Lecture 4

Electrical Design of Tx System

Electrical Design of Overhead Tx lines

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The main function of Tx lines are to transfer bulk amount of Power to Load Centers and industrial users up to the Primary distribution lines. A Tx line Consists of structures, Wires, Switching & Conversion Stations. it form the bone of a Power System which Connects the Generating station with the Load. Tx Systems are interconnected due to economic, Security & reliability reasons.

Representation of Tx Lines

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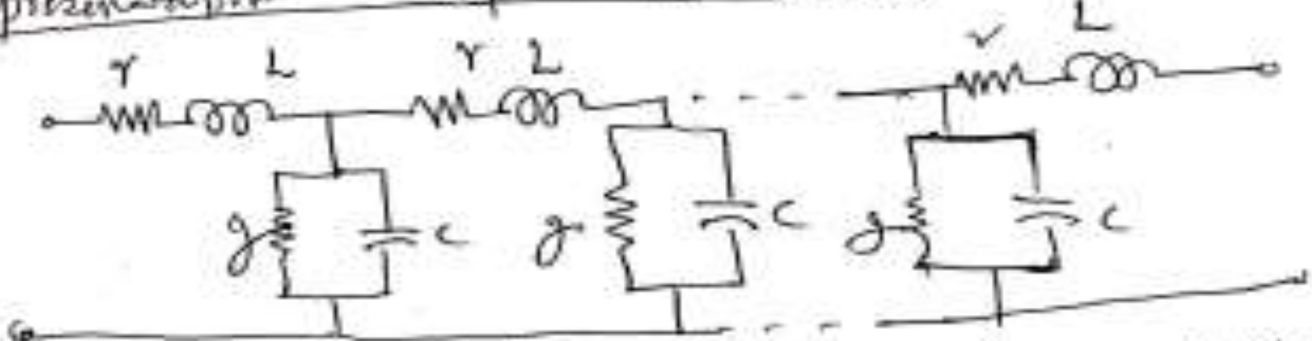


The Tx Capacity of a line mainly depends on the inductance and capacitance. as resistance & conductance are very small

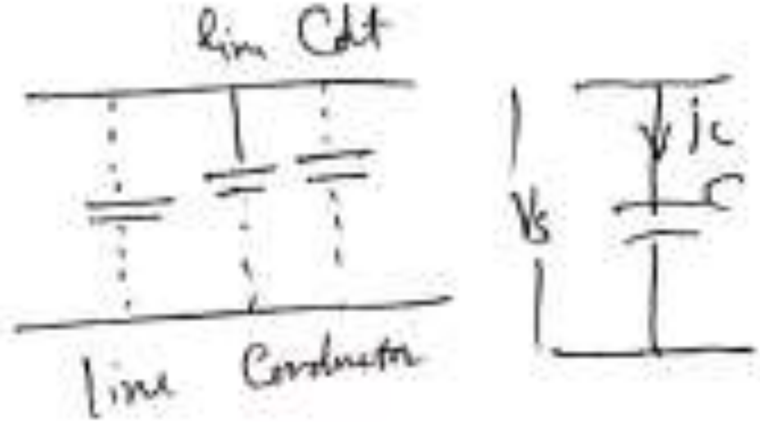
Inductors & Inductance

Inductance L is defined as the flux linkages per unit current. Mathematically it can be written if the flux linkages linearly changes with the current as

$$L = \frac{\text{Total Magnetic flux linkages}}{\text{Current}} = \frac{\lambda}{I} = \frac{N\phi}{I}$$

Capacitor × Capacitance

$C = q/v$ farad.



Ampere's Law : mmf around any closed Path equals the current enclosed by the Path.

$$mmf = H * l = I$$

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

Inductance of an inductor

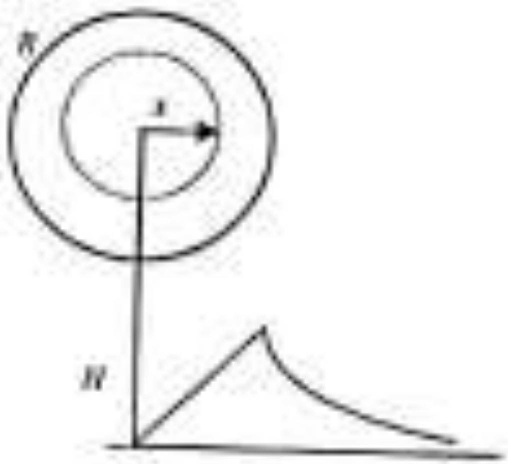


Figure 9.2 Variation of magnetic field intensity of a long conductor.

Magnetic field intensity outside the conductor

Let us calculate the magnetic field intensity (H_x) using Ampere's law at a distance x (>R). The length of enclosed path will be $2\pi x$ and the enclosed current is I. Using Equation (9.7),

$$\oint H_x dl = I \quad \text{or} \quad H_x 2\pi x = I \tag{9.9}$$

or

$$H_x = \frac{I}{2\pi x} \tag{9.10}$$

This shows that magnetic field intensity is inversely proportional to the distance x, out side the conductor.

Magnetic field intensity inside the conductor

Let us calculate the magnetic field intensity (H_x) using Ampere's Law at a distance x ($< R$). The length of enclosed path will be $2\pi x$ (Figure 9.2). Since the current density ($I_x/a' = I/a$) is same throughout the conductor where a' and a are the area of the conductor at radius x and R respectively, the enclosed current at x inside the conductor will be

$I_x/a' = I/a$

$$I_x = I\frac{\pi x^2}{\pi R^2} \quad \text{or} \quad \underline{I_x = I\left(\frac{x}{R}\right)^2} \qquad (9.11)$$

$a = \pi r^2$ X This shows that the current enclosed at path x is portion of I by $(x/R)^2$ $x<R$;

Using Ampere's law,

$$\oint \mathbf{H}_x dl = I_x \quad \text{or} \quad \mathbf{H}_x 2\pi x = I\left(\frac{x}{R}\right)^2 \tag{9.12}$$

or

$$\mathbf{H}_x = \frac{Ix}{2\pi R^2} \tag{9.13}$$

This indicates that magnetic field intensity at a distance x inside the conductor is directly proportional to the distance from the centre of the conductor. Following observation can be made from above calculations:

1. Magnetic field intensity at surface of the conductor is the highest.
2. Magnetic field intensity at the centre of the conductor is zero.
3. The presence of earth will affect the magnetic field geometry insignificantly.
4. Even the volume of the conductor is small, magnetic field energy ($W_e = 0.5\,\mu\mathrm{H}^2$) stored is not small.

9.6 INDUCTANCE OF A CONDUCTOR

Inductance of a conductor is defined as the flux linkage per ampere. Since there are two flux linkages: one is due to the internal flux and second is due to the external flux, inductances corresponding to these fluxes are calculated separately. Following assumptions are made:

(a) Current density in the conductor is uniform

(b) Relative permeability of conductor material is unity.

Inductance due to internal flux linkages. Magnetic flux density (B) can be written using Equation (9.13) as

$\mu_r = 1$

$$\mathbf{B} = \mu \mathbf{H} = \mu_0 \mu_r \mathbf{H} = \mu_0 \frac{Ix}{2\pi R^2}$$

This shows that flux density varies with the distance from the centre. Refer to Figure 9.3.

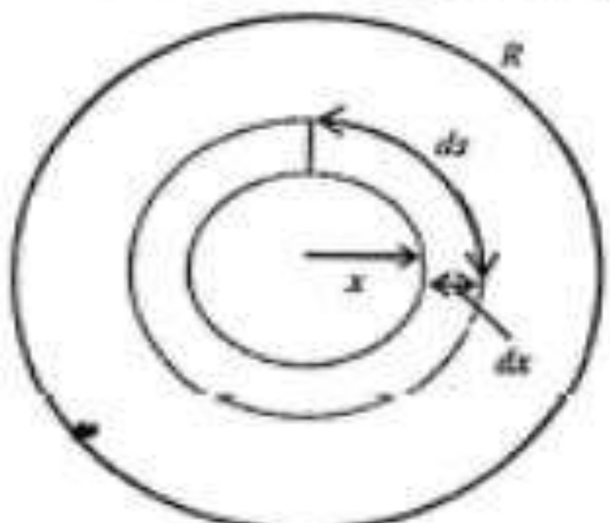


Figure 9.3 Cross-section of conductor.

Let us take magnetic field density ($\mathbf{B}_x$) is constant for small distance of dx at x from the centre. The flux ($d\phi$) passing through a small cylindrical shell of radii x and $x + dx$ will be

$$d\phi = \mathbf{B}_x dxl = \mu_0 I_x dxl/(2\pi R^2) \text{ Wb}$$

where l is the length of the wire. Since this flux links only the current enclosed in the radius of x, the flux linkage will be product of flux and number of turns. Thus

$$d\lambda = d\phi\left(\frac{x}{R}\right)^2 \quad \left(\text{since } \frac{I_x}{I} = \frac{\pi x^2}{\pi R^2}\right) \qquad d\lambda = d\phi\, N$$

or

$$d\lambda = \mu_0 \frac{Ix}{2\pi R^2}\left(\frac{x}{R}\right)^2 dx \qquad \text{(if length of wire } l = 1 \text{ metre)}$$

Thus total flux linkage will be

$$\lambda = \int_0^R d\lambda = \frac{I\mu_0}{2\pi R^4}\int_0^R x^3 dx = \frac{I\mu_0}{8\pi}$$

Inductance due to internal flux linkage (L_{int}) will be

$$L_{int} = \frac{\lambda}{I} = \frac{\mu_0}{8\pi} = \frac{10^{-7}}{2} \text{ H/m} \qquad (9.14)$$

Inductance due to external flux linkages. Let us calculate the flux linkage between two points A and B at distances d_1 and d_2 respectively from the centre of the conductor. The flux density ($\mathbf{B}_x$) at distance x from the centre of the conductor, as shown in Figure 9.4, can be expressed using Equation (9.10) as

$$\mathbf{B}_x = \mu_0 \mu_r \mathbf{H}_x = \frac{\mu_0 I}{2\pi x} \text{ Wb/m}^2 \quad (\text{taking } \mu_r \equiv 1)$$

Thus flux in the concentric circle shell will be

$$d\phi = \mathbf{B}_x dx l = \frac{\mu_0 I}{2\pi x} dx \; l \text{ Wb}$$

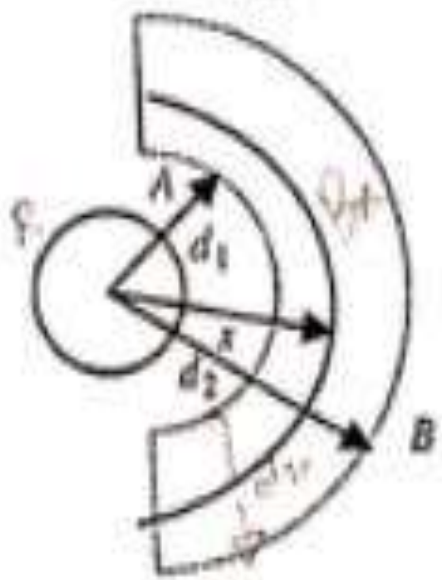


Figure 9.4 Flux linkage between two points.

This flux links the current I and thus the total flux linkage between points A and B will be

$$\lambda = \frac{I\mu_0}{2\pi}\int_{d_1}^{d_2}\frac{1}{x}dx$$

$\lambda = d\phi$

$$= \frac{I\mu_0}{2\pi}\ln\frac{d_2}{d_1} \text{ Wb-T/m length of conductor}$$

Therefore, the inductance due to external flux will be

$$L_{ext} = \frac{\lambda}{I} = \frac{\mu_0}{2\pi}\ln\frac{d_2}{d_1} \text{ H/m} \qquad (9.15)$$

9.7 INDUCTANCE OF A SINGLE-PHASE (TWO-WIRE) CONDUCTOR

Figure 9.5 shows an arrangement of one-phase two-wire system in which one conductor is used as return path. X denotes current passing through the conductor normal to the paper and the return current coming out of the paper is denoted by dot.

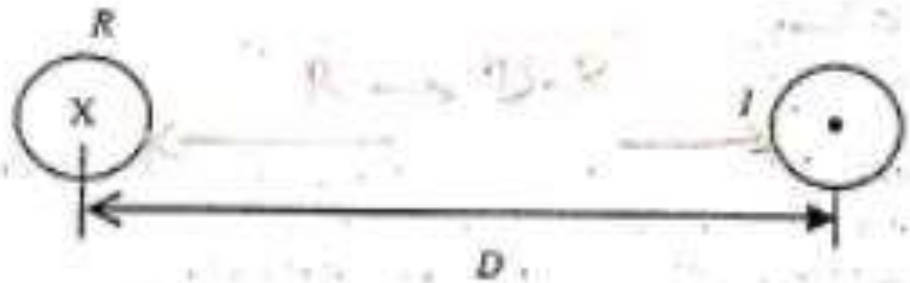


Figure 9.5 Single-phase two-wire system.

For conductor-1, there are two fluxes. One is due to the internal flux and other is due to external flux. The inductance due to internal flux will be the same as in Equation (9.14). The external flux will be from the distance R (radius of conductor) to $D + R$ but it should be noted that the flux links up to a distance $D - R$ (at the surface of the second conductor) with a current I and between $D - R$ and $D + R$, it links with varying current from I to zero. For simplicity, we can take the average distance D up to centre of the second conductor. For distances greater than D, there is no flux which encloses the conductor as sum of the current is zero. Therefore, flux linkage due to external flux between $D - R$ to R will be

$$\lambda_{ext} = \frac{\mu_0 I}{2\pi} \ln \frac{D-R}{R} \text{ Wb-T/m}$$

Normally, the radius of conductor is very small compared to the distance between the conductors ($R \ll D$). Thus $D - R \cong D$. The flux linkage due to external flux can be written as

$$\lambda_{ext} = \frac{\mu_0 I}{2\pi} \ln \frac{D}{R} \text{ Wb-T/m}$$

Total flux linkage of conductor-1 will be

$$\lambda = \lambda_{int} + \lambda_{ext} = \frac{\mu_0 I}{8\pi} + \frac{\mu_0 I}{2\pi} \ln \frac{D}{R} \text{ Wb-T/m} \tag{9.16}$$

Total inductance of the circuit due to the current in conductor-1 only is

$$L_1 = \frac{\lambda}{I} = \frac{\mu_0}{8\pi} + \frac{\mu_0}{2\pi} \ln \frac{D}{R}$$

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

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

$$= 2 \times 10^{-7} \ln \frac{D}{e^{-1/4} R}$$

$$= 2 \times 10^{-7} \ln \frac{D}{R'} \text{ H/m} \tag{9.17}$$

Since $e^{-1/4}$ is equal to 0.7788, therefore R' (called as geometric mean radius G.M.R.) is equal to $0.7788R$. This multiplying factor of 0.7788 adjusts the radius in order to account for internal flux linkages, which applies to solid round conductor.

Similarly, inductance due to the current in the second conductor will be

$$L_2 = 2 \times 10^{-7} \ln \frac{D}{R'} \text{ H/m}$$

The inductance will be given by

$$L = L_1 + L_2 = 4 \times 10^{-7} \ln \frac{D}{R'} \text{ H/m} \qquad (9.18)$$

Equation (9.18) can also be derived with the help of total flux linkages. The total flux linkages due to both the conductors will be the sum of the flux linkages caused by the currents flowing in both the conductors. Since the current in both the conductors is same, the total flux linkages will be double of Equation (9.16). The total inductance will be the total flux linkages divided by the current as

$$L = \frac{\lambda_1 + \lambda_2}{I}$$

$$= \frac{2\lambda}{I}$$