UNIT I
TRANSMISSION LINE PARAMETERS

Parameters of single and three phase transmission lines with single and double circuits - Resistance, inductance and capacitance of solid, stranded and bundled conductors, Symmetrical and unsymmetrical spacing and transposition - application of self and mutual GMD; skin and proximity effects - interference with neighboring communication circuits - Typical configurations, conductor types and electrical parameters of EHV lines, corona discharges.

TYPES OF CONDUCTORS

Conductors used for electrical system are those having less resistance, low weight, high tensile strength, low cost and low coefficient of expansion. Normally aluminum and copper are used as conductors. The main advantages of aluminum conductors over copper conductors are:

- Low weight
- Low conductivity (less resistance) and less corona loss
- Low cost

The main problems with aluminum conductors are:

- Low tensile strength
- High coefficient of expansion
- Large area

TYPES OF CONDUCTOR

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 aluminum in place of copper.

2. Aluminum

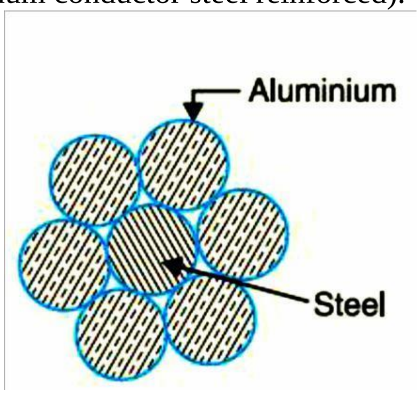
Aluminum is cheap and light as compared to copper but it has much smaller conductivity and tensile strength. The relative comparison of the two materials is briefed below:

(i) The conductivity of aluminum is 60% that of copper. The smaller conductivity of aluminum means that for any particular transmission efficiency, the X-sectional area of conductor must be larger in aluminum than in copper. For the same resistance, the diameter of aluminum conductor is about 1·26 times the diameter of copper conductor. The increased X-section of aluminum 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 aluminum (2·71 gm/cc) is lower than that of copper (8·9 gm/cc).Therefore, an aluminum conductor has almost one-half the weight of equivalent copper conductor. For this reason, the supporting structures for aluminum need not be made so strong as that of copper conductor.
(iii) Aluminum conductor being light is liable to greater swings and hence larger cross-arms are required.
(iv) Due to lower tensile strength and higher co-efficient of linear expansion of aluminum, the sag is greater in aluminum conductors. Considering the combined properties of cost, conductivity, tensile strength, weight etc., aluminum has an edge over copper. Therefore, it is being widely used as a conductor material. It is particularly profitable to use aluminum 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 aluminum

Due to low tensile strength, aluminum 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 aluminum conductor is reinforced with a core of galvanized steel wires. The composite conductor thus obtained is known as *steel cored aluminum* and is abbreviated as A.C.S.R. (aluminum conductor steel reinforced).



Steel-cored aluminum conductor consists of central core of galvanized steel wires surrounded by a number of aluminum strands. Usually, diameter of both steel and aluminum 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 aluminum conductor having one steel wire surrounded by six wires of aluminum. The result of this composite conductor is that steel core takes greater percentage of mechanical strength while aluminum strands carry the bulk of current. The steel cored aluminum 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 aluminum conductors will produce smaller sag and hence longer spans can be used.

(ii) Due to smaller sag with steel cored aluminum conductors, towers of smaller heights can be used.

4. Galvanised steel

Steel has very high tensile strength. Therefore, galvanised steel conductors can be used for extremely long spans or for short line sections exposed to abnormally high stresses due to climatic conditions. They have been found very suitable in rural areas where cheapness is the main consideration. Due to poor conductivity and high resistance of steel, such conductors are not suitable for transmitting large power over a long distance. However, they can be used to advantage for transmitting a small power over a small distance where the size of the copper conductor desirable from economic considerations would be too small and thus unsuitable for use because of poor mechanical strength.

5. Cadmium copper

The conductor material now being employed in certain cases is copper alloyed with cadmium. An addition of 1% or 2% cadmium to copper increases the tensile strength by about 50% and the conductivity is only reduced by 15% below that of pure copper. Therefore, cadmium copper conductor can be useful for exceptionally long spans. However, due to high cost of cadmium, such conductors will be economical only for lines of small X-section i.e., where the cost of conductor material is comparatively small compared with the cost of supports.

STRANDED CONDUCTORS

For transmission lines operating at high voltages normally stranded conductors are used. These conductors are known as composite conductors as they compose of two or more elements or strands electrically in parallel. The conductors used for transmission lines are stranded copper conductors, hollow copper conductors, ACSR conductors and copper weld conductors.

In modern overhead transmission systems bare aluminum conductors are used which are classified as:

AAC : all-aluminum conductor
AAAC : all-aluminum alloy conductor
ACSR : aluminum conductor steel reinforced
ACAR : aluminum conductor alloy reinforced

In order to increase the tensile strength aluminum conductor is reinforced with a core of galvanized steel wire, which is aluminum conductor steel reinforced. ACSR composite conductors are widely used for long distance transmission due to

- Steel cored aluminum conductors are cheaper than copper conductors of equal resistance and this economy is obtained without sacrificing efficiency.
- These conductors are corrosion resistant and are useful under unfavorable conditions.
- The superior mechanical strength of ACSR can be utilized by using spans of larger length results in smaller number of supports.
- Corona losses are reduced because of larger diameter of the conductors.

BUNDLED CONDUCTORS

For voltages in excess of 230KV it is in fact not possible to use a round single conductor. Instead of going in for a hollow conductor it is preferable to use more than one conductor per phase which is known as bundling of conductors. A bundle conductor is a conductor made up of two or more sub conductors and is used as one phase conductor.

ADVANTAGES IN USING BUNDLE CONDUCTORS

- Reduced reactance
- Reduced voltage gradient
- Reduced corona loss
- Reduced radio interference
- Reduced surge impedance

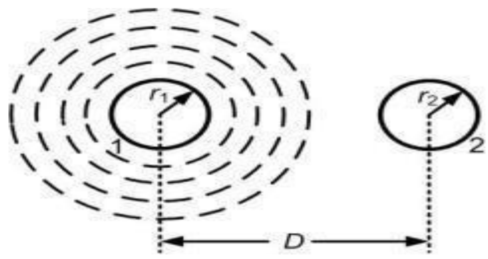
The basic difference between a stranded conductor and bundled conductor is that the sub conductors of bundled conductors are separated from each other by a distance of almost 30cms or more and the wires of composite conductors touch each other.

LINE PARAMETERS

An AC transmission line has resistance, inductance and capacitance uniformly distributed along its length. These are known as constants or parameters of a line. The performance of a transmission line depends upon these constants.

INDUCTANCE OF A SINGLE-PHASE LINE

Consider two solid round conductors with radii of r_1 and r_2 as shown in Fig. 1. One conductor is the return circuit for the other. This implies that if the current in conductor 1 is I then the current in conductor 2 is $-I$. First let us consider conductor 1. The current flowing in the conductor will set up flux lines. However, the flux beyond a distance $D + r_2$ from the center of the conductor links a net current of zero and therefore does not contribute to the flux linkage of the circuit. Also at a distance less than $D - r_2$ from the center of conductor 1 the current flowing through this conductor links the flux. Moreover since $D >> r_2$ we can make the following approximations



A single-phase line with two conductors.

$$D + r_1 \approx D \ and \ D - r_1 \approx D$$

We can specify the inductance of conductor 1 due to internal and external flux as

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

$$L_{ext} = 2 \times 10^{-7} \ln \frac{D_2}{D_1} \text{ H/m}$$

$$L_1 = \left(\frac{1}{2} + 2 \ln \frac{D}{r_1} \right) \times 10^{-7} \text{ H/m} \quad (1)$$

We can rearrange L_1 given in (1) as follows

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

Substituting $r_1' = r_1 e^{-1/4}$ in the above expression we get

$$L_1 = 2 \times 10^{-7} \left(\ln \frac{D}{r_1'} \right) \text{ H/m} \quad (2)$$

The radius r_1' can be assumed to be that of a fictitious conductor that has no internal flux but with the same inductance as that of a conductor with radius r_1.

In a similar way the inductance due current in the conductor 2 is given by

$$L_2 = 2 \times 10^{-7} \left(\ln \frac{D}{r_2'} \right) \text{ H/m} \quad (3)$$

Therefore the inductance of the complete circuit is

$$\begin{aligned} L = L_1 + L_2 &= 2 \times 10^{-7} \left(\ln \frac{D}{r_1'} \right) + 2 \times 10^{-7} \left(\ln \frac{D}{r_2'} \right) \\ &= 2 \times 10^{-7} \left(\ln \frac{D^2}{r_1' r_2'} \right) = 4 \times 10^{-7} \left(\ln \frac{D}{\sqrt{r_1' r_2'}} \right) \text{ H/m} \end{aligned} \quad (4)$$

If we assume $r_1' = r_2' = r'$, then the total inductance becomes

$$L = 4\times10^{-7}\left(\ln\frac{D}{r'}\right) \text{ H/m} \qquad (5)$$

Where $r' = re^{-1/4}$.

INDUCTANCE OF THREE-PHASE LINES WITH SYMMETRICAL SPACING

Consider the three-phase line shown in Fig.2. Each of the conductors has a radius of r and their centers form an equilateral triangle with a distance D between them. Assuming that the currents are balanced, we have

$$I_a + I_b + I_c = 0 \qquad (1)$$

Consider a point P external to the conductors. The distance of the point from the phases a, b and c are denoted by D_{pa}, D_{pb} and D_{pc} respectively.

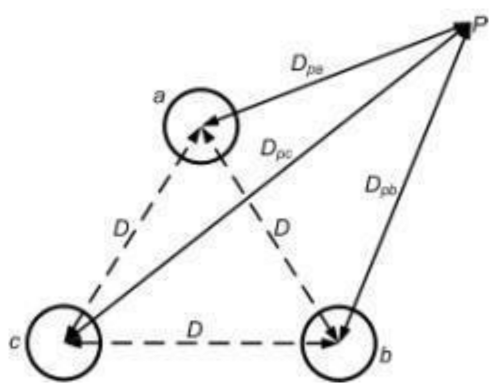


Fig.2 Three-phase symmetrically spaced conductors and an external point P.

Let us assume that the flux linked by the conductor of phase-a due to a current I_a includes the internal flux linkages but excludes the flux linkages beyond the point P . Then from

$$L_1 = 2\times10^{-7}\left(\ln\frac{D}{r_1'}\right)$$

We get

$$\lambda_{apa} = \left(\frac{1}{2} + 2\ln\frac{D_{pa}}{r}\right)I_a = 2\times10^{-7} I_a \ln\frac{D_{pa}}{r'} \qquad (2)$$

The flux linkage with the conductor of phase-a due to the current I_b , excluding all flux beyond

the point P , is given by as

$$\lambda_{apb} = 2\times10^{-7} I_b \ln\frac{D_{pb}}{D} \qquad (3)$$

Similarly the flux due to the current I_c is

$$\lambda_{apc} = 2\times10^{-7} I_c \ln\frac{D_{pc}}{D} \qquad (4)$$

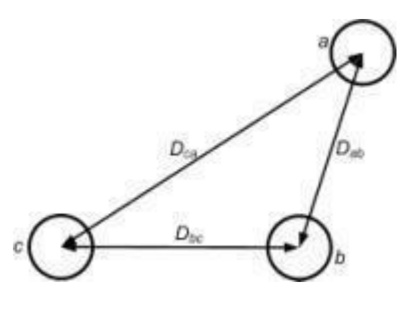
Therefore the total flux in the phase-a conductor is

$$\lambda_a = \lambda_{apa} + \lambda_{apb} + \lambda_{apc} = 2\times10^{-7}\left(I_a \ln\frac{D_{pa}}{r'} + I_b \ln\frac{D_{pb}}{D} + I_c \ln\frac{D_{pc}}{D}\right)$$

$$I_b + I_c = -I_a$$

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

$$L_a = 2\times10^{-7}\ln\frac{D}{r'}$$

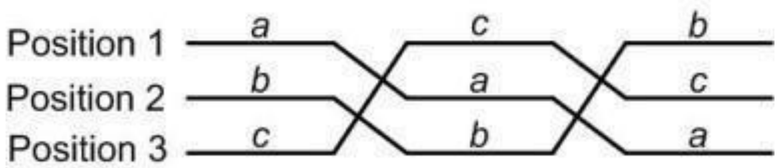


$$L_a = 2\times10^{-7}\left(\ln\frac{1}{r'} + a^2\ln\frac{1}{D_{ab}} + a\ln\frac{1}{D_{ca}}\right)$$
$$L_b = 2\times10^{-7}\left(\ln\frac{1}{r'} + a\ln\frac{1}{D_{ab}} + a^2\ln\frac{1}{D_{bc}}\right)$$
$$L_c = 2\times10^{-7}\left(\ln\frac{1}{r'} + a^2\ln\frac{1}{D_{ca}} + a\ln\frac{1}{D_{bc}}\right)$$

The inductances that are given in (1) to (3) are undesirable as they result in an unbalanced circuit configuration. One way of restoring the balanced nature of the circuit is to exchange the positions of the conductors at regular intervals. This is called transposition of line and is shown.

In this each segment of the line is divided into three equal sub-segments. The conductors of each of the phases a, b and c are exchanged after every sub-segment such that each of them is placed in each of the three positions once in the entire segment.

For example, the conductor of the phase-a occupies positions in the sequence 1, 2 and 3 in the three sub-segments while that of the phase-b occupies 2, 3 and 1. The transmission line consists of several such segments.



A segment of a transposed line.

In a transposed line, each phase takes all the three positions. The per phase inductance is the average value of the three inductances calculated in (1) to (3). We therefore have

$$L = \frac{L_a + L_b + L_c}{3} \tag{4}$$

This implies

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

We know

$$a^2 = e^{j240^0} = -\frac{1}{2} + j\frac{\sqrt{3}}{2} \text{ and } 1 + a + a^2 = 0$$

we have $a + a^2 = -1$. Substituting this in the above equation we get

$$L = \frac{2\times10^{-7}}{3}\left(3\ln\frac{1}{r'} - \ln\frac{1}{D_{ab}} - \ln\frac{1}{D_{bc}} - \frac{1}{D_{ca}}\right) \tag{5}$$

The above equation can be simplified as

$$L = 2\times10^{-7}\left(\ln\frac{1}{r'} - \ln\frac{1}{(D_{ab}D_{bc}D_{ca})^{1/3}}\right) = 2\times10^{-7}\ln\frac{(D_{ab}D_{bc}D_{ca})^{1/3}}{r'} \tag{6}$$

Defining the geometric mean distance (GMD) as

$$GMD = \sqrt[3]{D_{ab}D_{bc}D_{ca}} \quad (7)$$

equation (7) can be rewritten as

$$L = 2\times 10^{-7}\ln\frac{GMD}{r'} \text{ H/m} \quad (8)$$

Notice that (8) is of the same form as for symmetrically spaced conductors. Comparing these two equations we can conclude that *GMD* can be construed as the equivalent conductor spacing. The *GMD* is the cube root of the product of conductor spacing.

CAPACITANCE OF A SINGLE-PHASE LINE

Consider the single-phase line consisting of two round conductors as shown in Fig.5. The separation between the conductors is *D*. Let us assume that conductor 1 carries a charge of q_1 C/m while conductor 2 carries a charge q_2 C/m. The presence of the second conductor and the ground will disturb field of the first conductor.

However we assume that the distance of separation between the conductors is much larger compared to the radius of the conductor and the height of the conductor is much larger than *D* for the ground to disturb the flux. Therefore the distortion is small and the charge is uniformly distributed on the surface of the conductor.

Assuming that the conductor 1 alone has the charge q_1 , the voltage between the conductors is

$$V_{12}(q_1) = \frac{q_1}{2\pi\varepsilon_0}\ln\frac{D_2}{r_1} \text{ V} \quad (1)$$

Similarly if the conductor 2 alone has the charge q_2 , the voltage between the conductors is

$$V_{21}(q_2) = \frac{q_2}{2\pi\varepsilon_0}\ln\frac{D}{r_2}$$

The above equation implies that

$$V_{12}(q_2) = \frac{q_2}{2\pi\varepsilon_0}\ln\frac{r_2}{D} \text{ V} \quad (2)$$

From the principle of superposition we can write

$$V_{12} = V_{12}(q_1) + V_{12}(q_2) = \frac{q_1}{2\pi\varepsilon_0}\ln\frac{D}{r_1} + \frac{q_2}{2\pi\varepsilon_0}\ln\frac{r_2}{D} \text{ V} \quad (3)$$

For a single-phase line let us assume that q_1 (= $-q_2$) is equal to q. We therefore have

$$V_{12} = \frac{q}{2\pi\varepsilon_0}\ln\frac{D}{r_1} - \frac{q}{2\pi\varepsilon_0}\ln\frac{r_2}{D} = \frac{q}{2\pi\varepsilon_0}\ln\frac{D^2}{r_1r_2} \text{ V}$$

Assuming $r_1 = r_2 = r_3$, we can rewrite (4) as

(4)

$$V_{12} = \frac{q}{\pi\varepsilon_0}\ln\frac{D}{r} \qquad \text{V}$$

(5)

The capacitance between the conductors is given by

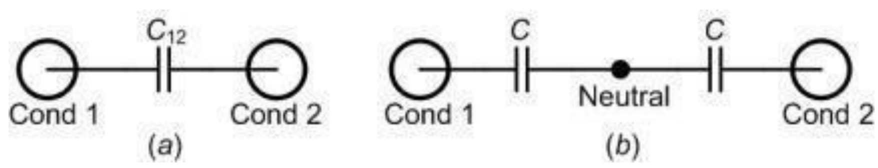
$$C_{12} = \frac{\pi\varepsilon_0}{\ln(D/r)} \qquad \text{F/m}$$

(6)

The above equation gives the capacitance between two conductors. For the purpose of transmission line modeling, the capacitance is defined between the conductor and neutral.

Therefore the value of the capacitance is given from Fig. 5 as

$$C = 2C_{12} = \frac{2\pi\varepsilon_0}{\ln(D/r)}$$



Capacitance between two conductors and (b) equivalent capacitance to ground.

CAPACITANCE OF A THREE-PHASE TRANSPOSED LINE

Consider the three-phase transposed line shown in Fig. 6. In this the charges on conductors of phases a, b and c are q_a, $q_b$and q_c espectively. Since the system is assumed to be balanced we have

$$q_a + q_b + q_c = 0 \quad (1)$$

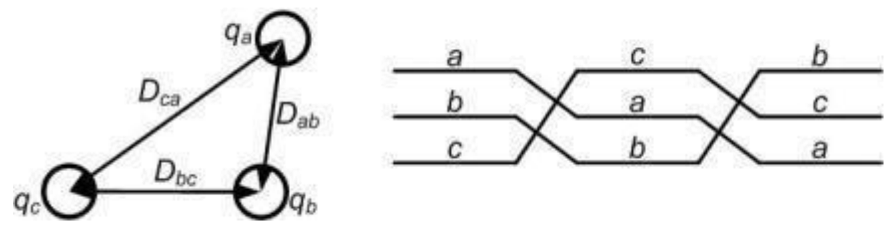


Fig. 6 Charge on a three-phase transposed line.

Using superposition, the voltage V_{ab} for the first, second and third sections of the transposition are given respectively as

$$V_{ab}(1) = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln\frac{D_{ab}}{r} + q_b \ln\frac{r}{D_{ab}} + q_c \ln\frac{D_{bc}}{D_{ca}}\right) \text{V} \quad (2)$$

$$V_{ab}(2) = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln\frac{D_{bc}}{r} + q_b \ln\frac{r}{D_{bc}} + q_c \ln\frac{D_{ca}}{D_{ca}}\right) \text{V} \quad (3)$$

$$V_{ab}(3) = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln\frac{D_{ca}}{r} + q_b \ln\frac{r}{D_{ca}} + q_c \ln\frac{D_{ab}}{D_{bc}}\right) \text{V} \quad (4)$$

Then the average value of the voltage is

$$V_{ab} = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln\frac{D_{ab}D_{bc}D_{ca}}{r^3} + q_b \ln\frac{r^3}{D_{ab}D_{bc}D_{ca}} + q_c \ln\frac{D_{ab}D_{bc}D_{ca}}{D_{ab}D_{bc}D_{ca}}\right) \text{V} \quad (5)$$

This implies

$$V_{ab} = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln\frac{\sqrt[3]{D_{ab}D_{bc}D_{ca}}}{r} + q_b \ln\frac{r}{\sqrt[3]{D_{ab}D_{bc}D_{ca}}}\right) \text{V} \quad (6)$$

From *GMD* of the conductors. We can therefore write

$$V_{ab} = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln\frac{GMD}{r} + q_b \ln\frac{r}{GMD}\right) \text{ V} \tag{7}$$

Similarly the voltage V_{ac} is given as

$$V_{ac} = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln\frac{GMD}{r} + q_c \ln\frac{r}{GMD}\right) \tag{8}$$

Adding (7) and (8) and using (1) we get

$$\begin{aligned} V_{ab} + V_{ac} &= \frac{1}{2\pi\varepsilon_0}\left[2q_a \ln\frac{GMD}{r} + (q_b + q_c)\ln\frac{r}{GMD}\right] \\ &= \frac{1}{2\pi\varepsilon_0}\left[2q_a \ln\frac{GMD}{r} - q_a \ln\frac{r}{GMD}\right] = \frac{3}{2\pi\varepsilon_0} q_a \ln\frac{GMD}{r} \end{aligned} \tag{9}$$

For a set of balanced three-phase voltages

$$\begin{aligned} V_{ab} &= V_{an}\angle 0° - V_{an}\angle -120° \\ V_{ac} &= V_{an}\angle 0° - V_{an}\angle -240° \end{aligned}$$

Therefore we can write

$$V_{ab} + V_{ac} = 2V_{an}\angle 0° - V_{an}\angle -120° - V_{an}\angle -240° = 2V_{an}\angle 0° \text{ V} \tag{10}$$

Combining (9) and (10) we get

$$V_{an} = \frac{1}{2\pi\varepsilon_0} q_a \ln\frac{GMD}{r} \text{ V} \tag{11}$$

Therefore the capacitance to neutral is given by

$$C = \frac{q_a}{V_{an}} = \frac{2\pi\varepsilon_0}{\ln(GMD/r)} \text{ F/m} \tag{12}$$

For bundles conductor

$$C = \frac{2\pi\varepsilon_0}{\ln(GMD/r)}$$

where

$$\begin{aligned} D_b &= \sqrt{\pi d} \text{ for 2 bundle} \\ &= \sqrt[3]{\pi d^2} \text{ for 3 bundle} \\ &= 1.094\sqrt[4]{\pi d^3} \text{ for 4 bundle conductors} \end{aligned}$$

EFFECT OF EARTH ON CAPACITANCE

In calculating the capacitance of transmission lines, the presence of earth was ignored, so far. The effect of earth on capacitance can be conveniently taken into account by the method of images.

METHOD OF IMAGES

- The electric field of transmission line conductors must conform to the presence of the earth below.
- The earth for this purpose may be assumed to be a perfectly conducting horizontal sheet of infinite extent which therefore acts like an equipotential surface.
- The electric field of two long, parallel conductors charged +q and –q per unit is such that it has a zero potential plane midway between the conductors as shown in Fig. 7.

- If a conducting sheet of infinite dimensions is placed at the zero potential plane, the electric field remains undisturbed.
- Further, if the conductor carrying charge -q is now removed, the electric field above the conducting sheet stays intact, while that below it vanishes.
- Using these well-known results in reverse, we may equivalently replace the presence of ground below a charged conductor by a fictitious conductor having equal and opposite charge and located as far below the surface of ground as the overhead conductor above it-such a fictitious conductor is the mirror image of the overhead conductor.
- This method of creating the same electric field as in the presence of earth is known as the method of images originally suggested by Lord Kelvin.

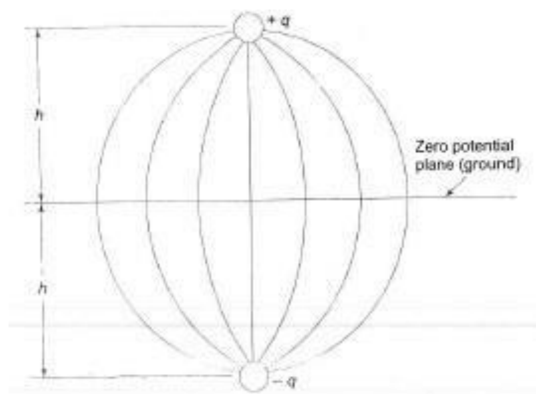
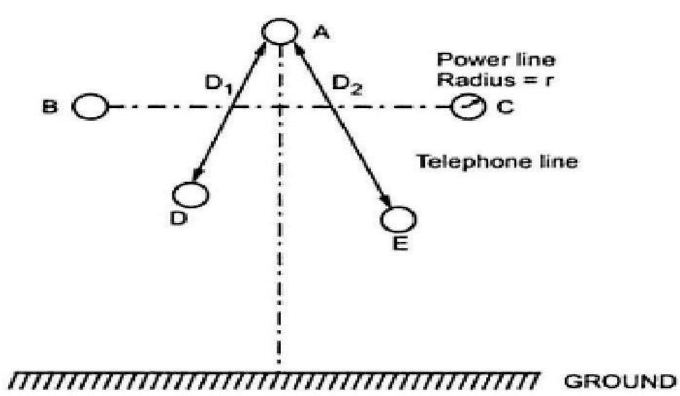


Fig. 7 Electric field of two long, parallel, oppositely charged conductors

EXPRESSION FOR THE VOLTAGE INDUCED IN COMMUNICATION LINESDUE TO THE CURRENT IN POWER LINES



The inductance of this loop is given by,

$$L_{AD} = 2 \times 10^{-7} \ln [D_1/r] \text{ H/m.}$$

The inductance of the loop AE is given by,

$$L_{AE} = 2 \times 10^{-7} \ln [D_2/r] \text{ H/m}$$

The mutual inductance between conductor A and the loop DE is given by,

$$M_A = L_{AE} - L_{AD} = 2 \times 10^{-7} [\ln [D_2/r] \ln [D_1/r]]$$

The net effect of the magnetic field will be,

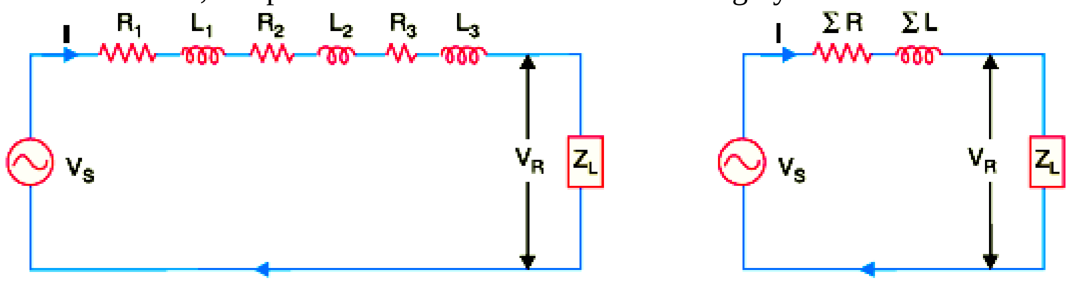
$$M = M_A + M_B + M_C$$

$$V = 2\Pi f I M \text{ volts /m.}$$

PARAMETERS OF SINGLE AND THREE PHASE TRANSMISSION LINES WITH SINGLE AND DOUBLE CIRCUITS

CONSTANTS OF A TRANSMISSION LINE

A transmission line has resistance, inductance and capacitance uniformly distributed along the whole length of the line. Before we pass on to the methods of finding these constants for a transmission line, it is profitable to understand them thoroughly.



(*i*) Resistance. It is the opposition of line conductors to current flow. The resistance is distributed uniformly along the whole length of the line as shown in Fig. However, the performance of a transmission line can be analysed conveniently if distributed resistance is considered as lumped as shown in Fig.

(*ii*) 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.*,

$$\text{Inductance,} \quad L = \frac{\psi}{I} \text{ henry}$$

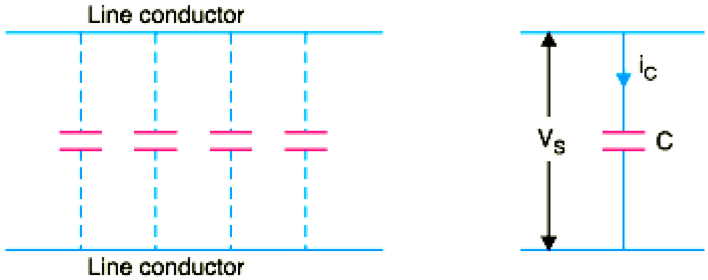
where ψ = flux linkages in weber-turns

I = current in amperes

The inductance is also uniformly distributed along the length of the * line as show in Fig. Again for the convenience of analysis, it can be taken to be lumped as shown in Fig

(*iii*) Capacitance. We know that any two conductors separated by an insulating material consti-tute a capacitor. As any two conductors of an overhead transmission line are separated by air which acts as an insulation, therefore, capacitance exists between any two overhead line conductors. The capacitance between the conductors is the charge per unit potential difference

(*iii*) Capacitance. We know that any two conductors separated by an insulating material consti-tute a capacitor. As any two conductors of an overhead transmission line are separated by air which acts as an insulation, therefore, capacitance exists between any two overhead line conductors. The capacitance between the conductors is the charge per unit potential difference *i.e.*, Capacitance, $C = \frac{q}{v}$ farad



where

q = charge on the line in coulomb

v = p.d. between the conductors in volts

The capacitance is uniformly distributed along the whole length of the line and may be regarded as a uniform series of capacitors connected between the conductors as shown in Fig. 9.2(*i*). When an alternating voltage is impressed on a transmission line, the charge on the conductors at any point increases and decreases with the increase and decrease of the instantaneous value of the voltage between conductors at that point. The result is that a current (known as *charging current*) flows between the conductors [See Fig. 9.2(*ii*)]. This charging current flows in the line even when it is open-circuited *i.e.,* supplying no load. It affects the voltage drop along the line as well as the efficiency and power factor of the line.

Resistance of a Transmission Line

The resistance of transmission line conductors is the most important cause of power loss in a transmission line. The resistance R of a line conductor having resistivity ρ, length l and area of cross-section a is given by ;

$R = \rho\, l/a$

The variation of resistance of metallic conductors with temperature is practically linear over the normal range of operation. Suppose R_1 and R_2 are the resistances of a conductor at t_1 ºC and t_2 ºC

($t_2 > t_1$) respectively. If α_1 is the temperature coefficient at t_1 °C, then,

$$R_2 = R_1\,[1 + \alpha_1\,(t_2 - t_1)]$$

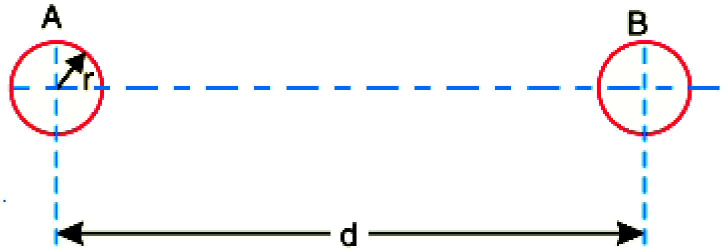
where $$\alpha_1 = \frac{\alpha_0}{1 + \alpha_0\, t_1}$$

$$\alpha_0 = \text{temperature coefficient at } 0^\circ\text{ C}$$

INDUCTANCE OF A 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 (or single phase line) 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.



Consider a single phase overhead line consisting of two parallel conductors A and B spaced d metres apart as shown in Fig. 9.7. 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 A 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

$$= \frac{\mu_0 I_B}{2\pi} \int_d^{\infty} \frac{dx}{x}$$

Total flux linkages with conductor A is

$$\psi_A = \text{exp. } (i) + \text{exp } (ii)$$

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

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

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

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{I_A}{4} + \log_e \infty \, (I_A + I_B) - I_A \log_e r - I_B \log_e d\right)\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{I_A}{4} - I_A \log_e r - I_B \log_e d\right] \quad (\because I_A + I_B = 0)$$

Now, $I_A + I_B = 0$ or $-I_B = I_A$

$\therefore$ $-I_B \log_e d = I_A \log_e d$

$$\therefore \quad \psi_A = \frac{\mu_0}{2\pi}\left[\frac{I_A}{4} + I_A \log_e d - I_A \log_e r\right] \text{wb-turns/m}$$

$$= \frac{\mu_0}{2\pi}\left[\frac{I_A}{4} + I_A \log_e \frac{d}{r}\right]$$

$$= \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{wb-turns/m}$$

Inductance of conductor $A, L_A = \dfrac{\psi_A}{I_A}$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{H/m} = \frac{4\pi \times 10^{-7}}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{H/m}$$

$$L_A = 10^{-7}\left[\frac{1}{2} + 2\log_e \frac{d}{r}\right] \text{H/m}$$

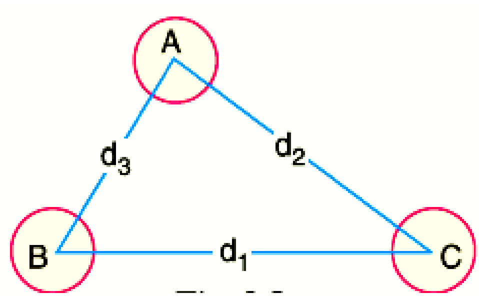
Loop inductance $= 2\,L_A$ H/m $= 10^{-7}\left[1 + 4\log_e \dfrac{d}{r}\right]$ H/m

Loop inductance $= 10^{-7}\left[1 + 4\log_e \dfrac{d}{r}\right]$ H/m

Note that eq. (ii) is the inductance of the two-wire line and is sometimes called loop inductance. However, inductance given by eq. (i) is the inductance per conductor and is equal to half the loop inductance.

INDUCTANCE OF A 3-PHASE OVERHEAD LINE

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 spacings 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 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



Flux linkages with conductor A due to its own current

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

Flux linkages with conductor A due to current I_B

$$= \frac{\mu_0 I_B}{2\pi}\int_{d_3}^{\infty}\frac{dx}{x}$$

Flux linkages with conductor A due to current I_C

$$= \frac{\mu_0 I_C}{2\pi}\int_{d_2}^{\infty}\frac{dx}{x}$$

Total flux linkages with conductor A is

$$\begin{aligned}
\psi_A &= (i)+(ii)+(iii)\\
&= \frac{\mu_0 I_A}{2\pi}\left(\frac{1}{4}+\int_r^{\infty}\frac{dx}{x}\right)+\frac{\mu_0 I_B}{2\pi}\int_{d_3}^{\infty}\frac{dx}{x}+\frac{\mu_0 I_C}{2\pi}\int_{d_2}^{\infty}\frac{dx}{x}\\
&= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4}+\int_r^{\infty}\frac{dx}{x}\right)I_A+I_B\int_{d_3}^{\infty}\frac{dx}{x}+I_C\int_{d_2}^{\infty}\frac{dx}{x}\right]\\
&= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4}-\log_e r\right)I_A-I_B\log_e d_3-I_C\log_e d_2+\log_e\infty\left(I_A+I_B+I_C\right)\right]
\end{aligned}$$

As $\qquad I_A+I_B+I_C = 0,$

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

SYMMETRICAL SPACING

If the three conductors A, B and C are placed symmetrically at the corners of an equilateral triangle of side d, then, d1 = d2 = d3 = d. Under such conditions, the flux Derived in a similar way, the expressions for inductance are the same for conductors B and C.

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

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

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

$$= \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{ werber-turns/m}$$

$$L_A = \frac{\psi_A}{I_A} \text{ H / m} = \frac{\mu_0}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{ H/m}$$

$$= \frac{4\pi \times 10^{-7}}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{ H/m}$$

$$L_A = 10^{-7}\left[0 \cdot 5 + 2\log_e \frac{d}{r}\right] \text{ H/m}$$

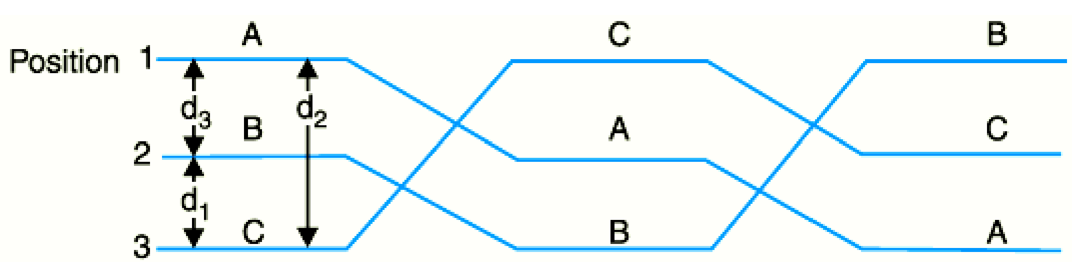
UNSYMMETRICAL SPACING

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. 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. 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.,

$$I_A + I_B + I_C = 0$$

Let the line currents be :



$$I_A = I(1 + j\,0)$$
$$I_B = I(-0{\cdot}5 - j\,0{\cdot}866)$$
$$I_C = I(-0{\cdot}5 + j\,0{\cdot}866)$$

As proved above, the total flux linkages per metre length of conductor A is

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

Putting the values of I_A, I_B and I_C, we get,

$$\psi_A = \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4}-\log_e r\right)I - I(-0\cdot5 - j\,0\cdot866)\log_e d_3 - I(-0\cdot5 + j\,0\cdot866)\log_e d_2\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4}I - I\log_e r + 0\cdot5\,I\log_e d_3 + j\,0\cdot866\log_e d_3 + 0\cdot5\,I\log_e d_2 - j\,0\cdot866\,I\log_e d_2\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4}I - I\log_e r + 0\cdot5\,I\left(\log_e d_3 + \log_e d_2\right) + j\,0\cdot866\,I\left(\log_e d_3 - \log_e d_2\right)\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4}I - I\log_e r + I^*\log_e\sqrt{d_2 d_3} + j\,0\cdot866\,I\log_e\frac{d_3}{d_2}\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4}I + I\log_e\frac{\sqrt{d_2\,d_3}}{r} + j\,0\cdot866\,I\log_e\frac{d_3}{d_2}\right]$$

$$= \frac{\mu_0 I}{2\pi}\left[\frac{1}{4} + \log_e\frac{\sqrt{d_2 d_3}}{r} + j\,0\cdot866\log_e\frac{d_3}{d_2}\right]$$

$\therefore$ Inductance of conductor A is

$$L_A = \frac{\psi_A}{I_A} = \frac{\psi_A}{I}$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4} + \log_e\frac{\sqrt{d_2\,d_3}}{r} + j\,0\cdot866\log_e\frac{d_3}{d_2}\right]$$

$$= \frac{4\pi\times10^{-7}}{2\pi}\left[\frac{1}{4} + \log_e\frac{\sqrt{d_2\,d_3}}{r} + j\,0\cdot866\log_e\frac{d_3}{d_2}\right]\text{ H/m}$$

$$= 10^{-7}\left[\frac{1}{2} + 2\log_e\frac{\sqrt{d_2\,d_3}}{r} + j\,1\cdot732\log_e\frac{d_3}{d_2}\right]\text{ H/m}$$

Similarly inductance of conductors B and C will be :

$$L_B = 10^{-7}\left[\frac{1}{2} + 2\log_e\frac{\sqrt{d_3\,d_1}}{r} + j\,1\cdot732\log_e\frac{d_1}{d_3}\right]\text{ H/m}$$

$$L_C = 10^{-7}\left[\frac{1}{2} + 2\log_e\frac{\sqrt{d_1\,d_2}}{r} + j\,1\cdot732\log_e\frac{d_2}{d_1}\right]\text{ H/m}$$

Inductance of each line conductor

$$= \frac{1}{3}(L_A + L_B + L_C)$$

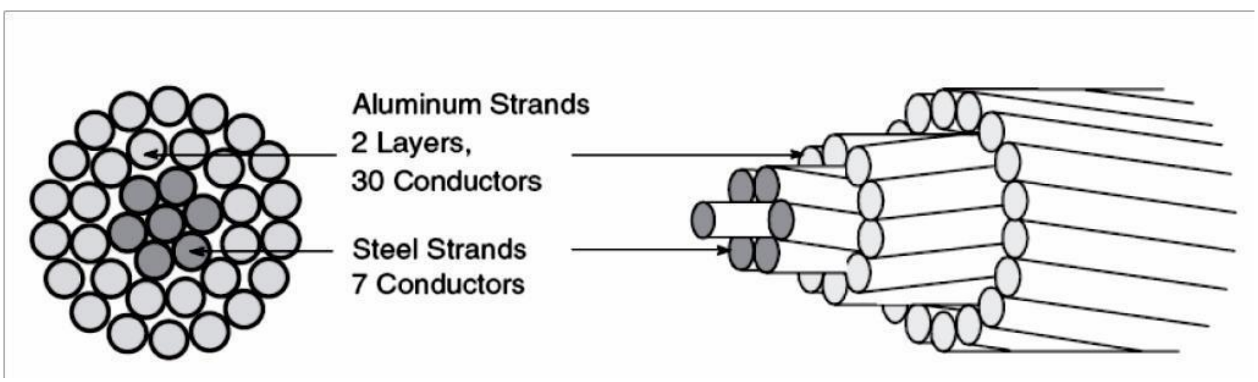
$$= * \left[\frac{1}{2} + 2\log_e \frac{\sqrt[3]{d_1 d_2 d_3}}{r}\right] \times 10^{-7} \text{ H/m}$$

$$= \left[0 \cdot 5 + 2\log_e \frac{\sqrt[3]{d_1 d_2 d_3}}{r}\right] \times 10^{-7} \text{ H/m}$$

If we compare the formula of inductance of an un symmetrically spaced transposed line with that of symmetrically spaced line, we find that inductance of each line conductor in the two cases will be equal if $d = \sqrt[3]{d_1 d_2 d_3}$ The distance d is known as equivalent equilateral spacing for un symmetrically transposed line

SPIRALING AND BUNDLE CONDUCTOR EFFECT

There are two types of transmission line conductors: overhead and underground. Overhead conductors, made of naked metal and suspended on insulators, are preferred over underground conductors because of the lower cost and easy maintenance. Also, overhead transmission lines use aluminum conductors, because of the lower cost and lighter weight compared to copper conductors, although more cross-section area is needed to conduct the same amount of current. There are different types of commercially available aluminum conductors: aluminum-conductor-steel-reinforced (ACSR), aluminum-conductor-alloy-reinforced (ACAR), all-aluminum-conductor (AAC), and all-aluminumalloy- conductor (AAAC).



ACSR is one of the most used conductors in transmission lines. It consists of alternate layers of stranded conductors, spiraled in opposite directions to hold the strands together, surrounding a core of steel strands. Figure 13.4 shows an example of aluminum and steel strands combination. The purpose of introducing a steel core inside the stranded aluminum conductors is to obtain a high strength-to-weight ratio. A stranded conductor offers more flexibility and easier to manufacture than a solid large conductor. However, the total resistance is increased because the outside strands are larger than the inside strands on account of the spiraling. The resistance of each wound conductor at any layer, per unit length, is based on its total length as follows:

$$R_{cond} = \frac{\rho}{A}\sqrt{1+\left(\pi\frac{1}{P}\right)^2}\ \ \Omega/m$$

CONCEPT OF SELF-GMD AND MUTUAL-GMD

The use of self geometrical mean distance (abbreviated as self-GMD) and mutual geometrical mean distance (mutual-GMD) simplifies the inductance calculations, particularly relating to multi conductor arrangements. The symbols used for these are respectively Ds and Dm. We shall briefly discuss these terms.

(i) Self-GMD (Ds)

In order to have concept of self-GMD (also sometimes called Geometrical mean radius; GMR), consider the expression for inductance per conductor per metre already derived in Art. Inductance/conductor/m

$$= 2\times10^{-7}\left(\frac{1}{4}+\log_e\frac{d}{r}\right)$$
$$= 2\times10^{-7}\times\frac{1}{4}+2\times10^{-7}\log_e\frac{d}{r}$$

In this expression, the term 2 × 10-^{7} × (1/4) is the inductance due to flux within the solid conductor. For many purposes, it is desirable to eliminate this term by the introduction of a concept called self-GMD or GMR. If we replace the original solid conductor by an equivalent hollow cylinder with extremely thin walls, the current is confined to the conductor surface and internal conductor flux linkage would be almost zero. Consequently, inductance due to internal flux would be zero and the term 2 × 10-^{7} × (1/4) shall be eliminated. The radius of this equivalent hollow cylinder must be sufficiently smaller than the physical radius of the conductor to allow room for enough additional flux to compensate for the absence of internal flux linkage. It can be proved mathematically that for a solid round conductor of radius r, the self-GMD or GMR = 0·7788 r. Using self-GMD, the eq. (i) becomes :

Inductance/conductor/m = 2 × 10-7log$_e$ d/ Ds *

Where

Ds = GMR or self-GMD = 0·7788 r

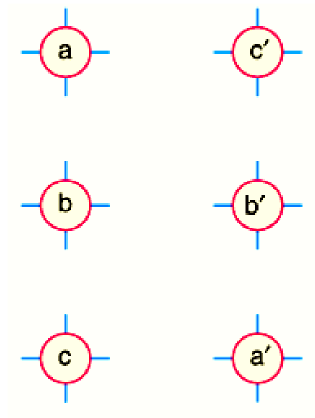
It may be noted that self-GMD of a conductor depends upon the size and shape of the conductor and is independent of the spacing between the conductors.

(ii) Mutual-GMD

The mutual-GMD is the geometrical mean of the distances form one conductor to the other and, therefore, must be between the largest and smallest such distance. In fact, mutual-GMD simply represents the equivalent geometrical spacing.

(a) The mutual-GMD between two conductors (assuming that spacing between conductors is large compared to the diameter of each conductor) is equal to the distance between their centres i.e. Dm = spacing between conductors = d

(b) For a single circuit 3-φ line, the mutual-GMD is equal to the equivalent equilateral spacing i.e., $(d_1 d_2 d_3)^{1/3}$.



(c) The principle of geometrical mean distances can be most profitably employed to 3-φ double circuit lines. Consider the conductor arrangement of the double circuit shown in Fig. Suppose the radius of each conductor is r.
Self-GMD of conductor = 0·7788 r
Self-GMD of combination aa' is

$$D_{s1} = (**D_{aa} \times D_{aa'} \times D_{a'a'} \times D_{a'a})^{1/4}$$

Self-GMD of combination bb' is

$$D_{s2} = (D_{bb} \times D_{bb'} \times D_{b'b'} \times D_{b'b})^{1/4}$$

Self-GMD of combination cc' is

$$D_{s3} = (D_{cc} \times D_{cc'} \times D_{c'c'} \times D_{c'c})^{1/4}$$

Equivalent self-GMD of one phase

$$D_s = (D_{s1} \times D_{s2} \times D_{s3})^{1/3}$$

The value of Ds is the same for all the phases as each conductor has the same radius.
Mutual-GMD between phases A and B is

$$D_{AB} = (D_{ab} \times D_{ab'} \times D_{a'b} \times D_{a'b'})^{1/4}$$

Mutual-GMD between phases B and C is

$$D_{BC} = (D_{bc} \times D_{bc'} \times D_{b'c} \times D_{b'c'})^{1/4}$$

Mutual-GMD between phases C and A is

$$D_{CA} = (D_{ca} \times D_{ca'} \times D_{c'a} \times D_{c'a'})^{1/4}$$

Equivalent mutual-GMD, $D_m = (D_{AB} \times D_{BC} \times D_{CA})^{1/3}$

It is worthwhile to note that mutual GMD depends only upon the spacing and is substantially independent of the exact size, shape and orientation of the conductor.

Inductance Formulas in Terms of GMD

The inductance formulas developed in the previous articles can be conveniently expressed in terms of geometrical mean distances.

(i) Single phase line

$$\text{Inductance/conductor/m} = 2 \times 10^{-7} \log_e \frac{D_m}{D_s}$$

where $D_s = 0{\cdot}7788\, r$ and D_m = Spacing between conductors = d

(ii) Single circuit 3-ϕ line

$$\text{Inductance/phase/m} = 2 \times 10^{-7} \log_e \frac{D_m}{D_s}$$

where $D_s = 0{\cdot}7788\, r$ and $D_m = (d_1\, d_2\, d_3)^{1/3}$

(iii) Double circuit 3-ϕ line

$$\text{Inductance/phase/m} = 2 \times 10^{-7} \log_e \frac{D_m}{D_s}$$

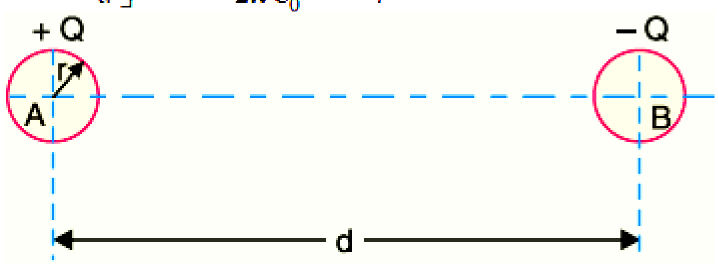
where $D_s = (D_{s1}\, D_{s2}\, D_{s3})^{1/3}$ and $D_m = (D_{AB} \times D_{BC} \times D_{CA})^{1/3}$

CAPACITANCE OF A 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. The total p.d. between conductor A and neutral "infinite" plane is

$$V_A = \int_r^{\infty} \frac{Q}{2\pi\, x\, \varepsilon_0}\, dx + \int_d^{\infty} \frac{-Q}{2\pi\, x\, \varepsilon_0}\, dx$$

$$= \frac{Q}{2\pi\, \varepsilon_0}\left[\log_e \frac{\infty}{r} - \log_e \frac{\infty}{d}\right] \text{volts} = \frac{Q}{2\pi\, \varepsilon_0} \log_e \frac{d}{r} \text{ volts}$$



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

$$V_B = \int_r^{\infty} \frac{-Q}{2\pi x\, \varepsilon_0}\, dx + \int_d^{\infty} \frac{Q}{2\pi x\, \varepsilon_0}\, dx$$

$$= \frac{-Q}{2\pi\, \varepsilon_0}\left[\log_e \frac{\infty}{r} - \log_e \frac{\infty}{d}\right] = \frac{-Q}{2\pi\, \varepsilon_0} \log_e \frac{d}{r} \text{ volts}$$

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

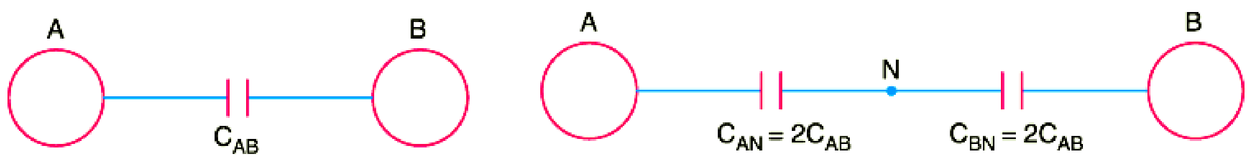
$$V_{AB} = 2V_A = \frac{2Q}{2\pi \varepsilon_0} \log_e \frac{d}{r} \text{ volts}$$

Capacitance, $$C_{AB} = Q/V_{AB} = \frac{Q}{\frac{2Q}{2\pi \varepsilon_0} \log_e \frac{d}{r}} \text{ F/m}$$

$$C_{AB} = \frac{\pi \varepsilon_0}{\log_e \frac{d}{r}} \text{ F / m}$$

Capacitance to neutral

Equation (i) 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



$$\text{Capacitance to neutral, } C_N = C_{AN} = C_{BN} = 2C_{AB}$$

$$C_N = \frac{2\pi \varepsilon_0}{\log_e \frac{d}{r}} \text{ F / m}$$

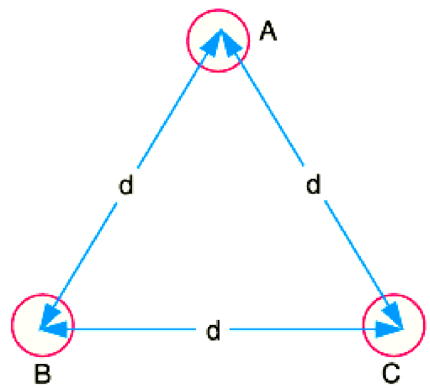
The reader may compare eq. (ii) to the one for inductance. One difference between the equations for capacitance and inductance should be noted carefully. The radius in the equation for capacitance is the actual outside radius of the conductor and not the GMR of the conductor as in the inductance formula. Note that eq. (ii) applies only to a solid round conductor.

2.7.1 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 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 meter length respectively. Let the conductors be equidistant (d meters) from each other. We shall find the capacitance from line conductor to neutral in this symmetrically spaced line. Referring to Fig,



Overall potential difference between conductor A and infinite neutral plane is given by

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

$$= \frac{1}{2\pi\varepsilon_0}\left[Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d} + Q_C \log_e \frac{1}{d}\right]$$

$$= \frac{1}{2\pi\varepsilon_0}\left[Q_A \log_e \frac{1}{r} + (Q_B + Q_C) \log_e \frac{1}{d}\right]$$

Assuming balanced supply, we have, $Q_A + Q_B + Q_C = 0$

$$\therefore \quad Q_B + Q_C = -Q_A$$

$$\therefore \quad V_A = \frac{1}{2\pi\varepsilon_0}\left[Q_A \log_e \frac{1}{r} - Q_A \log_e \frac{1}{d}\right] = \frac{Q_A}{2\pi\varepsilon_0} \log_e \frac{d}{r} \text{ volts}$$

$\therefore$ Capacitance of conductor A w.r.t neutral,

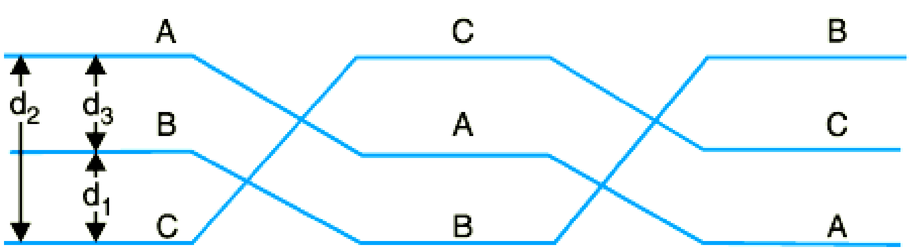
$$C_A = \frac{Q_A}{V_A} = \frac{Q_A}{\frac{Q_A}{2\pi\varepsilon_0}\log_e \frac{d}{r}} \text{ F/m} = \frac{2\pi\varepsilon_0}{\log_e \frac{d}{r}} \text{ F/m}$$

$$C_A = \frac{2\pi\varepsilon_0}{\log_e \frac{d}{r}} \text{ F/m}$$

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. shows a 3-phase transposed line having unsymmetrical spacing. Let us assume balanced conditions i.e. $Q_A + Q_B + Q_C = 0$.



Considering all the three sections of the transposed line for phase A,

$$\text{Potential of 1st position,} \quad V_1 = \frac{1}{2\pi\varepsilon_0}\left(Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_3} + Q_C \log_e \frac{1}{d_2}\right)$$

$$\text{Potential of 2nd position,} \quad V_2 = \frac{1}{2\pi\varepsilon_0}\left(Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_1} + Q_C \log_e \frac{1}{d_3}\right)$$

$$\text{Potential of 3rd position,} \quad V_3 = \frac{1}{2\pi\varepsilon_0}\left(Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_2} + Q_C \log_e \frac{1}{d_1}\right)$$

Average voltage on conductor A is

$$V_A = \frac{1}{3}(V_1 + V_2 + V_3)$$

$$= \frac{1}{3\times 2\pi\varepsilon_0} * \left[Q_A \log_e \frac{1}{r^3} + (Q_B + Q_C)\log_e \frac{1}{d_1 d_2 d_3} \right]$$

As $Q_A + Q_B + Q_C = 0$, therefore, $Q_B + Q_C = -Q_A$

$$\therefore \quad V_A = \frac{1}{6\pi\varepsilon_0}\left[Q_A \log_e \frac{1}{r^3} - Q_A \log_e \frac{1}{d_1 d_2 d_3} \right]$$

$$= \frac{Q_A}{6\pi\varepsilon_0} \log_e \frac{d_1 d_2 d_3}{r^3}$$

$$= \frac{1}{3} \times \frac{Q_A}{2\pi\varepsilon_0} \log_e \frac{d_1 d_2 d_3}{r^3}$$

$$= \frac{Q_A}{2\pi\varepsilon_0} \log_e \left(\frac{d_1 d_2 d_3}{r^3} \right)^{1/3}$$

$$= \frac{Q_A}{2\pi\varepsilon_0} \log_e \frac{(d_1 d_2 d_3)^{1/3}}{r}$$

Capacitance from conductor to neutral is

$$C_A = \frac{Q_A}{V_A} = \frac{2\pi\varepsilon_0}{\log_e \frac{\sqrt[3]{d_1 d_2 d_3}}{r}} \ F/m$$

INDUCTIVE INTERFERENCE WITH NEIGHBOURING COMMUNICATION CIRCUITS

It is usual practice to run telephone lines along the same route as the power lines. The transmission lines transmit bulk power at relatively high voltages and, therefore, these lines give rise to electro-magnetic and electrostatic fields of sufficient magnitude which induce are superposed on the true speech currents in the neighboring telephone wires and set up distortion while the voltage so induced raise the potential of the communication circuit as a whole. In extreme cases the effect of these may make it impossible to transmit any message faithfully and may raise the potential of the telephone receiver above the ground to such an extent to render the handling of the telephone receiver extremely dangerous and in such cases elaborate precautions are required to be observed to avoid this danger.

In practice it is observed that the power lines and the communication lines run along the same path. Sometimes it can also be seen that both these lines run on same supports along the same route. The transmission lines transmit bulk power with relatively high voltage. Electromagnetic and electrostatic fields are produced by these lines having sufficient magnitude. Because of these fields, voltages and currents are induced in the neighbouring communication lines. Thus it gives rise to interference of power line with communication circuit.

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

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

There are various factors influencing the telephone interference. These factors are as follows

1) Because of harmonics in power circuit, their frequency range and magnitudes.
2) Electromagnetic coupling between power and telephone conductor.

The electric coupling is in the form of capacitive coupling between power and telephone conductor whereas the magnetic coupling is through space and is generally expressed in terms of mutual inductance at harmonic frequencies.

3) Due to unbalance in power circuits and in telephone circuits.
4) Type of return telephone circuit i.e. either metallic or ground return.
5) Screening effects.

Steps for Reducing Telephone Interference

There are various ways that can reduce the telephone interference. Some of them are as listed below

i) The harmonics at the source can be reduced with the use of A.C. harmonic filters, D.C. harmonic filters and smoothing rectors.
ii) Use greater spacing between power and telephone lines.
iii) The parallel run between telephone line and power line is avoided.
iv) Instead of using overhead telephone wires, underground telephone cables may be used.
v) If the telephone circuit is ground return then replace it with metallic return.
vi) Use microwave or carrier communication instead of telephone communication.
vii) The balance of AC power line is improved by using transposition. Transposition of lines reduces the induced voltages to a considerable extent. The capacitance of the lines is balanced by transposition leading to balance in electro statically induced voltages. Using transposition the fluxes due to positive and negative phase sequence currents cancel out so the electromagnetically induced e.m.f 's are diminished. For zero sequence currents the telephone lines are also transposed which is shown in the Fig.

INDUCTIVE INTERFERENCE WITH NEIGHBOURING CIRCUITS

The factors influencing the telephone interference are:

- Because of harmonics in power circuit, their frequency range and magnitudes
- Electromagnetic coupling
- Due to unbalance in power circuits and in telephone circuits
- Type of return telephone circuit
- Screening effects

STEPS FOR REDUCING TELEPHONE INTERFERENCE

- Harmonics can be reduced with the use of AC harmonic filters, DC harmonic filters and smoothening reactors
- Use greater spacing between power and telephone lines
- Parallel run between telephone and power line is avoided
- If telephone circuit is ground return, replace with metallic return.