega c}}$$

When a voltage surge of magnitude  $U$  reaches a junction between two sections with surge impedances  $Z_1$  and  $Z_2$ , then a part is transmitted and a part is reflected back. In traversing the second line, if the attenuation factor is  $k$ , then on reaching the termination at the end of the second line its amplitude would be reduced to  $U \cdot k$ . The lattice diagram may now be constructed as follows. Set the ends of the lines at intervals equal to the time of transit of each line. If a suitable time scale is chosen, then the diagonals on the diagram show the passage of the waves.

High Voltage Transient Analysis

In the Bewley lattice diagram, the following properties exist.

- (2) The position of any wave at any time can be deduced directly from the diagram.
- (3) The total potential at any point, at any instant of time is the superposition of all the waves which have arrived at that point up until that instant of time, displaced in position from each other by intervals equal to the difference in their time of arrival.
- (4) The history of the wave is easily traced. It is possible to find where it came from and just what other waves went into its composition.
- (5) Attenuation is included, so that the wave arriving at the far end of a line corresponds to the value entering multiplied by the attenuation factor of the line.

#### 4.3.1 Analysis of an open-circuit line fed from ideal source

Let  $2$  is the time taken for a wave to travel from one end of the line to the other end of the line (i.e. single transit time) and  $k$  the corresponding attenuation factor.

Consider a step voltage wave of amplitude unity starting from the generator end at time  $t = 0$ . Along the line the wave is attenuated and a wave of amplitude  $k$  reaches the open end at time  $2$ . At the open end, this wave is reflected without a loss of magnitude or a change of sign. The wave is again attenuated and at time  $2$  reaches the generator end with amplitude  $k^2$ . In order to keep the generator voltage unchanged, the surge is reflected with a change of sign ( $-k^2$ ), and after a time  $2$  reaches the open end being attenuated to  $-k^3$ . It is then reflected without a change of sign and reaches the generator end with amplitude  $-k^4$  and reflected with amplitude  $+k^4$ . The whole process is now repeated for the wave of amplitude  $k^4$ .

# **UNIT-V**

## **Various Factors Governing the performance of Transmission line**

## 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 to as the **skin effect in transmission lines**. Such a phenomenon 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 need 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 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 ?

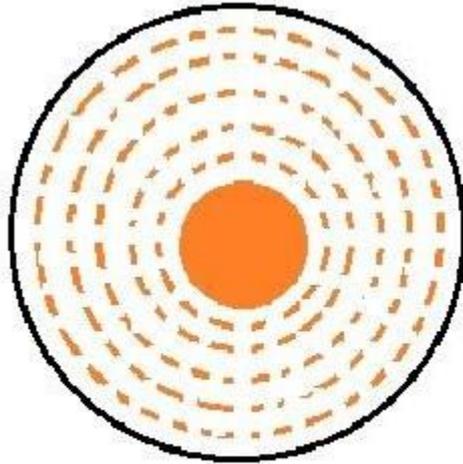
Having understood the phenomena of skin effect let us now see why this arises in case of an a.c. system. To have a clear understanding of that look into the cross sectional view of the conductor during the flow of alternating current given in the diagram below.

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

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 inductance 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 ununiform 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.



## Cross sectional view of 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.

### **FERRANTI EFFECT**

In general practice we know, that for all electrical systems current flows from the region of higher potential to the region of lower potential, to compensate for the potential difference that exists in the system. In all practical cases the sending end voltage is higher than the receiving end, so current flows from the source or the supply end to the load. But Sir S.Z. Ferranti, in the year 1890, came up with an astonishing theory about medium or long distance transmission lines suggesting that in case of light loading or no load operation of transmission system, the receiving end voltage often increases beyond the sending end voltage, leading to a phenomenon known as **Ferranti effect in power system**.

### **Why Ferranti effect occurs in a transmission line?**

A long transmission line can be considered to be composed of a considerably high amount of capacitance and inductance distributed across the entire length of the line. Ferranti Effect occurs when the current drawn by the distributed capacitance of the line itself is greater than the current associated with the load at the receiving end of the line (during light or no load). This capacitor charging current leads to a voltage drop across the line inductance of the transmission system which is in phase with the sending end voltages. This voltage drop keeps on increasing additively as we move towards the load end of the line and subsequently the

receiving end voltage tends to get larger than applied voltage leading to the phenomena called Ferranti effect in power system. It is illustrated with the help of a phasor diagram below.

Thus both the capacitance and inductance effect of transmission line are equally responsible for this particular phenomena to occur, and hence Ferranti effect is negligible in case of a short transmission lines as the inductance of such a line is practically considered to be nearing zero. In general for a 300 Km line operating at a frequency of 50 Hz, the no load receiving end voltage has been found to be 5% higher than the sending end voltage.

Now for analysis of Ferranti effect let us consider the phasor diagram shown above.

Here  $V_r$  is considered to be the reference phasor, represented by OA.

$$\text{Thus } V_r = V_r(1 + j0)$$

$$\text{Capacitance current, } I_c = j\omega CV_r$$

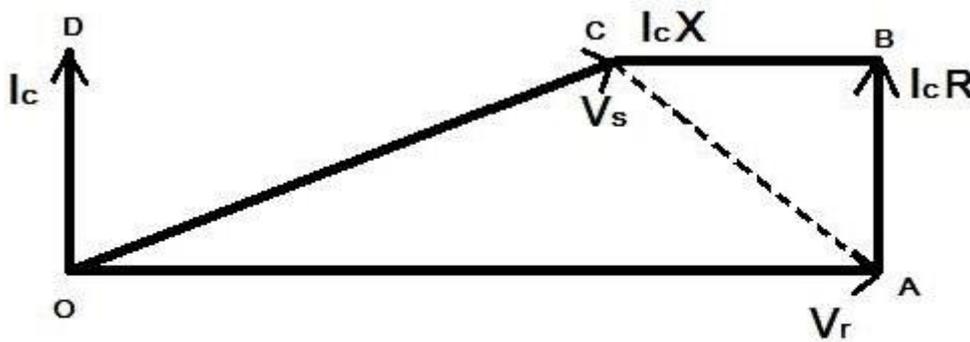
Now sending end voltage  $V_s = V_r + \text{resistive drop} + \text{reactive drop}$ .

$$= V_r + I_c R + jI_c X$$

$$= V_r + I_c (R + jX)$$

$$= V_r + j\omega C V_r (R + j\omega L) \quad [\text{since } X = \omega L]$$

$$\text{Now } V_s = V_r - \omega^2 C L V_r + j\omega C R V_r$$



### Ferranti effect in transmission lines.

This is represented by the phasor OC.

Now in case of a long transmission line, it has been practically observed that the line resistance is negligibly small compared to the line reactance, hence we can assume the length of the phasor  $I_c R = 0$ , we can consider the rise in the voltage is only due to  $OA - OC =$  reactive drop in the line.

Now if we consider  $C_0$  and  $L_0$  are the values of capacitance and inductance per km of the transmission line, where  $l$  is the length of the line.

Thus capacitive reactance  $X_c = 1/(\omega l C_0)$

Since, in case of a long transmission line the capacitance is distributed throughout its length, the average current flowing is,

$$I_c = \frac{1}{2} V_r / X_c = \frac{1}{2} V_r \omega l C_0$$

Now the inductive reactance of the line =  $\omega L_0 l$

Thus the rise in voltage due to line inductance is given by,

$$I_c X = \frac{1}{2} V_r \omega l C_0 X = \omega L_0 l$$

$$\text{Voltage rise} = \frac{1}{2} V_r \omega^2 l^2 C_0 L_0$$

From the above equation it is absolutely evident, that the rise in voltage at the receiving end is directly proportional to the square of the line length, and hence in case of a long transmission line it keeps increasing with length and even goes beyond the applied sending end voltage at times, leading to the phenomena called Ferranti effect in power system.

## CORONA

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 inevitably 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.

### What is corona effect in power system and why it occurs?

For corona effect to occur effectively, two factors here are of prime importance as mentioned below:-

- 1) Alternating potential difference must be supplied across the line.
- 2) The spacing of the conductors, must be large enough compared to the line diameter.



### Corona Effect in Transmission Line

When an alternating current is made to flow across two conductors of the transmission line whose spacing is large compared to their diameters, the 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, the field strength increases and 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 phenomena 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 dielectric 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 it's 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 be 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 di-electric stress on the air reduces and consequently the effect of corona reduces as well. If the spacing is made too large than corona for that region of the transmission line might not occur at all.

# **UNIT-VI**

## **OVERHEAD LINE INSULATORS**

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, e.i. **Stay 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, two 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.

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 becomes more and a quite thick single piece porcelain insulator can not be 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 two parts and for 66KV three parts pin insulator are generally used.

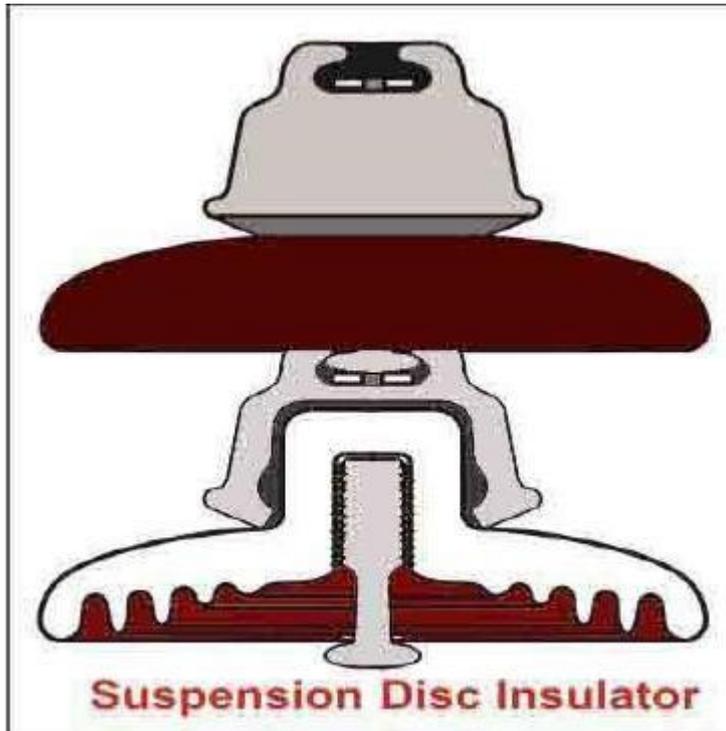
## Designing consideration of Electrical Insulator

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

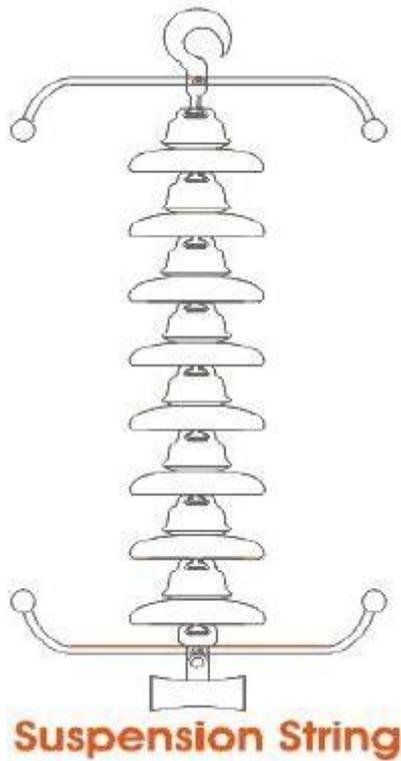


In higher voltage, beyond 33KV, it becomes uneconomical to use pin insulator because size, weight of the insulator become more. Handling and replacing bigger size single unit insulator are quite difficult task. For overcoming these difficulties, **suspension insulator** was developed.

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

1. Each suspension disc is designed for normal voltage rating 11KV(Higher voltage rating 15KV), so by using different numbers of discs, a suspension string can be made suitable for any voltage level.
2. If any one of the disc insulators in a suspension string is damaged, it can be replaced much easily.
3. Mechanical stresses on the suspension insulator is less since the line hangs on a flexible suspension string.
4. As the current carrying conductors are suspended from supporting structure by suspension string, the height of the conductor position is always less than the total height of the supporting structure. Therefore, the conductors may be safe 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.

### 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 use 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.

