CLASS NOTES

ON

ELECTRICAL POWER TRANSMISSION AND DISTRIBUTION

A COURSE IN 6TH SEMESTER OF

BACHELOR OF TECHNOLOGY PROGRAMME IN ELECTRICAL ENGINEERING

(COURSE CODE-BEE605)

DEPARTMENT OF ELECTRICAL ENGINEERING

VEER SURENDRA SAI UNIVERSITY OF TECHNOLOGY

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FOREWORD BY THE AUTHOR

The invention of the electric lamp by Edison in the late 1870s led to rapid expansion in the use of electric power. To facilitate the electric power has to be generated and transmitted to the consumers via a transmission and distribution network. In 1882 the first electric power station Pearl street Electric station in New York city went into operation.

The original electrical distribution system developed by Thomas Edison was an underground direct current (DC) system. This was followed by first ac transmission line by Westinghouse in 1886. Ferranti constructed a 10kV link from Deptford, Kent to New Bond Street in London. From the turn of the century to the late 1920s there had been a gradual increase in machine voltage up to 11kV. In 1928, the first 33kV machine was commissioned. Since then there have gradual change in technology, which has enabled the system to operate at extra high voltage 220kV, 400kVand ultra high voltage of 750kV, 1500kV.

Thus the study of transmission and distribution has become very fundamental for electrical engineering students. After studying this subject, the student shall be able to address and understand the issues related to the transmission and distribution.

ELECTRIC POWER TRANSMISSION AND DISTRIBUTION (3-1-0)

SYLLABUS

MODULE-I (10 HOURS)

General Introduction to power transmission by D.C. and A.C. overhead lines

Lines Constants: Resistance, inductance and capacitance of single and three phase lines with symmetrical and unsymmetrical spacing transposition, charging current, skin effect and proximity effect

Performance of transmission Lines: Analysis of short, medium and long lines, equivalent circuit, representation of the lines and calculation of transmission parameters, use of static or synchronous condensers for improvement of regulation.

MODULE-II (10 HOURS)

Corona: Power loss due to corona, practical importance of corona, and inductive interference with neighboring communication lines, use of bundled conductors in E.H.V. transmission lines and its advantages

Overhead line Insulators: Voltage distribution in suspension type insulators, method of equalizing, voltage distribution, economic use of insulators.

Mechanical Design of Overhead Transmission Line, Sag and stress calculation, tension and sag at erection, effect of ice and wind, vibration dampers

Under Ground Cable: Type and construction, grading of cables, capacitance in 3 core cables and dielectric loss

MODULE-III (10 HOURS)

Distribution System; types of distributors and feeders (radial & ring), voltage drop and load calculation for concentrated and distributed loads, Primary and secondary distribution network, Capacitor placement in distribution network, Distribution system planning, Service area calculation.

MODULE-IV (10 HOURS)

Substation & Earthing: Types of substations, arrangement of bus-bars and control equipments, solid earthing, resistance earthing and Peterson coil

Per unit system one line diagram Power flow through transmission line, Power circle diagram, Series and shunt compensation.

Introduction to Flexible AC Transmission System (FACTS), SVC, TCSC, SSSC, STATCOM and UPFC

BOOKS

[1]. John J Grainger, W. D. Stevenson, *“Power System Analysis”*, TMH Publication

[2]. I. J. Nagrath & D. P. Kothari, *"Power System Analysis",* TMH Publication

CHAPTER-1
TRANSMISSION LINE PARAMETERS-I

INTRODUCTION

The transmission line performance is based on its electrical parameters such as resistance, inductance and capacitance. As we know the transmission line are used for delivering electrical power from one end to other end or one node to other node, the path of power flow i.e. the transmission line can be represented as an electrical circuit having its parameters connected in a particular pattern. Since the transmission line consists of conductors carrying power, we need to calculate the resistance, inductance and capacitance of these conductors.

RESISTANCE OF TRANSMISSION LINE

The resistance of the conductor thus transmission line can be determined by (1.1).

$$R = \rho \frac{l}{A} \tag{1.1}$$

Where $'\rho'$ is the resistivity of the wire in Ω-m, $'l'$ is the length in meter and $'A'$ is the cross sectional area in m^2.

When alternating current flows through a conductor, the current density is not uniform over the entire cross section but is somewhat higher at the surface. This is called the skin effect and this makes the ac resistance a little more than the dc resistance. Moreover in a stranded conductor, the length of each strand is more that the length of the composite conductor thus increasing the value of the resistance from that calculated in (1.1).

INDUCTANCE OF TRANSMISSION LINE

In order to determine the inductance of transmission line, we shall first drive expression for the inductance of a solid conductor and it will be extended to a single phase transmission line. Then we shall derive expression for inductance of a group of conductors and then extend it to three phase transmission line.

INDUCTANCE OF SOLID CONDUCTOR

The inductance of solid conductor can be determined by calculating the flux linkage due to current flowing and using (1.2).

$$L = \frac{\lambda}{I} \tag{1.2}$$

Where L is the inductance in Henry, λ is the flux linkage in Weber-turns and I is the phasor current in Ampere.

INDUCTANCE OF SOLID CONDUCTOR DUE TO INTERNAL FLUX

Let us consider a solid conductor of radius $'r'$ cm and the current flowing is $'I'$ A as shown in Fig.-1.1.

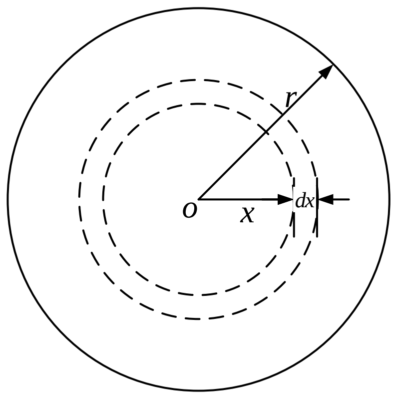


FIG.-1.1 INTERNAL FLUX LINKAGE OF A ROUND CONDUCTOR.

As we know Ampere's law states that the magnetomotive force (mmf) in ampere-turns around a closed path is equal to the net current in amperes enclosed by the path. Mathematically is written as (1.3).

$$mmf = \oint H \bullet ds = I \tag{1.3}$$

Where H is the magnetic field intensity in At/m, s is the distance along the path in meter.

Let us consider a tubular element of thickness $'dx'$ of the conductor at a distance $'x'$ from the center of the conductor and the field intensity as $'H_x'$ at $'x'$. It is constant at all points that are at a distance $'x'$ from the center of the conductor. Therefore $'H_x'$ is constant over the concentric circular path with a radius of $'x'$ and is tangent to it. Let the current enclosed by this path is $'I_x'$. Hence by (1.3) we can write as follows.

$$\oint H_x \bullet dx = I_x \Rightarrow 2\pi x H_x = I_x \tag{1.4}$$

$$\therefore H_x = \frac{I_x}{2\pi x} \tag{1.5}$$

Assuming the current density to be uniform thorugh out the cross section of the conductor, the current at a radius of $'x'$ is given by (1.6)

$$I_x = \frac{2\pi x^2}{2\pi r^2} I \tag{1.6}$$

Substituting (1.6) in (1.5) we get

$$H_x = \frac{x}{2\pi r^2} I \tag{1.7}$$

The flux density at a distance of $'x'$ is given by

$$B_x = \mu H_x = \mu_0 \mu_r H_x \tag{1.8}$$

Considering the unit length of the conductor i.e. one metre, the flux in the tubular element of thickness $'dx'$ of the conductor can be given by (1.9).

$$d\phi_x = B_x dx \tag{1.9}$$

Combining (1.7), (1.8) and (1.9)

$$d\phi_x = \mu \frac{I}{2\pi r^2} x dx \tag{1.9}$$

The flux linkage at $'x'$ can be given by

$$d\lambda_x = \frac{\pi x^2}{\pi r^2} d\phi_x = \mu \frac{I}{2\pi r^4} x^3 dx \tag{1.10}$$

The total internal flux linkage can be obtained by integrating (1.10) over the range of $'x'$, i.e., from $'0'$ to $'r'$ as follows.

$$\lambda = \int_0^r d\lambda_x = \int_0^r \mu \frac{I}{2\pi r^4} x^3 dx \tag{1.11}$$

$$\lambda = \mu \frac{I}{8\pi} \tag{1.12}$$

For relative permeability to be $\mu_r = 1$ we have $\mu_0 = 4\pi \text{ X} 10^{-7}$, hence (1.12) can be written as follows, which is the flux linkage due to internal flux.

$$\lambda_{\text{int}} = \frac{I}{2} \text{X} 10^{-7} \text{ Wb-T/m} \tag{1.13}$$

Hence the inductance of the conductor due to internal flux is obtained by using (1.2) and (1.13).

$$L_{\text{int}} = \frac{\lambda_{\text{int}}}{I} = \frac{1}{2} \text{X} 10^{-7} \text{ H/m} \tag{1.14}$$

INDUCTANCE OF SOLID CONDUCTOR DUE TO EXTERNAL FLUX

Now we shall calculate the inductance of solid conductor due to flux linking with the conductor externally. Let us consider two points $'P_1'\&'P_2'$ at a distance of $'D_1'\&'D_2'$ from the center of the conductor and external to it. Let us consider a tubular element of thickness $'dx'$ of the conductor at a distance $'x'$ from the center of the conductor and the field intensity as $'H_x'$ at $'x'$. as shown in Fig.-1.2.

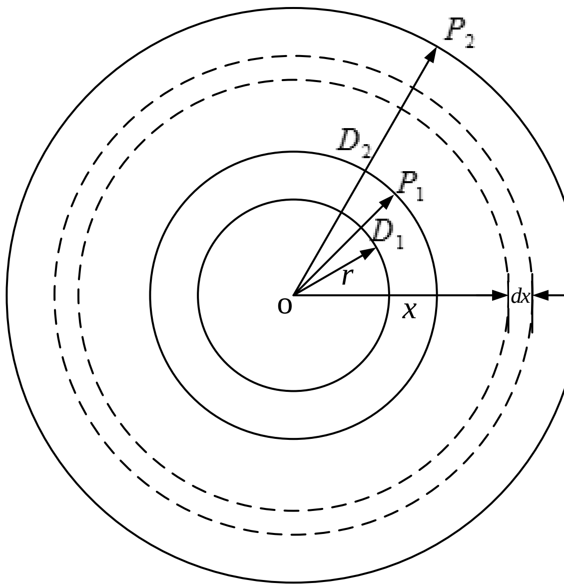


FIG.-1.2 EXTERNAL FLUX LINKAGE OF A ROUND CONDUCTOR.

The current enclosed by the tubular element is the total current i.e. $'I'$. Hence the fieled intensity is given by (1.15).

$$H_x = \frac{I}{2\pi x} \tag{1.15}$$

The flux density at a distance of $'x'$ is given by

$$B_x = \mu H_x = \mu_0 \mu_r H_x \tag{1.16}$$

Considering the unit length of the conductor i.e. one metre, the flux in the tubular element of thickness $'dx'$ of the conductor can be given by (1.17).

$$d\phi_x = B_x dx \tag{1.17}$$

Combining (1.15), (1.16) and (1.17)

$$d\phi_x = \mu \frac{I}{2\pi x} dx \tag{1.18}$$

The flux linkage at $'x'$ can be given by

$$d\lambda_x = \mu \frac{I}{2\pi x} dx \tag{1.19}$$

The total internal flux linkage can be obtained by integrating (1.19) between two points $'P_1' \& 'P_2'$ as follows.

$$\lambda = \int_{D_1}^{D_2} d\lambda_x = \int_{D_1}^{D_2} \mu \frac{I}{2\pi x} dx \tag{1.20}$$

$$\lambda = \mu \frac{I}{2\pi} \ln \frac{D_2}{D_1} \tag{1.21}$$

For relative permeability to be $\mu_r = 1$ we have $\mu_0 = 4\pi \text{ X} 10^{-7}$, hence (1.12) can be written as follows, which is the flux linkage due to external flux.

$$\lambda_{ext} = 2 \text{ X} 10^{-7} I \ln \frac{D_2}{D_1} \text{ Wb-T/m} \tag{1.22}$$

Hence the inductance of the conductor due to external flux is obtained by using (1.2) and (1.22).

$$L_{ext} = \frac{\lambda_{ext}}{I} = 2 \text{ X} 10^{-7} \ln \frac{D_2}{D_1} \quad \text{(H/m)} \tag{1.23}$$

Therefore the total inductance due to internal and external flux can be given by combining (1.14) and (1.23).

$$L = L_{\text{int}} + L_{ext} = \frac{1}{2} \text{X} 10^{-7} + 2 \text{ X} 10^{-7} \ln \frac{D_2}{D_1} \quad \text{(H/m)} \tag{1.23}$$

$$L = 2 \text{ X} 10^{-7} \left(\frac{1}{4} + \ln \frac{D_2}{D_1} \right) \quad \text{(H/m)} \tag{1.24}$$

Considering the flux linking with the conductor up to a point $'P'$ at a distance $'D'$ from the center of the conductor (1.24) can be modified as

$$L = 2 \text{ X} 10^{-7} \left(\frac{1}{4} + \ln \frac{D}{r} \right) \quad \text{(H/m)} \tag{1.25}$$

Or we can write

$$L = 2 \text{ X} 10^{-7} \left(\ln \frac{D}{e^{-\frac{1}{4}} r} \right) = 2 \text{ X} 10^{-7} \left(\ln \frac{D}{r'} \right) \quad \text{(H/m)} \tag{1.26}$$

INDUCTANCE OF A SINGLE-PHASE LINE

Now we shall calculate the inductance of a single phase transmission line having solid conductors as shown in Fig.-1.3. 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.

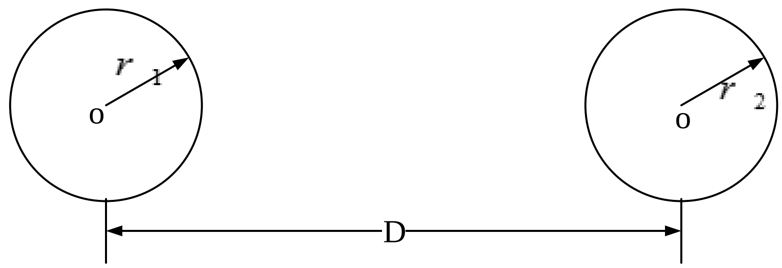


FIG.-1.3 SINGLE PHASE TRANSMISSION LINE

The inductance of the conductor-1 and conductor-2 is given by (1.27) and (1.28) respectively.

$$L_1 = 2\,\mathrm{X}\,10^{-7}\left(\ln\frac{D}{r_1^{'}}\right) \text{ (H/m)} \tag{1.27}$$

$$L_2 = 2\,\mathrm{X}\,10^{-7}\left(\ln\frac{D}{r_2^{'}}\right) \text{ (H/m)} \tag{1.28}$$

The total inductance of the single phase transmission line is then can be calculated as the sum of these inductances since the flux lines set up by current in conductor-1 shall have same direction as the flux lines set up by the current in conductor-2. Hence

$$L = L_1 + L_2 = 2\,\mathrm{X}\,10^{-7}\left(\ln\frac{D}{r_1^{'}} + \ln\frac{D}{r_2^{'}}\right)\text{(H/m)} \tag{1.29}$$

If $r_1 = r_2 = r$ then

$$L = 4\,\mathrm{X}\,10^{-7}\left(\ln\frac{D}{r^{'}}\right) \text{ (H/m)} \tag{1.30}$$

FLUX LINKAGE IN A GROUP OF CONDUCTORS

Let us consider a group of conductors as shown in Fig.-1.4. The total current in this group of conductors is the phasor sum of all the currents and given by (1.31).

$$I_a + I_b + I_c + \cdots\cdots + I_j + \cdots\cdots + I_n = 0 \tag{1.31}$$

Where $'I_j'$ is the current in the $'j^{th}'$ conductor

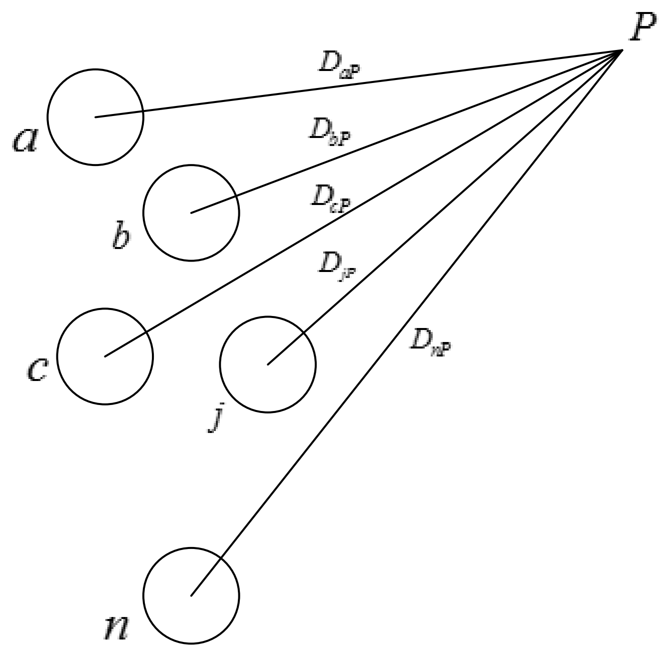


FIG.-1.4 FLUX LINKAGE IN A GROUP OF CONDUCTORS

By (1.14) and (1.22) we can write the flux linkage of $conductor - a$ up to point $'P'$ due to current I_a i.e. including internal flux linkage and excluding all the flux linkage beyond point $'P'$ (because all the flux lines beyond point $'P'$ enclose a total zero current).

$$\lambda_{aPa} = 2\,\mathrm{X}\,10^{-7}\left(\frac{I_a}{4} + I_a \ln\frac{D_{aP}}{r_a}\right) \tag{1.32}$$

$$\lambda_{aPa} = 2\,\mathrm{X}\,10^{-7} I_a \ln\frac{D_{aP}}{r'_a} \tag{1.33}$$

The flux linkage of $conductor - a$ up to point $'P'$ due to current I_b is the flux produced by current I_b between the point $'P'$ and $conductor - a$ i.e. within limiting distances D_{bP} & D_{ab} and can be written as (1.34).

$$\lambda_{aPb} = 2\,\mathrm{X}\,10^{-7} I_b \ln\frac{D_{bP}}{D_{ab}} \tag{1.34}$$

Similarly the total flux linkage $conductor - a$ up to point $'P'$ due to all the currents can then be given by (1.35).

$$\lambda_{aP} = 2\,\text{X}\,10^{-7}\left[I_a \ln\frac{D_{aP}}{r'_a} + I_b \ln\frac{D_{bP}}{D_{ab}} + I_c \ln\frac{D_{cP}}{D_{ac}} + \cdots\cdots + I_j \ln\frac{D_{jP}}{D_{aj}} + \cdots\cdots + I_n \ln\frac{D_{nP}}{D_{an}} \right] \tag{1.35}$$

Let the point $'P'$ to move far away infinitely it mean we consider all the flux linkages with the conductor due to all the currents in the group. Using (1.31) in (1.35) and rearranging logarithm terms and assuming distances $D_{aP}, D_{bP}, D_{cP}, \cdots\cdots D_{nP}$ are nearly to be same as compared to the radius of the conductors, we get (1.36), which is the flux linkage of $conductor - a$ up to point $'P'$ in group of conductors.

$$\lambda_a = 2\,\text{X}\,10^{-7}\left[I_a \ln\frac{1}{r'_a} + I_b \ln\frac{1}{D_{ab}} + I_c \ln\frac{1}{D_{ac}} + \cdots\cdots + I_j \ln\frac{1}{D_{aj}} + \cdots\cdots + I_n \ln\frac{1}{D_{an}} \right] \tag{1.36}$$

The above derivation is true for the sum of all currents to be zero in the group.

INDUCTANCE OF COMPOSITE CONDUCTOR LINES

Let us consider two groups of conductors as shown in Fig.-1.5. Each group form one side of a line. The parallel filaments are cylindrical and share equal currents. The $conductor - A_1$ consists of $'n'$ parallel filaments each carrying $'\frac{I}{n}'$ current and the $conductor - A_2$ consists of $'m'$ parallel filaments each carrying $'-\frac{I}{m}'$ current. The distances between the conductors are given corresponding subscripts such as $'D_{ab}'$ represents the distance between filament $'a'$ and $'b'$.

From (1.36) we can write the flux linkage with $filament - a$ as follows due to filaments in both the groups of conductors.

$$\begin{aligned} \lambda_a = {} & 2\,\text{X}\,10^{-7}\,\frac{I}{n}\left[\ln\frac{1}{r'_a} + \ln\frac{1}{D_{ab}} + \ln\frac{1}{D_{ac}} + \cdots\cdots + \ln\frac{1}{D_{aj}} + \cdots\cdots + \ln\frac{1}{D_{an}} \right] \\ & - 2\,\text{X}\,10^{-7}\,\frac{I}{m}\left[\ln\frac{1}{D_{aa'}} + \ln\frac{1}{D_{ab'}} + \ln\frac{1}{D_{ac'}} + \cdots\cdots + \ln\frac{1}{D_{aj'}} + \cdots\cdots + \ln\frac{1}{D_{am}} \right] \end{aligned} \tag{1.37}$$

It can be simplified as

$$\lambda_a = 2\,\text{X}\,10^{-7}\,I\left[\ln\frac{\sqrt[m]{D_{aa'}D_{ab'}D_{ac'}\cdots\cdots D_{aj'}\cdots\cdots D_{am}}}{\sqrt[n]{r'_a D_{ab} D_{ac}\cdots\cdots D_{aj}\cdots\cdots D_{an}}} \right] \tag{1.38}$$

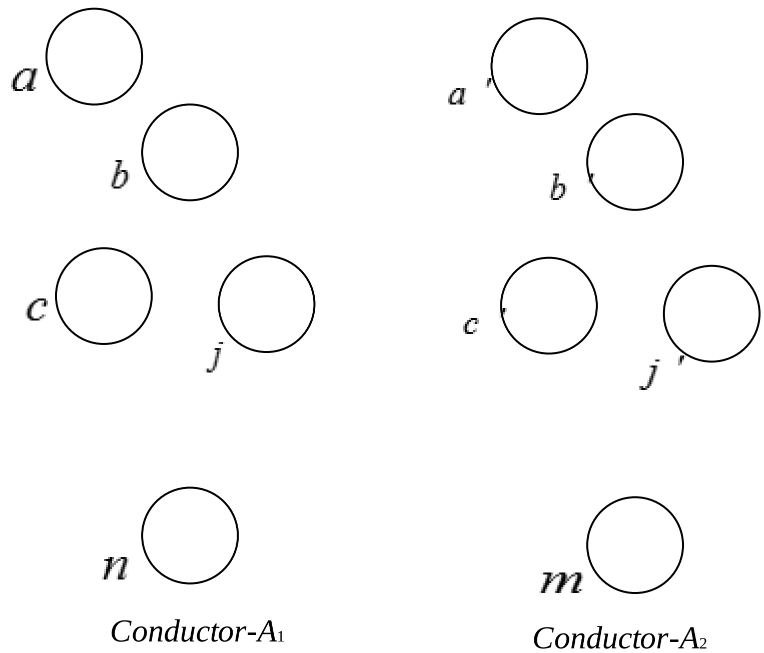


FIG.-1.5 SINGLE PHASE LINE CONSITING OF COMPOSITE CONDUCTORS

The inductance of $filament-a$ is given by

$$L_a = \frac{\lambda_a}{I/n} = 2\,\text{X}\,10^{-7}\,n\left[\ln\frac{\sqrt[m]{D_{aa'}D_{ab'}D_{ac'}\cdots\cdots D_{aj'}\cdots\cdots D_{am}}}{\sqrt[n]{r'_a D_{ab}D_{ac}\cdots\cdots D_{aj}\cdots\cdots D_{an}}}\right] \quad (1.39)$$

Similarly the inductance of $filament-b$ is given by

$$L_b = \frac{\lambda_b}{I/n} = 2\,\text{X}\,10^{-7}\,n\left[\ln\frac{\sqrt[m]{D_{ba'}D_{bb'}D_{bc'}\cdots\cdots D_{bj'}\cdots\cdots D_{bm}}}{\sqrt[n]{D_{ba}r'_b D_{bc}\cdots\cdots D_{bj}\cdots\cdots D_{bn}}}\right] \quad (1.40)$$

The average inductance of the filaments of $conductor-A_1$ is

$$L_{av} = \frac{L_a + L_b + L_c + \cdots\cdots + L_n}{n} \quad (1.41)$$

Since all the filaments of this group are electrically in parallel the total inductance of $conductor-A_1$ is given by (1.42)

$$L_{A_1} = \frac{L_{av}}{n} = \frac{L_a + L_b + L_c + \cdots\cdots + L_n}{n^2} \quad (1.42)$$

$$L_{A_1} = 2\,\text{X}\,10^{-7}\left[\ln\frac{\sqrt[mn]{(D_{aa'}D_{ab'}D_{ac'}\cdots D_{am})(D_{ba'}D_{bb'}D_{bc'}\cdots D_{bm})\cdots\cdots(D_{na'}D_{nb'}D_{nc'}\cdots D_{nm})}}{\sqrt[n^2]{(r'_a D_{ab}D_{ac}\cdots D_{an})(D_{ba}r'_b D_{bc}\cdots D_{bn})\cdots\cdots(D_{na}D_{nb}D_{nc}\cdots r'_n)}}\right]$$

(1.43)

Replacing the term r_a' by D_{aa} and so on for all the filaments, we can rewrite the (1.43) as

$$L_{A_1} = 2\,\mathrm{X}\,10^{-7}\left[\ln \frac{\sqrt[mn]{\left(D_{aa'}D_{ab'}D_{ac'}\cdots D_{am}\right)\left(D_{ba'}D_{bb'}D_{bc'}\cdots D_{bm}\right)\cdots\cdots\left(D_{na'}D_{nb'}D_{nc'}\cdots D_{nm}\right)}}{\sqrt[n^2]{\left(D_{aa}D_{ab}D_{ac}\cdots D_{an}\right)\left(D_{ba}D_{bb}D_{bc}\cdots D_{bn}\right)\cdots\cdots\left(D_{na}D_{nb}D_{nc}\cdots D_{nn}\right)}}\right] \tag{1.44}$$

A closer look at the above equation for inductance conclude that the terms of numerator consists of distances between the filaments of two groups and the terms of denominator consists of distances between the filaments of the same group. Hence the numerator of the logarithm term is known as mutual geometric mean distances (mutual GMD) and the denominator of the logarithm term is known as self geometric mean distances (self GMD). The self GMD is also called as geometric mean radius or GMR. Hence (1.44) can be written as

$$L_{A_1} = 2\,\mathrm{X}\,10^{-7}\left[\ln \frac{mutual\ GMD}{\text{self}\ GMD}\right] = 2\,\mathrm{X}\,10^{-7}\left[\ln \frac{D_m}{D_s}\right] \tag{1.44}$$

Similarly the inductance of $conductor - A_2$ can be determined and the total inductance of the line is given by (1.45)

$$L = L_{A_1} + L_{A_2} \tag{1.45}$$

INDUCTANCE OF THREE PHASE LINE

Continuing as above we shall first calculate the flux linkage and then the inductance. As we know for a three phase line the phasor sum of currents is zero assuming a balance system. Let us consider a three phase line as shown in Fig.-1.6.

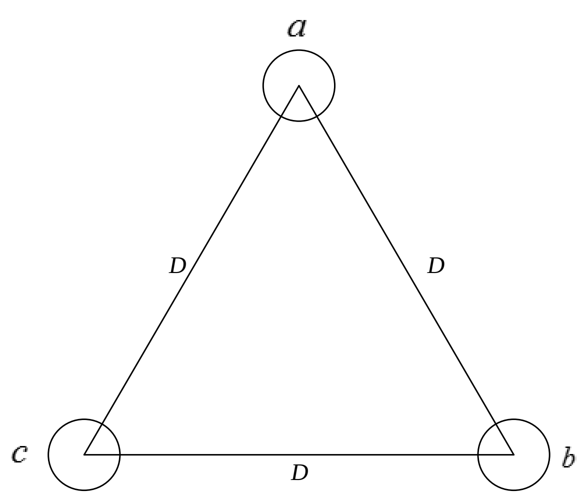


FIG.-1.6 THREE PHASE LINES HAVING CONDUCTORS WITH SYMMETRICAL SPACING

For this three phase system the flux linkage with $conductor - a$ due to all the currents is given by (1.46) by referring to (1.36).

$$\lambda_a = 2\,X\,10^{-7}\left[I_a \ln\frac{1}{r'_a} + I_b \ln\frac{1}{D} + I_c \ln\frac{1}{D}\right] \tag{1.46}$$

Since $I_a + I_b + I_c = 0$, (1.46) can be reduced to (1.47)

$$\lambda_a = 2\,X\,10^{-7}\left[I_a \ln\frac{D}{r'_a}\right] \tag{1.47}$$

Hence the inductance of phase-a is given as

$$L_a = \frac{\lambda_a}{I_a} = 2\,X\,10^{-7} \ln\frac{D}{r'_a} \tag{1.48}$$

Similarly the inductance for other two phase can be determined by (1.49) and (1.50) as below.

$$L_b = \frac{\lambda_b}{I_b} = 2\,X\,10^{-7} \ln\frac{D}{r'_b} \tag{1.49}$$

$$L_c = \frac{\lambda_c}{I_c} = 2\,X\,10^{-7} \ln\frac{D}{r'_c} \tag{1.50}$$

However if the conductors are spaced asymmetrically as shown Fig.-1.7, then the inductance of three phase line can be calculated as below.

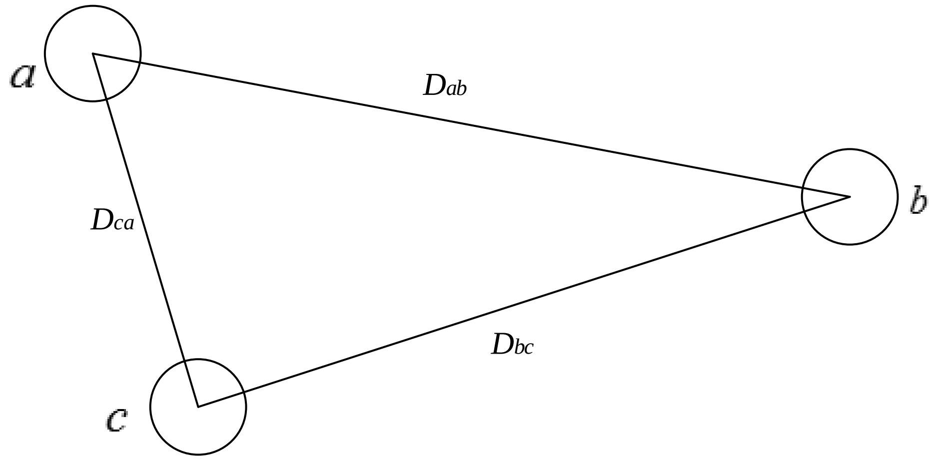


FIG.-1.7 THREE PHASE LINES HAVING CONDUCTORS WITH ASYMMETRICAL SPACING

The flux linkage of $conductor - a$ due to all the currents can be given by (1.51)

$$\lambda_a = 2\,X\,10^{-7}\left[I_a \ln\frac{1}{r'_a} + I_b \ln\frac{1}{D_{ab}} + I_c \ln\frac{1}{D_{ca}}\right] \tag{1.51}$$

The flux linkage of $conductor-b$ due to all the currents can be given by (1.52)

$$\lambda_b = 2\,X10^{-7}\left[I_a \ln\frac{1}{D_{ba}} + I_b \ln\frac{1}{r'_b} + I_c \ln\frac{1}{D_{bc}}\right] \tag{1.52}$$

The flux linkage of $conductor-c$ due to all the currents can be given by (1.53)

$$\lambda_c = 2\,X10^{-7}\left[I_a \ln\frac{1}{D_{ca}} + I_b \ln\frac{1}{D_{cb}} + I_c \ln\frac{1}{r'_c}\right] \tag{1.53}$$

As we see the flux linkage with all the three phases are different hence the inductance of three phases shall be different and can be calculated as above. However to make it equal a method known as transposition is used. In this method each conductor occupies each position for one third length of the transmission line total length as shown in Fig.-1.8.

Hence the flux linkage of $conductor-a$ due to all the currents at the $position-1$, $position-2$ and $position-3$ can be given by (1.54)

$$\lambda_{a1} = 2\,X10^{-7}\left[I_a \ln\frac{1}{r'_a} + I_b \ln\frac{1}{D_{ab}} + I_c \ln\frac{1}{D_{ca}}\right] \tag{1.54a}$$

$$\lambda_{a2} = 2\,X10^{-7}\left[I_a \ln\frac{1}{r'_a} + I_b \ln\frac{1}{D_{bc}} + I_c \ln\frac{1}{D_{ab}}\right] \tag{1.54b}$$

$$\lambda_{a3} = 2\,X10^{-7}\left[I_a \ln\frac{1}{r'_a} + I_b \ln\frac{1}{D_{ca}} + I_c \ln\frac{1}{D_{bc}}\right] \tag{1.54c}$$

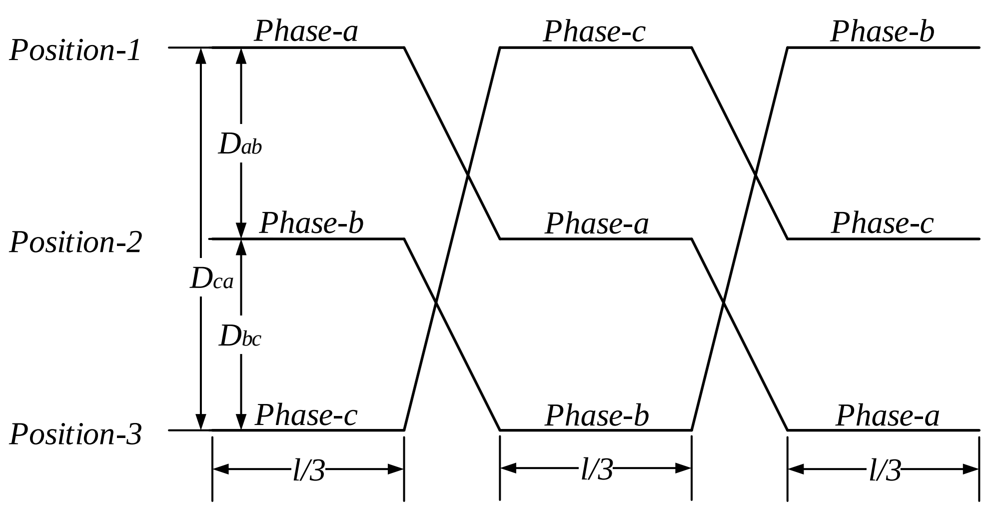


FIG.-1.8 TRANSPOSITION OF PHASES

The total flux linkage of the phase –a of the transposed line is given by average of the flux linkage in these three positions.

$$\lambda_a = \frac{\lambda_{a1} + \lambda_{a2} + \lambda_{a3}}{3} \tag{1.55}$$

Using (1.54) and (1.55) and the fact that $I_a = -(I_b + I_c)$ we get

$$L_a = \frac{\lambda_a}{I_a} = 2\,\mathrm{X}\,10^{-7} \ln \frac{\sqrt[3]{D_{ab}D_{bc}D_{ca}}}{r_a'} \tag{1.56}$$

(1.56) can be written as

$$L_a = 2\,\mathrm{X}\,10^{-7} \ln \frac{D_{eq}}{D_s} \tag{1.57}$$

Where $D_{eq} = \sqrt[3]{D_{ab}D_{bc}D_{ca}}$ and $D_s = r_a'$

We have derived expression for inductance of transmission line. It can b seen that the expression contains a logarithm of a ratio. This numerator of this ratio is the mutual distances between the conductors of different phases and the denominator is the distance between the conductors of same group or the sub-conductors. It can also be seen that inductance depends upon the size of the conductors and the distances between the conductors i.e. the configuration of the conductors.

INDUCTANCE OF BUNDLE CONDUCTOR

In extra high voltage transmission line bundle conductors are used to reduce the effect of corona. The bundle conductors consists of two or more sub-conductors as shown in Fig.-1.9.

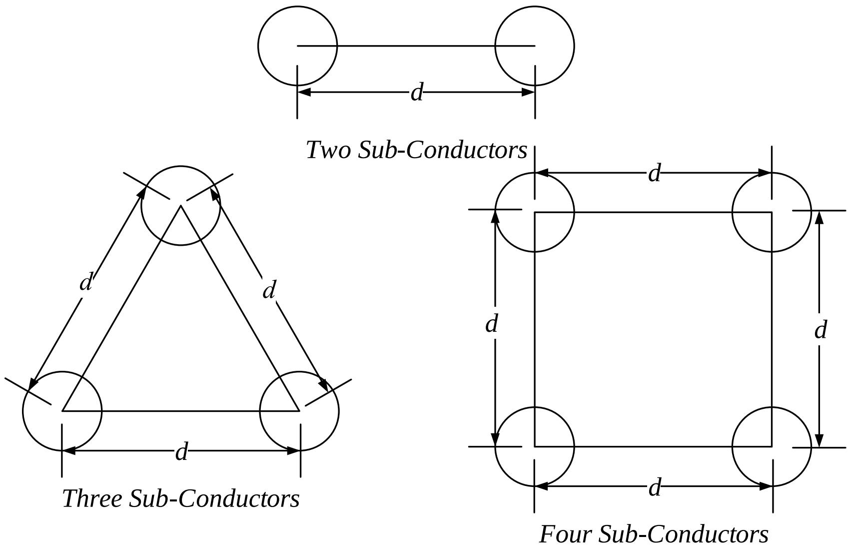


FIG.-1.9 BUNDLE CONDUCTORS

The inductance of bundle conductors can be calculated by determining its self GMD as follows.

For a bundle conductor having two sub-conductors the self GMD is given by

$$D_{s,bundle} = \sqrt[4]{(D_s X d)^2} = \sqrt{D_s d}$$

For a bundle conductor having three sub-conductors the self GMD is given by

$$D_{s,bundle} = \sqrt[9]{(D_s \mathrm{X} d \mathrm{X} d)^3} = \sqrt[3]{D_s d^2}$$

For a bundle conductor having four sub-conductors the self GMD is given by

$$D_{s,bundle} = \sqrt[16]{\left(D_s \mathrm{X} d \mathrm{X} d \mathrm{X} \sqrt{2} d\right)^4} = 1.09\sqrt[4]{D_s d^3}$$

The bundle conductors have reduced reactance. Increasing the number of sub-conductors reduces the reactance because of increased GMR of the bundle. For the calculation of inductance

CHAPTER-2

TRANSMISSION LINE PARAMETERS-II

INTRODUCTION

In the previous chapter we have calculated the inductance of the transmission line for single phase and three phase transmission lines. The transmission line also have capacitance due to charge accumulated on the conductors. It can be determined by fundamental Coulombs Law

CAPACITANCE OF LONG SOLID CONDUCTOR LINE

Let us consider a solid conductor as shown in Fig.-2.1 having radius $'r'$. The electric flux density at $'x'$ meters from the conductor can be computed by imagining a cylindrical surface concentric with the conductor from the conductor.

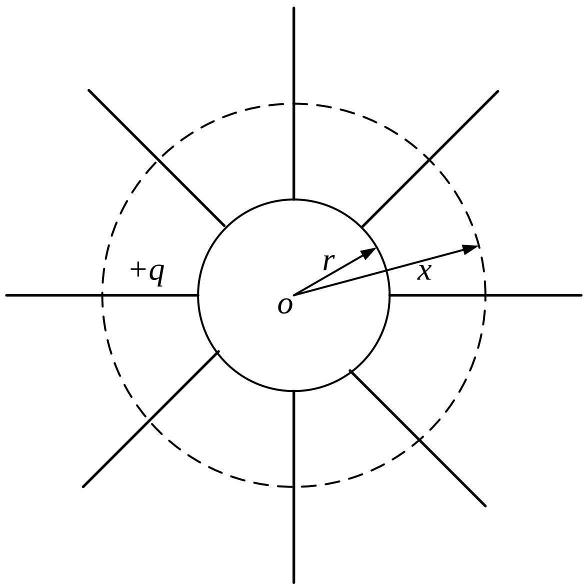


FIG.-2.1 SOLID CONDUCTOR HAVING CHARGE $'q'$

The cylindrical surface is the surface of equipotential and the electric flux density on the surface is equal to the flux leaving the conductor per unit length divided by the area of the surface in an axial length. The electric flux density is given by (2.1).

$$D_f = \frac{q}{2\pi x} C/m^2 \tag{2.1}$$

Where $'q'$ is the charge on the conductor per unit length. The electric filed intensity is defined as the ratio of electric flux density to the permittivity of the medium and given by (2.2)

$$E = \frac{q}{2\pi xk} V/m \tag{2.2}$$

Let us take two points $'P_1 \& P_2'$ be located at distances $'D_1 \& D_2'$ respectively from the center of the conductor as shown in Fig.-2.2.

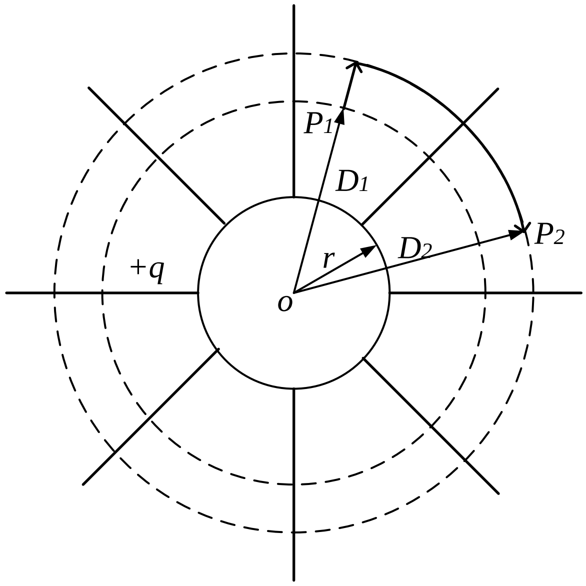


FIG.-2.2 POTENTIAL DIFFERENCE BETWEEN TWO POINTS $'P_1 \& P_2'$

The conductor is an equipotential surface in which we can assume that the uniformly distributed charge is concentrated at the center of the conductor. The potential difference $'V_{12}'$ between the points $'P_1 \& P_2'$ is the work done in moving a unit of charge from $'P_2'$ to $'P_1'$. Therefore the voltage drop between the two points can be computed by integrating the field intensity over a radial path between the equipotential surfaces and given by (2.3).

$$V_{12} = \int_{D_1}^{D_2} E dx = \int_{D_1}^{D_2} \frac{q}{2\pi xk} dx = \frac{q}{2\pi k} \ln \frac{D_2}{D_1} \text{ (V)} \tag{2.3}$$

The capacitance between the conductors of two wire line is defined as charge on the conductors per unit of potential difference between them. It can be given by (2.4)

$$C = \frac{q}{V} \,(F/m) \tag{2.4}$$

Let us consider two conductors having charges $'q_a \& q_b'$ on two conductors as shown in Fig.-2.3.

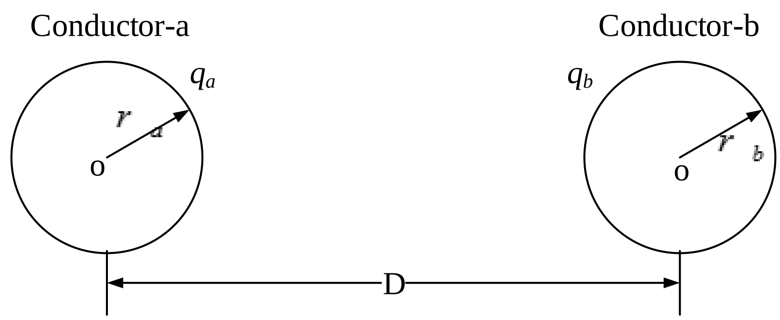


FIG.-2.3 CAPACITANCE BETWEEN TWO WIRE LINE

The potential difference between two conductors is given by (2.5)

$$V_{ab} = \frac{q_a}{2\pi k}\ln\frac{D}{r_a} + \frac{q_b}{2\pi k}\ln\frac{r_b}{D} \text{ (V)} \tag{2.5}$$

For $q_a = -q_b = q$

$$V_{ab} = \frac{q_a}{2\pi k}\ln\frac{D^2}{r_a r_b} \text{ (V)} \tag{2.6}$$

For $r_a = r_b = r$

$$V_{ab} = \frac{q}{\pi k}\ln\frac{D}{r} \text{ (V)} \tag{2.7}$$

The capacitance between the conductors is hence given by (2.8)

$$C_{ab} = \frac{q}{V} = \frac{\pi k}{\ln\frac{D}{r}} \text{ (F/m)} \tag{2.8}$$

Referring to Fig.-2.4 where capacitance to neutral is considered. The capacitance to neutral between the conductors is hence given by (2.9)

$$C_n = C_{an} = C_{bn} = 2C_{ab} = \frac{2\pi k}{\ln(D/r)} \text{ (F/m to neutral)} \tag{2.9}$$

CAPACITANCE OF THREE PHASE LINE

Let us derive expression for capacitance of three phase line whose conductors are spaced equilaterally as shown in Fig.-1.6.

The voltage between two phases $'a \,\&\, b''$ shall be expressed as follows.

$$V_{ab} = \frac{q_a}{2\pi k}\ln\frac{D}{r} + \frac{q_b}{2\pi k}\ln\frac{r}{D} + \frac{q_c}{2\pi k}\ln\frac{D}{D} \text{ (V)} \tag{2.10}$$

Where $'q_a, q_b \,\&\, q_c'$ are the charges on the conductors of phases $'a, b \,\&\, c'$ respectively.

Similarly the voltage between two phases $'a \,\&\, c''$ shall be expressed as follows.

$$V_{ac} = \frac{q_a}{2\pi k}\ln\frac{D}{r} + \frac{q_b}{2\pi k}\ln\frac{D}{D} + \frac{q_c}{2\pi k}\ln\frac{r}{D} \text{ (V)} \tag{2.11}$$

Adding (2.10) and (2.11)We get

$$V_{ab} + V_{ac} = \frac{1}{2\pi k}\left[2q_a \ln\frac{D}{r} + (q_b + q_c)\ln\frac{r}{D}\right] \text{ (V)} \tag{2.12}$$

Since for a balanced system the phasor sum is given as $q_a + q_b + q_c = 0$ and the voltage phasor is given as $V_{ab} + V_{ac} = 3V_{an}$ we can write

$$V_{an} = \frac{q_a}{2\pi k}\ln\frac{D}{r} \text{ (V)} \tag{2.13}$$

Hence the capacitance is determined as

$$C_{an} = \frac{q_a}{V_{an}} = \frac{2\pi k}{\ln\left(D_{eq}/r\right)} \text{ (F/m to neutral)} \tag{2.14}$$

However if the conductors of three phase line are not equally spaced then the capacitance of the line is derived as follows.

Let us consider the conductors as shown in Fig.-1.7 and the conductors are transposed as shown in Fig.-1.8.

Hence for position-1, the voltage between two phases $'a \,\&\, b''$ shall be expressed as

$$V_{ab} = \frac{1}{2\pi k}\left[q_a \ln\frac{D_{12}}{r} + q_b \ln\frac{r}{D_{12}} + q_c \ln\frac{D_{23}}{D_{31}}\right] \text{ (V)} \tag{2.15}$$

Hence for position-2, the voltage between two phases $'a \,\&\, b''$ shall be expressed as

$$V_{ab} = \frac{1}{2\pi k}\left[q_a \ln\frac{D_{23}}{r} + q_b \ln\frac{r}{D_{23}} + q_c \ln\frac{D_{31}}{D_{12}}\right] \text{ (V)} \tag{2.16}$$

Hence for position-3, the voltage between two phases $'a \,\&\, b''$ shall be expressed as

$$V_{ab} = \frac{1}{2\pi k}\left[q_a \ln\frac{D_{31}}{r} + q_b \ln\frac{r}{D_{31}} + q_c \ln\frac{D_{12}}{D_{23}}\right] \text{ (V)} \tag{2.17}$$

Using (2.15), (2.16) and (2.17), the average voltage is given by

$$V_{ab} = \frac{1}{2\pi k}\left[q_a \ln\frac{D_{eq}}{r} + q_b \ln\frac{r}{D_{eq}}\right] \text{ (V)} \tag{2.18}$$

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

Similarly the voltage between two phases $'a\,\&\,c''$ shall be expressed as follows.

$$V_{ac} = \frac{1}{2\pi k}\left[q_a \ln\frac{D_{eq}}{r} + q_c \ln\frac{r}{D_{eq}}\right] \text{ (V)} \tag{2.19}$$

Using (2.18) and (2.19) we can write

$$V_{an} = \frac{q_a}{2\pi k}\ln\frac{D_{eq}}{r} \text{ (V)} \tag{2.20}$$

Hence the capacitance is determined as

$$C_{an} = \frac{q_a}{V_{an}} = \frac{2\pi k}{\ln\left(D_{eq}/r\right)} \text{ (F/m to neutral)} \tag{2.21}$$

CAPACITANCE OF BUNDLE CONDUCTOR

The capacitance of bundles conductor can be calculated as above and given by (2.22)

$$C_{an} = \frac{2\pi k}{\ln\left(D_{eq}/D_{sC,bundle}\right)} \text{ (F/m to neutral)} \tag{2.22}$$

Where $'D_{sC,bundle}'$ is the modified GMR of the bundle conductor and can be given as follows for different bundle conductors as shown in Fig.-1.9.

For a bundle conductor having two sub-conductors

$$D_{sC,bundle} = \sqrt[4]{(rXd)^2} = \sqrt{rd}$$

For a bundle conductor having three sub-conductors

$$D_{sC,bundle} = \sqrt[9]{(rXdXd)^3} = \sqrt[3]{rd^2}$$

For a bundle conductor having four sub-conductors

$$D_{sC,bundle} = \sqrt[16]{\left(rXdXdX\sqrt{2}d\right)^4} = 1.09\sqrt[4]{rd^3}$$

Earth affects the calculation of capacitance of three-phase lines as its presence alters the electric field lines. Usually the height of the conductors placed on transmission towers is much larger than the spacing between the conductors. Therefore the effect of earth can be neglected for capacitance calculations, especially when balanced steady state operation of the power system is considered. However for unbalanced operation when the sum of the three line currents is not zero, the effect of earth needs to be considered.

CHAPTER-3
TRANSMISSION LINE PERFORMANCE

INTRODUCTION

We have derived expression for resistance, inductance and capacitance for transmission line in last two chapters. It can be seen that all these parameters depend upon the size of conductors and its configuration. Furthermore we also conclude that the parameters depend upon the length of the transmission line. In fact these parameters are distributed throughout the transmission line not just single element. The circuit consisting of these parameters are shown in Fig.3.1 below.

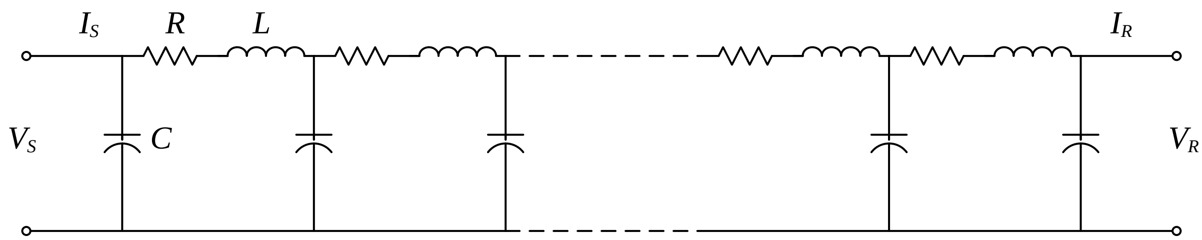


FIG.-3.1 TRANSMISSION LINE PARAMETERS

The resistance and inductance are known as series parameters and hence forms series impedance of the transmission line. The capacitance is known as shunt parameters and hence forms shunt admittance. The transmission line can be represented as two port network as shown in Fig.-3.2 such that we can write:

$$V_S = AV_R + BI_R \tag{3.1}$$

$$I_S = CV_R + DI_R \tag{3.2}$$

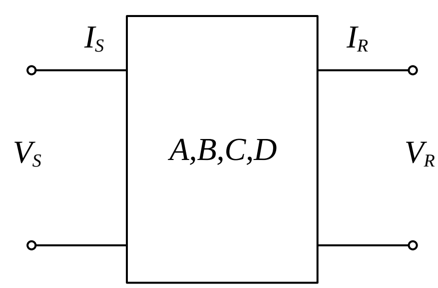


FIG.-3.2 TWO PORT EQUIVALENT OF TRANSMISSION LINE

The performance of the transmission line depend upon the total value of series impedance and shunt admittance. This is the reason that the transmission line is classified into three categories.

Short length transmission line (Generally up to 80 kms)

Medium length transmission line (Generally up to 80 to 240 kms)

Long length transmission line (Generally above 240 kms)

The total series impedance and shunt admittance of the transmission line is given by

$$Z = (R + j\omega L)l \tag{3.3}$$

$$Y = j\omega Cl \tag{3.4}$$

Where $'l'$ is the length of the transmission line in kms, $'Z \,\&\, Y'$ are the total series impedance and shunt admittance respectively.

SHORT LENGTH TRANSMISSION LINE

Since the length of the line is less, the total value of series impedance is quite comparable with respect to shunt admittances and hence the shunt admittance is neglected and the transmission line consists of only series impedance as shown in Fig.-3.3

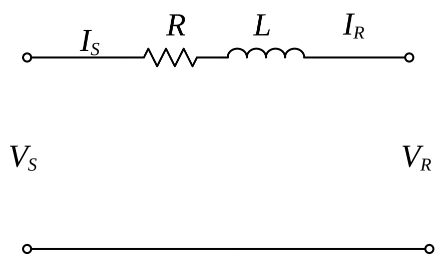


FIG.-3.3 SHORT LENGTH EQUIVALENT OF TRANSMISSION LINE

For the circuit in Fig.-3.3 the network equations are given by

$$V_S = V_R + ZI_R \tag{3.5}$$

$$I_S = I_R \tag{3.6}$$

Hence comparing (3.1), (3.2), (3.5) and (3.6) we get for short transmission line:

$$A = 1 \quad B = Z \tag{3.7}$$

$$C = 0 \quad D = 1 \tag{3.8}$$

MEDIUM LENGTH TRANSMISSION LINE

The shunt admittance cannot be neglected if the length of the line is more. However it can be approximated to be consisting of lumped parameters. The lumped parameters representation of the line can be of two types (i) nominal π representation and (ii) nominal T representation as shown in Fig.-3.4 and Fig.-3.5. The A, B, C, D parameters of such circuit can be determined as follows.

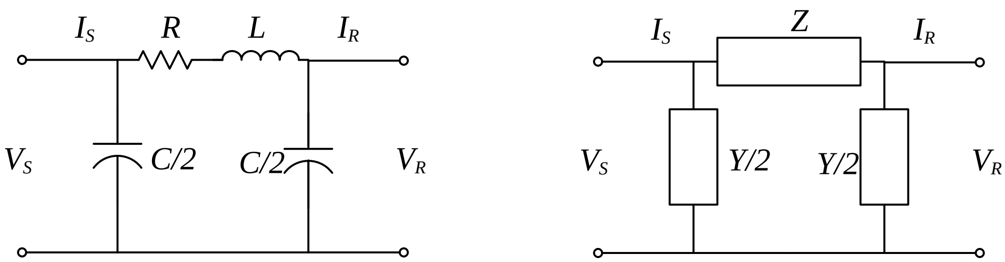


FIG.-3.4 NOMINAL π REPRESENTATION OF TRANSMISSION LINE

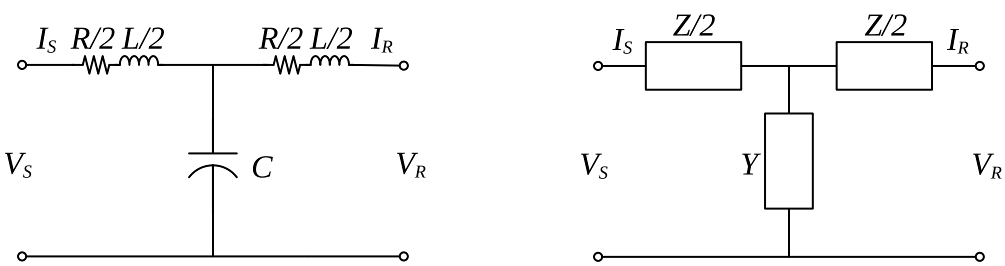


FIG.-3.5 NOMINAL T REPRESENTATION OF TRANSMISSION LINE

NOMINAL π REPRESENTATION

Let us derive the A, B, C, D parameters of this circuit. Let us consider the current flowing in the branches as follows.

'I_{cR}'- Current flowing in the shunt branch on receiving end side.

'I_{cS}'- Current flowing in the shunt branch on sending end side.

'I_{se}'- Current flowing in the series branch.

Hence we can write the circuit equation by using KCL and KVL as follows.

$$I_{cR} = V_R \frac{Y}{2} \tag{3.9a}$$

$$I_{se} = I_{cR} + I_R = V_R \frac{Y}{2} + I_R \tag{3.9b}$$

$$V_S = I_{se} Z + V_R = \left(V_R \frac{Y}{2} + I_R \right) Z + V_R \tag{3.9c}$$

$$V_S = \left(1 + \frac{ZY}{2} \right) V_R + Z I_R \tag{3.9}$$

Similarly the current at sending end is derived as follows.

$$I_S = I_{cS} + I_{se} = V_S \frac{Y}{2} + V_R \frac{Y}{2} + I_R \tag{3.10a}$$

$$I_S = \left[\left(1+\frac{ZY}{2}\right)V_R + ZI_R\right]\frac{Y}{2} + V_R\frac{Y}{2} + I_R \tag{3.10b}$$

$$I_S = Y\left(1+\frac{ZY}{4}\right)V_R + \left(1+\frac{ZY}{2}\right)I_R \tag{3.10}$$

Hence comparing (3.1), (3.2), (3.9) and (3.10) we get for medium transmission line (nominal π representation):

$$A = 1+\frac{ZY}{2} \qquad B = Z \tag{3.11}$$

$$C = Y\left(1+\frac{ZY}{4}\right) \qquad D = 1+\frac{ZY}{2} \tag{3.12}$$

NOMINAL T REPRESENTATION

The A, B, C, D parameters of this circuit can be derived similar to above procedure. Let

$'I_c'$- Current flowing in the shunt branch of the circuit.

$'V_c'$- Voltage at the node of shunt branch of the circuit.

Hence by using KCL and KVL, we can write the circuit equation as follows.

$$I_c = V_c Y \tag{3.13a}$$

$$I_S = I_c + I_R = V_c Y + I_R \tag{3.13b}$$

$$V_c = V_R + I_R\frac{Z}{2} \tag{3.13c}$$

$$I_S = I_c + I_R = V_c Y + I_R = \left(V_R + I_R\frac{Z}{2}\right)Y + I_R \tag{3.13d}$$

$$V_S = V_c + \left(\frac{Z}{2}\right)I_S = \left(\frac{Z}{2}\right)I_S + \left(\frac{Z}{2}\right)I_R + V_R \tag{3.14a}$$

Substituting for $'I_S'$ from (3.13d) in (3.14a) and solving the algebra

$$V_S = \left(1+\frac{ZY}{2}\right)V_R + Z\left(1+\frac{ZY}{4}\right)I_R \tag{3.13}$$

From (3.13d) we can write

$$I_S = YV_R + \left(1+\frac{ZY}{2}\right)I_R \tag{3.14}$$

Hence comparing (3.1), (3.2), (3.13) and (3.14) we get for medium transmission line (nominal T representation):

$$A = 1 + \frac{ZY}{2} \qquad B = Z\left(1 + \frac{ZY}{4}\right) \tag{3.15}$$

$$C = Y \qquad D = 1 + \frac{ZY}{2} \tag{3.16}$$

LONG LENGTH TRANSMISSION LINE

The parameters of transmission line cannot approximated as lumped parameters if the length is long as because for such line series impedance and shunt admittance both effects the performance significantly. Hence these parameters are considered to be distributed as shown in Fig.-3.1. To derive the A, B, C, D parameters of the long transmission line, let us consider the circuit as shown in Fig.-3.6. Let us consider an elemental length of the transmission line $'dx'$ at a distance of $'x'$ from the receiving end. The series impedance and shunt admittance of this elemental length is given by $'zdx'\&'ydx'$ respectively, where $'z'\&'y'$ are series impedance and shunt admittance of transmission line per unit length. The voltage and current in this elemental length is shown in the Fig.-3.6.

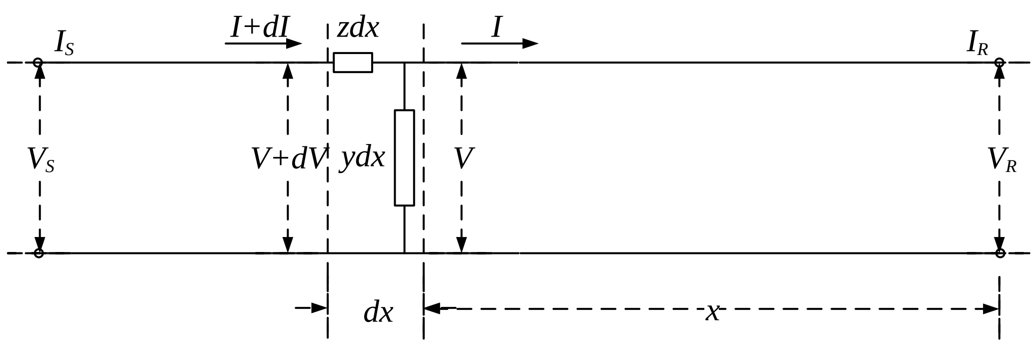


FIG.-3.6 LONG LINE REPRESENTATION OF TRANSMISSION LINE

For elemental section under consideration we can write the circuit equations as follows.

$$dV = Izdx \Rightarrow \frac{dV}{dx} = zI \tag{3.17a}$$

$$dI = Vydx \Rightarrow \frac{dI}{dx} = yV \tag{3.17b}$$

Differentiating (3.17a) with respect to $'x'$ and substituting (3.17b) we get

$$\frac{d^2V}{dx^2} = zyI \tag{3.18}$$

The general solution of (3.18) can be given by

$$V = K_1 e^{\gamma x} + K_2 e^{-\gamma x} \tag{3.19}$$

Where $\gamma = \sqrt{zy}$. Using (3.19) and (3.17b)

$$I = \frac{1}{Z_C}\left(K_1 e^{\gamma x} - K_2 e^{-\gamma x}\right) \tag{3.20}$$

Where $Z_C = \sqrt{\frac{z}{y}}$. Using boundary conditions of the transmission line $'x = 0 \Rightarrow V = V_R, I = I_R$, (3.19) and (3.20) becomes

$$V_R = K_1 + K_2 \tag{3.21}$$

$$I_R = \frac{1}{Z_C}\left(K_1 - K_2\right) \tag{3.22}$$

The constants $'K_1'\&'K_2'$ are evaluated using above equation.

$$K_1 = \frac{1}{2}\left(V_R + Z_C I_R\right) \tag{3.23}$$

$$K_2 = \frac{1}{2}\left(V_R - Z_C I_R\right) \tag{3.24}$$

Hence the voltage and current for the transmission line at a distance $'x'$ from the receiving end is given by putting the values of $'K_1'\&'K_2'$ in (3.19) and (3.20).

$$V = \frac{1}{2}\left(V_R + Z_C I_R\right)e^{\gamma x} + \frac{1}{2}\left(V_R - Z_C I_R\right)e^{-\gamma x} \tag{3.25}$$

$$I = \frac{\left(V_R + Z_C I_R\right)}{2Z_C}e^{\gamma x} - \frac{\left(V_R - Z_C I_R\right)}{2Z_C}e^{-\gamma x} \tag{3.26}$$

The (3.25) and (3.26) can rewritten as

$$V = \left(\frac{e^{\gamma x} + e^{-\gamma x}}{2}\right)V_R + \left(\frac{e^{\gamma x} + e^{-\gamma x}}{2}\right)Z_C I_R \tag{3.27}$$

$$I = \frac{1}{Z_C}\left(\frac{e^{\gamma x} + e^{-\gamma x}}{2}\right)V_R + \left(\frac{e^{\gamma x} + e^{-\gamma x}}{2}\right)I_R \tag{3.28}$$

The (3.27) and (3.28) can rewritten as

$$V = \left(Cosh\gamma x\right)V_R + \left(Z_C Sinh\gamma x\right)I_R \tag{3.29}$$

$$I = \left(\frac{1}{Z_C} Sinh\gamma x\right)V_R + (Cosh\gamma x)I_R \tag{3.30}$$

For the full length of the transmission line $'x = l'$ hence the sending end voltage and current is given as follows.

$$V_S = (Cosh\gamma l)V_R + (Z_C Sinh\gamma l)I_R \tag{3.31}$$

$$I_S = \left(\frac{1}{Z_C} Sinh\gamma l\right)V_R + (Cosh\gamma l)I_R \tag{3.32}$$

Thus A, B, C, D parameters of the long transmission line is given by

$$A = Cosh\gamma l \qquad B = Z_C Sinh\gamma l \tag{3.33}$$

$$C = \frac{1}{Z_C} Sinh\gamma l \qquad D = Cosh\gamma l \tag{3.34}$$

In the derivation of A, B, C, D parameters of the long transmission line we introduce two new parameters $'\gamma' \& 'Z_C'$.

$'\gamma'$- is a complex quantity and known as the propagation constant and given as $\gamma = \alpha + j\beta$, where $'\alpha'$ is the attenuation constant and $'\beta'$ is the phase constant.

$'Z_C'$- is the characteristics impedance. For a given transmission line is a constant. Generally for overhead transmission line it is approximately equal to 400Ω.

The equation (3.25) can be rewritten by using the components of propagation constant.

$$V = \frac{1}{2}(V_R + Z_C I_R)e^{\alpha x}e^{j\beta x} + \frac{1}{2}(V_R - Z_C I_R)e^{-\alpha x}e^{-j\beta x} \tag{3.35}$$

The first term increases in magnitude and advances in phase as distance $'x'$ from the receiving end increases. We can say that this term decreases in magnitude and retarded in phase as we move from the sending end towards the receiving end. This is the characteristic of a travelling wave. Hence the first term is known as the incident voltage. The second term diminishes in magnitude and retarded in phase from the receiving end towards the sending end. It is called as reflected voltage. The voltage at any point on the transmission line is the sum of incident and reflected voltage.

If the line is terminated in its characteristics impedance, the receiving end voltage $V_R = Z_C I_R$ and there is no reflected wave. Thus the line is said to be *flat line or infinite line*.

For a lossless transmission line the characteristics impedance is given by $Z_C = \sqrt{\frac{L}{C}}$. Under such condition the characteristics impedance is known as surge impedance and the loading under such condition is known as surge impedance loading (SIL).

$$SIL = \frac{V_L^2}{\sqrt{L/C}} \tag{3.36}$$

FERRANTI EFFECT

In case of EHV very long transmission lines, the voltage at the receiving end is more that the sending end voltage at light load or no-load condition. This is known as Ferranti effect. The rise is voltage is due to the shunt capacitors of the transmission line, which draw charging current. This charging current becomes dominant as compared to load current

POWER FLOW IN A TRANSMISSION LINE

The power flow in a transmission line can be calculated by considering the system shown in Fig.-3.7. It consists of a single transmission line connected between two buses. These buses are Sending end bus and Receiving end bus.

FIG.-3.7 TRANSMISSION LINE POWER FLOW

The line is characterized by its line constants as follows

$A = |A|\angle\alpha, B = |B|\angle\beta$

So that the power received at the receiving end is given by

$$S_R = P_R + jQ_R = V_R I_R^* \tag{3.37}$$

As we know the line equation in terms of $ABCD$ constant are

$$V_S = AV_R + BI_R \tag{3.38}$$

$$I_S = CV_R + DI_R \tag{3.39}$$

From (3.38)

$$I_R = \frac{V_S - AV_R}{B} \tag{3.40}$$

$$I_R^* = \left(\frac{V_S - AV_R}{B}\right)^* \tag{3.41}$$

$$I_R^* = \frac{(|V_S|\angle -\delta) - (|A|\angle -\alpha)(|V_R|\angle 0)}{(|B|\angle -\beta)} \tag{3.42}$$

We have

$$P_R + jQ_R = (|V_R|\angle 0)\frac{(|V_S|\angle -\delta) - (|A|\angle -\alpha)(|V_R|\angle 0)}{(|B|\angle -\beta)} \tag{3.43}$$

$$P_R + jQ_R = \frac{|V_R||V_S|}{|B|}\angle(\beta - \delta) - \frac{|V_R|^2|A|}{|B|}\angle(\beta - \alpha) \tag{3.44}$$

Equating the real and imaginary part

$$P_R = \frac{|V_R||V_S|}{|B|}Cos(\beta - \delta) - \frac{|V_R|^2|A|}{|B|}Cos(\beta - \alpha) \tag{3.45}$$

$$Q_R = -\left[\frac{|V_R||V_S|}{|B|}Sin(\beta - \delta) - \frac{|V_R|^2|A|}{|B|}Sin(\beta - \alpha)\right] \tag{3.46}$$

APPROXIMATION OF POWER FLOW EQUATION

For the transmission line series resistance is very less as compared to series reactance and $|A| \approx 1.0, \alpha \approx 0.0, |B| = Z \approx X, \beta \approx 90^\circ$

Hence (3.45) can be fairly approximated as (3.47)

$$P_R = \frac{|V_R||V_S|}{X}Sin\delta \tag{3.47}$$

From (3.47) we conclude that the power transmitted over a transmission line is determined by the voltage at both the ends, the reactance of the line and phase difference between the voltages of both ends. Similarly the power flow between two buses can be given by (3.48)

$$P = \frac{|V_1||V_2|}{X_{12}}Sin(\delta_1 - \delta_2) \tag{3.48}$$

LINE COMPENSATION

As stated above the power flow in a transmission line depends upon the voltage at both the ends, the reactance of the line and phase difference between the voltages. If the power flow has to be increased or decreased then we have to control these variables. It can be controlled by

- Voltage magnitude control
- Transmission line reactance control
- Phase angle control

Once the installation of the transmission line is over its A, B, C, D parameters are constant because these depend upon the size and material of conductors and the configurations of the conductors. And hence the value of reactance and resistance are also fixed. The value of reactance X however can be controlled by providing compensation.

Since the series impedance of the transmission line consists of inductive reactance, the total series reactance can be reduced by connecting a capacitor in series. The shunt admittance of the transmission line consists of capacitive reactance, the effect of which can be compensated by connecting a shunt reactor. These processes are known as providing line compensation. The line compensation are of two types.

- Series compensation
- Shunt compensation

In series compensation as mentioned above, a suitable value of capacitor is connected in series with the transmission line as shown in Fig.-3.8. The location of this capacitor is optional and depend upon the requirement of transmission company.

FIG.-3.8TRANSMISSION LINE WITH SERIES COMPENSATION

In shunt compensation a shunt reactor of suitable capacity is connected as a shunt element at the required bus of the transmission line as shown in Fig.-3.9.

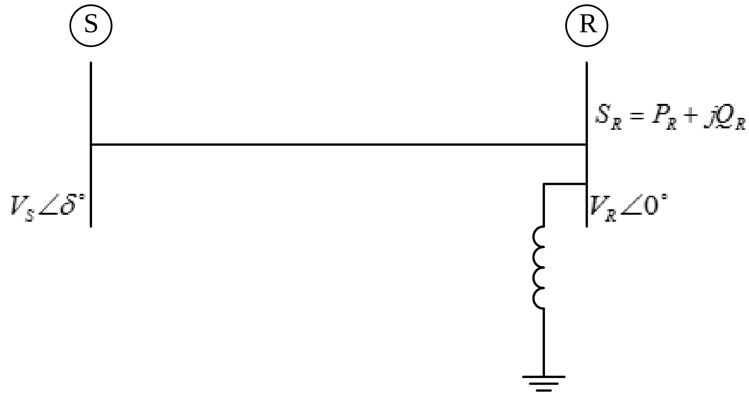


FIG.-3.9 TRANSMISSION LINE WITH SHUNT COMPENSATION

The value of series compensation and shunt compensation known as degree of compensation depend upon operational policy. It is seen that the series compensation is very much effective in controlling the power transfer over the transmission line where as the shunt compensation is most proved way for voltage control at the bus at which the compensation has been provided.

In power system most of the loads are inductive in nature resulting in reducing the voltage at which it is connected, it is well known to connect the capacitor at that voltage. It improves the power factor at that bus by supplying reactive power at the said bus. Thus Fig.-3.9 can be modified to Fig.-3.10.

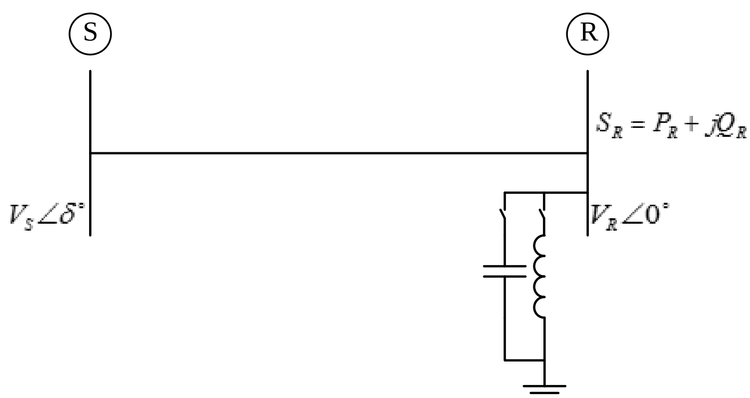


FIG.-3.10 TRANSMISSION LINE WITH SHUNT COMPENSATION

If the magnitude of voltage at the bus is less than the required magnitude then the shunt capacitor is connected. If the magnitude of voltage at the bus is more than the required magnitude then the shunt reactor is connected. Other way we can say, the shunt capacitor is used to improve the voltage and the shunt reactor is used to avoid the overvoltage.

The $'A, B, C, D'$ parameters of a compensated transmission line is calculated by using the following procedure.

If a line is compensated by a series capacitor connected at the end of receiving end of the line.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{Equivalent} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{Line} \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{SeriesCapacitor} \tag{3.49}$$

If a line is compensated by a shunt capacitor/reactor connected at the end of receiving end of the line.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{Equivalent} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{Line} \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{ShuntCapacitor/Reactor} \tag{3.50}$$

If a line is compensated by a series capacitor connected at the mid point of the line.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{Equivalent} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{HalfLine} \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{SeriesCapacitor} \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{HalfLine} \tag{3.51}$$

The $'A, B, C, D'$ parameters of series capacitor is given by

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{SeriesCapacitor} = \begin{bmatrix} 1 & Z_{SeriesCapacitor} \\ 0 & 1 \end{bmatrix} \tag{3.52}$$

The $'A, B, C, D'$ parameters of shunt capacitor/reactor is given by

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{ShuntCapacitor/Reactor} = \begin{bmatrix} 1 & 0 \\ Y_{ShuntCapacitor/Reactor} & 1 \end{bmatrix} \tag{3.53}$$

With the insertion of compensation the circuit parameters changes and thus the operation of the power system. The line compensation provides:

- Improvement in power flow
- Power flow control
- Share of power between the transmission lines
- Voltage control
- Improved stability
- Improved security

Modern power system uses flexible AC transmission system (FACTS) devices to achieve required degree of compensation and thus control over the system operation.

PER UNIT SYSTEM

In per unit system, the power system variables such as voltage, current and impedances etc. are represented on a common base. For this purpose we need to define base quantity of the system. Generally two base quantities *'Base KVA or Base MVA' and 'Base KV'* are defined and others can be calculated.

Let

$$Base\,Current = I_{Base}$$

$$Base\ Impednace = Z_{Base}$$

If the voltage and power are given for single phase:

$$I_{Base} = \frac{Base\ KVA_{1\varphi}}{Base\ KV_{LN}} \tag{3.54}$$

$$Z_{Base} = \frac{Base\ KV_{LN}^{2}\ X\ 10^{3}}{Base\ KVA_{1\varphi}} \tag{3.55}$$

Or (3.55) can be written as

$$Z_{Base} = \frac{Base\ KV_{LN}^{2}}{Base\ MVA_{1\phi}} \tag{3.56}$$

If the voltage and power are given for three phase:

$$I_{Base} = \frac{Base\ KVA_{3\phi}}{\sqrt{3}\ X\ Base\ KV_{LL}} \tag{3.57}$$

$$Z_{Base} = \frac{\left(\dfrac{Base\ KV_{LL}}{\sqrt{3}}\right)^{2}\ X\ 10^{3}}{\left(\dfrac{Base\ KVA_{3\phi}}{3}\right)} \tag{3.58}$$

$$Z_{Base} = \frac{\left(Base\ KV_{LL}\right)^{2}\ X\ 10^{3}}{Base\ KVA_{3\phi}} \tag{3.59}$$

$$Z_{Base} = \frac{\left(Base\ KV_{LL}\right)^{2}}{Base\ MVA_{3\phi}} \tag{3.60}$$

The per unit value of any variable is given by (3.61)

$$p.u.Value\ \ of\ \ the\,Variable = \frac{Actual\ Value\ of\ \ the\,Variable}{Base\,Value\ of\ \ the\,Variable} \tag{3.61}$$

Say for voltage (3.62)

$$V_{p.u.} = \frac{V_{Actual}}{V_{Base}} \tag{3.62}$$

Similarly for current, impedance and power it is given by (3.63) to (3.65)

$$I_{p.u.} = \frac{I_{Actual}}{I_{Base}} \tag{3.63}$$

$$Z_{p.u.} = \frac{Z_{Actual}}{Z_{Base}} \tag{3.64}$$

$$MVA_{p.u.} = \frac{MVA_{Actual}}{MVA_{Base}} \tag{3.65}$$

Many a times the per unit quantities need to be calculated to a new base. It can be done by calculating the actual value at first and then converted to per unit on a new base.

Let the old base is given by $BaseKV_{Old}, BaseMVA_{Old}$ and new base is given by $BaseKV_{New}, BaseMVA_{New}$.

The old and new per unit value of impedance is given by $Z_{p.u..(Old)}$ & $Z_{p.u..(New)}$ respectively.

From (3.64) we get at the old base:

$$Z_{Actual} = Z_{p.u..(Old)}\ X\ Z_{Base(Old)} = Z_{p.u..(Old)} X \frac{\left(Base\ KV_{LL(Old)}\right)^2}{Base\ MVA_{3\phi(Old)}} \tag{3.66}$$

But the actual impedance on a new base can be given by

$$Z_{Actual} = Z_{p.u..(New)}\ X\ Z_{Base(New)} = Z_{p.u..(New)} X \frac{\left(Base\ KV_{LL(New)}\right)^2}{Base\ MVA_{3\phi(New)}} \tag{3.67}$$

Equating (3.66) and (3.67)

$$Z_{p.u..(New)} = Z_{p.u..(old)} X \frac{\left(Base\ KV_{LL(Old)}\right)^2}{Base\ MVA_{3\phi(Old)}}\ X\ \frac{Base\ MVA_{3\phi(New)}}{\left(Base\ KV_{LL(New)}\right)^2} \tag{3.68}$$

$$Z_{p.u..(New)} = Z_{p.u..(old)} X \frac{Base\ MVA_{3\phi(New)}}{Base\ MVA_{3\phi(Old)}}\ X\ \frac{\left(Base\ KV_{LL(Old)}\right)^2}{\left(Base\ KV_{LL(New)}\right)^2} \tag{3.69}$$

$$Z_{p.u..(New)} = Z_{p.u..(old)} X \frac{Base\ MVA_{3\phi(New)}}{Base\ MVA_{3\phi(Old)}}\ X \left(\frac{Base\ KV_{LL(Old)}}{Base\ KV_{LL(New)}}\right)^2 \tag{3.70}$$

By (3.70) the per unit impedance can be calculated on the new base.

CHAPTER-4
CORONA

INTRODUCTION

When an alternating current is made to flow across two conductors of the transmission line whose spacing is large compared to their diameters, then air surrounding the conductors (composed of ions) is subjected to di-electric 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, then the field strength at the surface of conductor increases and then the air surrounding it experiences stress high enough to be dissociated into ions making the atmosphere conducting if the stress increases beyond threshold value of 30 kV (peak) known as the break down voltage of air at normal temperature and pressure. 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.

FACTORS AFFECTING CORONA

Atmospheric Conditions: It has been physically proven that the voltage gradient for di-electric breakdown of air is directly proportional to the density of air. Hence in a stormy day, due to continuous air flow the number of ions present surrounding the conductor is far more than normal, and hence it is more likely to have electrical discharge in transmission lines on such a day, compared to a day with fairly clear weather.

Condition of Conductors: 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 then corona for that region of the transmission line might not occur at all.

METHODS TO REDUCE THE EFFECTS OF CORONA

- The use of bundle conductors reduce corona loss
- Spacing between conductors is selected so that corona is tolerable
- Since the shape of conductors affect corona loss, cylindrical shape conductors have uniform field that reduces corona loss than any other shape
- The voltage stress and electric field gradient should be minimized which can be accomplished by following good high voltage design practices.
- Using conductors with large radii reduce corona loss
- Void free solid conductors and insulators should be used
- The terminals on high voltage equipment are designed with smooth round diameter rounded shapes like balls
- Addition of corona rings to insulators of high voltage transmission lines

CRITICAL DISRUPTIVE VOLTAGE

Let us refer to Fig.-4.1 wherein two conductors having charges and radii as shown are spaced apart by a distance *'D'*.

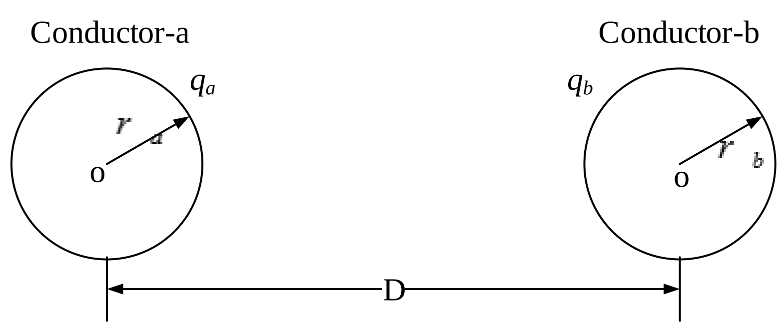


FIG.-4.1 A TWO CONDUCTOR LINE

Let $q_a = q_b = q$ and $r_a = r_b = r$, since both conductors form one transmission line. The electric field intensity at any pint *'P'* at distance *'x'* from the center of the *conductor-a* due to both the charges shall be

$$E = \frac{q}{2\pi k}\left(\frac{1}{x} + \frac{1}{D-x}\right) \tag{4.1}$$

The potential difference between two conductors is given by

$$V = -\int_{D-r}^{r} E dx = \int_{D-r}^{r} \frac{q}{2\pi k}\left(\frac{1}{x} + \frac{1}{D-x}\right)dx \tag{4.2}$$

$$V = \frac{q}{\pi k}\ln\frac{D}{r} \tag{4.3}$$

Substituting for *'q'* from (4.3) in (4.1) we get

$$E = \frac{\pi k V}{\ln\frac{D}{r}}\frac{1}{2\pi k}\frac{D}{x(D-x)} \tag{4.4}$$

$$E = \frac{V'D}{x(D-x)\ln\frac{D}{r}} \tag{4.5}$$

Where $V' = \frac{V}{2}$ and for three phase line $V' = \frac{V_{Line}}{\sqrt{3}}$

The electric stress is maximum at $x = r$ and given by

$$g_{\max} = \frac{V'D}{r(D-r)\ln\frac{D}{r}} \cong \frac{V'}{r\ln\frac{D}{r}} \tag{4.6}$$

From (4.6) we can determine the expression for disruptive critical voltage

$$V_d = g_0 \delta r \ln\frac{D}{r} \text{ (kV)} \tag{4.7}$$

Where,

$\delta = \frac{3.92b}{t+273}$ is the air density factor, in which *'b'* is the atmospheric pressure in cm of Hg and *'t'* is the atmospheric temperature in degree Celsius.

g_0 is the dielectric strength of the air at normal temperature and pressure in kV and equal to 30kV/cm (peak), thus equals to 21.2 kV/cm (rms)

Taking into the surface condition of conductors we introduce surface irregularity factor *'m'*

$$V_d = 21.2 m\delta r \ln\frac{D}{r} \text{ (kV)} \tag{4.8}$$

For three phase line

$$V_d = 21.2 m\delta r \ln\frac{D}{r} \text{ (kV)(line to neutral)} \tag{4.9}$$

For smooth polished conductor- $m = 1$,

For rough surfaces conductor- $m = 0.92 \le m \le 0.98$

For stranded conductor- $m = 0.82 \le m \le 0.88$

At this value of critical disruptive voltage, the corona starts but nor visible because the charges ions do not get sufficient energy to cause further ionization by collisions. To make the corona visible the potential difference between the conductors should be more. The expression for critical disruptive voltage for visual corona is given by modifying (4.9) as shown below.

$$V_v = 21.2 m\delta r\left(1 + \frac{0.3}{\sqrt{r\delta}}\right)\ln\frac{D}{r} \text{ (kV)(line to neutral)} \tag{4.10}$$

For smooth polished conductor- $m_v = 1$,

For rough surfaces conductor- $m_v = 0.82$

For stranded conductor- $m_v = 0.72$

POWER LOSS DUE TO CORONA

The corona also results in power loss. The power loss due to corona can be calculated by Peeks formula as given in (4.11).

$$P_c = \frac{241}{\delta}(f + 25)\sqrt{\frac{r}{D}}(V - V_D)^2 \text{X}10^{-5} \text{ (kW/Phase/km)} \tag{4.11}$$

Or by Peterson formula

$$P_c = \frac{21\text{X}10^{-6}\text{X}fV^2F}{\left[\log_{10}\left(D/r\right)^2\right]} \text{ (kW/Phase/km)} \tag{4.12}$$

Where $'f'$ is the supply frequency and $'F'$ is the corona factor determined by test.

The corona loss can be reduced by employing the methods explained above.

CHAPTER-5
OVERHEAD LINE INSULATOR

INTRODUCTION

The overhead line conductors are supported over the tower structures by means of line insulators. The line insulators provide sufficient mechanical strength as well as insulation between the live conductors and tower structures.

In general, the insulators should have the following desirable properties.

- High mechanical strength in order to withstand conductor load, wind load etc.
- High electrical resistance of insulator material in order to avoid leakage currents to earth.
- High relative permittivity of insulator material in order that dielectric strength is high.
- The insulator material should be non-porous, free from impurities and cracks otherwise the permittivity will be lowered.
- High ratio of puncture strength to flashover.

The most commonly used material for insulators of overhead line is porcelain but glass, steatite and special composition materials are also used to a limited extent. Porcelain is produced by firing at a high temperature a mixture of kaolin, feldspar and quartz. It is stronger mechanically than glass, gives less trouble from leakage and is less affected by changes of temperature. The successful operation of an overhead line depends to a considerable extent upon the proper selection of insulators.

There are three types of insulators used in connection with overhead lines. They are:

- Pin-type.
- Suspension-type.
- Strain-type.

PIN-TYPE INSULATORS

As the name suggests, the pin-type insulator shown in Fig.-5.1 is attached to a steel bolt or pin, which is secured to a cross-arm on the transmission pole.

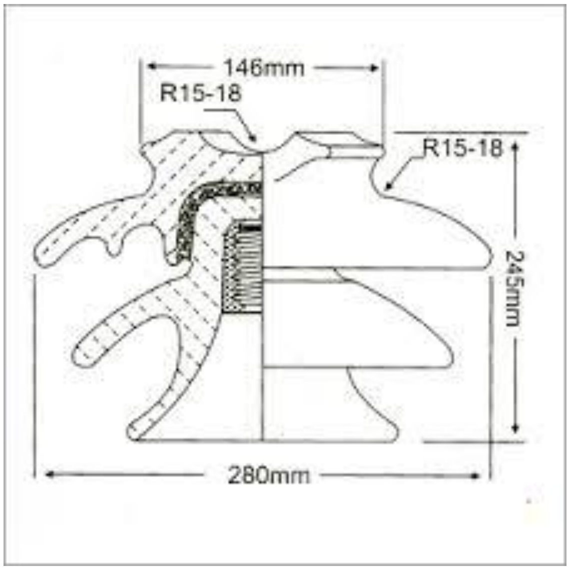


FIG.-5.1 PIN TYPE INSULATORS

The Standards Specification requires that the porcelain shall not engage directly with a hard metal screw. It recognizes two methods:

- The provision of a taper thread cut on the head of the pin, which screws into a threaded soft metal thimble cemented into the insulator.
- The provisions of a cast lead thread on the steel spindle, which screws directly into a thread formed in the porcelain; on the continent the pin, which has a plain top, is still sometimes wrapped in hemp and the threaded porcelain screwed on.

For operating voltages up to about 11 kV with ordinary designs of insulator a one-piece construction can be adopted. Recent progress in design and manufacture has enabled much thicker sections to be adopted, with the result that for working voltages up to 33 kV a single-piece construction is possible, and not more than two parts even in the largest sizes. Actually, the tendency is to use pin-type insulators for voltages up to 33 kV only, since they become uneconomical for higher voltages. This is because their cost increases much more rapidly than the voltage.

There should be sufficient thickness of porcelain between the line conductor and the insulator pin (or other metal work) to give a factor of safety of up to 10 against puncture, but the insulator should be designed so that it will spark-over before it will puncture. The ratio of the spark-over voltage to the working voltage is called the safety factor, and for pin-type insulators this factor is much higher for low voltages than it is for high. The present tendency is to use pin-type insulators for low voltages only, say up to 11 kV, for which the factors of safety are 8.3 dry and 5 wet. With a wet insulator, the surfaces of the various pieces, or 'sheds' as they are sometimes called, have no insulating value, so that the total arcing distance is the sum of the shortest distances from the edge of one shed to the nearest point on the next lower shed, plus the distance from the edge of the next lowest shed to the pin.

The insulator and its pin, or other support, should be sufficiently strong mechanically to withstand the resultant force due to the combined effects of wind pressure and weight of span (and ice load, if any). At terminal poles there is, in addition, the almost horizontal pull due to the tension of the conductor. This, in particular, causes such a great bending moment at the bottom of the pin, with pin-type insulators, this being transmitted to the cross-arm, that for a line insulated with pin-type insulators, it is desirable to use some type of strain insulator at all terminal or dead-ending poles. In connection with the mechanical strength, it is to be noted that the insulator is stronger than the pin.

SUSPENSION INSULATORS

We have seen that the cost of a pin-type insulator increases very rapidly as the working voltage is increased. For high voltages this type is therefore uneconomical, and there is the further disadvantage that replacements are expensive. For these reasons, high-voltage lines are insulated by means of suspension insulators in which, as their name indicates, the line conductor is suspended below the point of support by means of the insulator or insulators. Several important advantages follow from this system.

- Each insulator is designed for a comparatively low working voltage, usually about 11 kV, and the insulation for any required line voltage can be obtained by using a 'string' of a suitable number of such insulators.
- In the event of a failure of an insulator, one unit - instead of the whole string - has to be replaced.
- The mechanical stresses are reduced, since the line is suspended flexibly; with pin-type insulators, the rigid nature of the attachment results in fatigue and ultimate brittleness of the wire, due to the alternating nature of the stress. Also, since the string is free to swing, there is an equalization of the tensions in the conductors of successive spans.

- In the event of an increase in the operating voltage of the line, this can be met by adding the requisite number of units to each string, instead of replacing all insulators, as would be necessary with pin-type.
- Owing to the free suspension, the amplitude of swing of the conductors may be large compared with that on a pin-type insulated line, and the spacing should therefore be increased.

There are several types of suspension insulator that illustrated in Fig.-5.2 being most frequently used in this country, having been adopted for the insulation of the Grid lines. It will be seen that it consists of a single disc-shaped piece of porcelain, grooved on the under-surface to increase the surface leakage path, and to a metal cap at the top, and to a metal pin underneath. The cap is recessed so as to take the pin of another unit, and in this way a string of any required number of units can be built up. The cap is secured to the insulator by means of cement. Various means of securing the pin have been tried, but all have been abandoned in favor of cementing. Mechanical methods of fixing have proved unsatisfactory since they caused concentrations of mechanical stress, which led to failure in service. On the other hand, cement acts as a good distributor of mechanical stress, and cemented insulators of good mechanical design have an excellent service record.

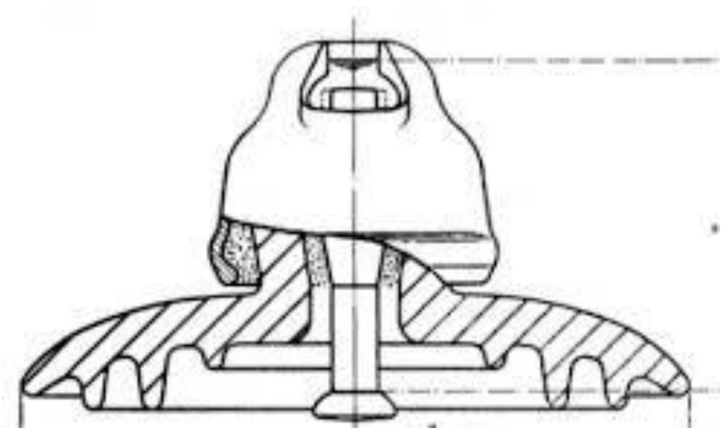


FIG.-5.2 SUSPENSION TYPE INSULATORS

The usual diameter of this type of insulator is ten inches, since it has been found that this size gives a suitable ratio of spark-over to puncture voltage. Increasing the diameter raises the spark-over voltage, of course, but it also lowers the above ratio, and this is undesirable.

STRAIN INSULATORS

These insulators are used to take the tension of the conductors at line terminals and at points where the line is dead-ended, as for example some road-crossings, junctions of overhead lines with cables, river crossings, at angle towers where there is a change in direction of the line, and so on. For light low-voltage lines, say up to 11 kV, the shackle insulator is suitable, but for higher voltages a string of suspension-type insulators is necessary. Where the tension is exceedingly high, as at long river spans, two, three, or even four strings of insulators in parallel have been used.

VOLTAGE DISTRIBUTION IN A STRING OF INSULATOR

Let us consider a string consists of four insulators as shown in Fig.-5.3 operating at voltage $'V'$ (Line to Ground). Each insulator is represented by its capacitor.

$'C'$-The capacitance of each insulator

$'KC'$-The capacitance of insulator pin to ground

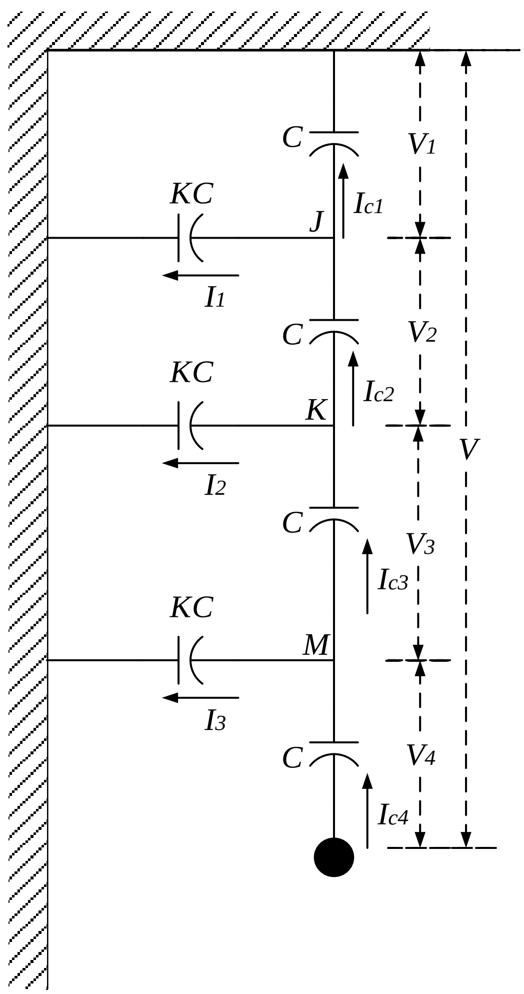


FIG.-5.3 STRING OF FOUR INSULATORS

At node $'J'$ using KCL we can write

$$I_{c2} = I_{c1} + I_1 \tag{5.1a}$$

$$\omega CV_2 = \omega CV_1 + \omega KCV_1 \tag{5.1b}$$

Which can be simplified to (5.2)

$$V_2 = (1 + K)V_1 \tag{5.2}$$

At node $'K'$ using KCL we can write

$$I_{c3} = I_{c2} + I_2 \tag{5.3a}$$

$$\omega CV_3 = \omega CV_2 + \omega KC(V_1 + V_2) \tag{5.3b}$$

Which can be simplified to (5.4) by using (5.2)

$$V_3 = (1 + 3K + K^2)V_1 \tag{5.4}$$

At node $'M'$ using KCL we can write

$$I_{c4} = I_{c3} + I_3 \tag{5.5a}$$

$$\omega CV_4 = \omega CV_3 + \omega KC(V_1 + V_2 + V_3) \tag{5.5b}$$

Which can be simplified to (5.6) by using (5.2) and (5.4)

$$V_4 = (1 + 6K + 5K^2 + K^3)V_1 \tag{5.6}$$

For the whole string we have

$$V = V_1 + V_2 + V_3 + V_4 \tag{5.7}$$

Using the above equations we can determine the voltage across each insulator and it can be seen that they are not equal i.e. voltage distribution in the string is not uniform. At this point let us define string efficiency as follows:

$$\eta_{string} = \frac{\text{Votlage across string}}{\text{No. of Insulators X Voltage across the Insulator adjacent to the conductor}} \tag{5.8}$$

This efficiency is very low because of unequal voltage distribution. It can be increased by the following methods which is also known as grading of the insulators.

LENGTH OF THE CROSS ARM

As we can see the voltage distribution depends largely on the value of $'K'$. Hence if the value of $'K'$ is reduced the distribution can be made equal and string efficiency can be improved.

It can be done by increasing the length of the cross arm. However there is limitation to it because of mechanical strength of the supporting tower.

GRADING OF INSULATORS UNITS

It is observed from the above derivation that the insulators having same capacitors have been used in the string. To make voltage distribution equal we can use insulators having different capacitance as shown in Fig.-5.4 such that we will result in the following equations.

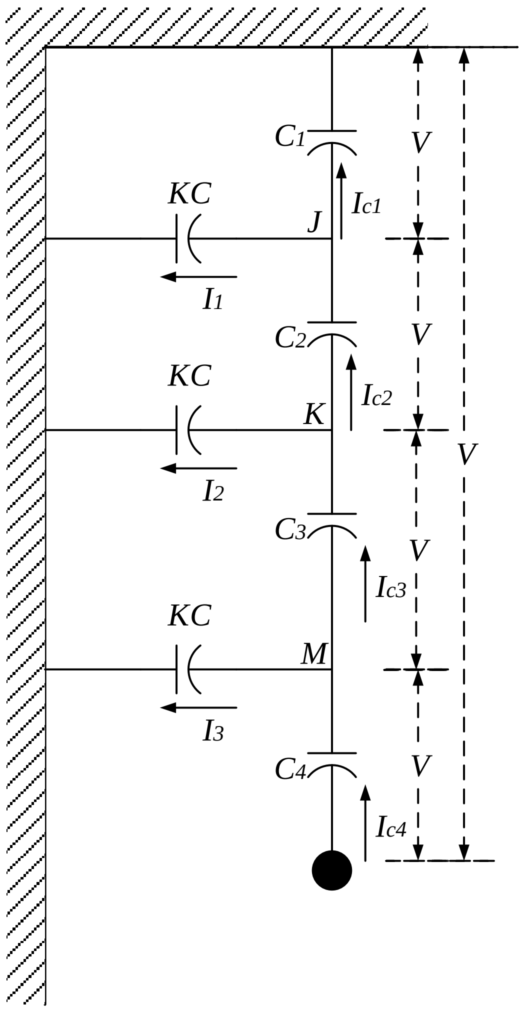


FIG.-5.4 GRADING OF STRING OF FOUR INSULATORS

$$I_{c2} = I_{c1} + I_1 \tag{5.9a}$$

$$\omega C_2 V = \omega C_1 V + \omega K C_1 V \tag{5.9b}$$

Which can be simplified to (5.10)

$$C_2 = (1 + K) C_1 \tag{5.10}$$

Similarly we can use for the other nodes and can determine the capacitor of each insulators of the string. However this method is not practically feasible because of large no. of insulators in the string for very high voltage transmission line.

STATIC SHIELDING

The voltage distribution can also be equalized by using static shielding. The basic objective is provide the charging current flowing through the capacitance between insulator pin and the ground by another alternate path. So that the current flowing in each insulator shall be equal and hence the voltage across each insulator shall be equal as shown in Fig.-5.5.

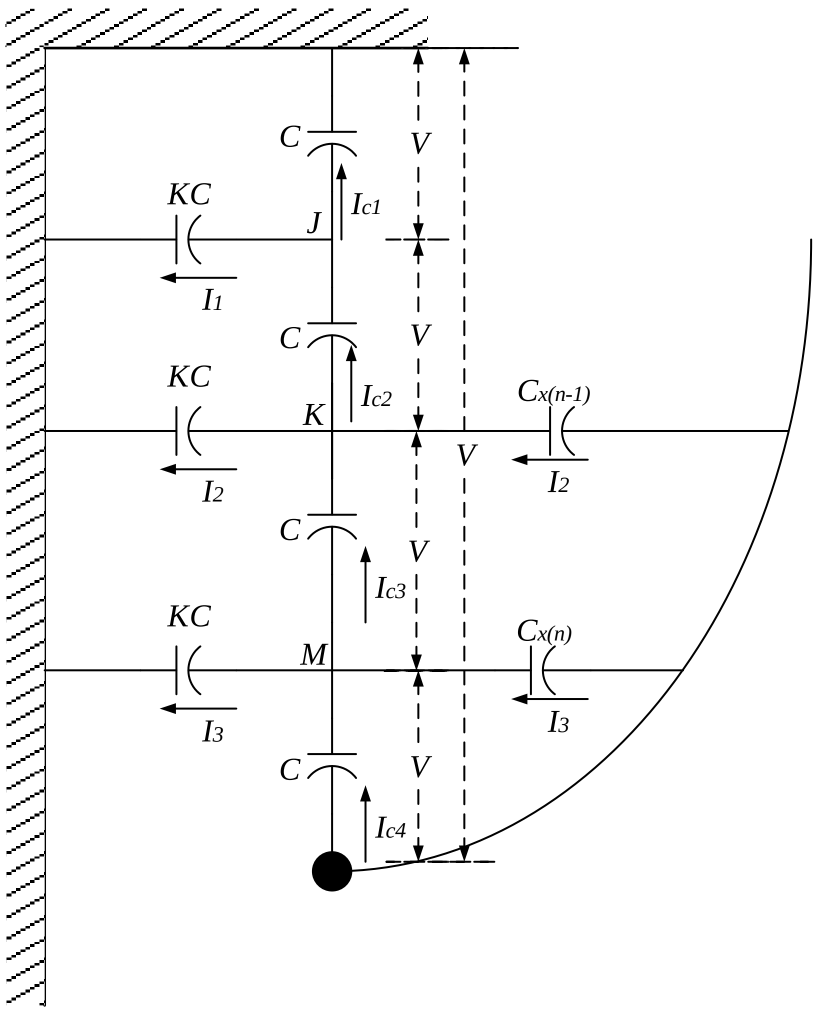


FIG.-5.5 STATIC SHIELDING OF STRING OF FOUR INSULATORS

TESTING OF INSULATORS

The testing of insulators are made into three categories: flash-over tests, sample tests, and routine tests. In each category, there is a group of individual tests. Flash-over tests are a design test taken to three insulators only to prove the correction of the design; sample tests are to prove the quality of manufacture, and are taken on 1/2 per cent. of the insulators supplied; routine tests are carried out on all insulators.

Flashover Tests

- 50 per cent. dry impulse flash-over test.
- Dry flash-over and dry one-minute test.
- Wet flash-over and one-minute rain test.

Sample Tests

- Temperature-cycle test.
- Mechanical test.
- Electro-mechanical test.
- Puncture test.
- Porosity test.

Routine Tests

- Electrical routine test.
- Mechanical routine test.

The details methodology of these tests can be referred from Bureau of Indian Standard.

CAUSES OF INSULATOR FAILURE

Insulators are required to withstand both mechanical and electrical stresses. The latter type is primarily due to line voltage and may cause the breakdown of the insulator. The electrical breakdown of the insulator can occur either by flash-over or puncture. In flashover, an arc occurs between the line conductor and insulator pin (i.e., earth) and the discharge jumps across the air gaps, following shortest distance. In case of flash-over, the insulator will continue to act in its proper capacity unless extreme heat produced by the arc destroys the insulator.

In case of puncture, the discharge occurs from conductor to pin through the body of the insulator. When such breakdown is involved, the insulator is permanently destroyed due to excessive heat. In practice, sufficient thickness of porcelain is provided in the insulator to avoid puncture by the line voltage. The ratio of puncture strength to flashover voltage is known as safety factor.

CHAPTER-6

MECHANICAL DESIGN OF OVERHEAD TRANSMISSION LINE

INTRODUCTION

We know that the overhead line conductors are supported on the tower structure by means of line insulators. These conductors, which are made of copper or aluminum or its alloys have its own weight, especially in extra high voltage transmission line these conductors re very heavy. Due to its weight it exerts pressure on the insulators and the towers thus stress at the point of supports as well as the conductors are also subjected to high tension. It is very important that conductors are under safe tension. If the conductors are too much stretched between supports in a bid to save conductor material, the stress in the conductor may reach unsafe value and in certain cases the conductor may break due to excessive tension. In order to permit safe tension in the conductors, they are not fully stretched but are allowed to have a dip or sag.

The difference in level between points of supports and the lowest point on the conductor is called sag. The conductor sag should be kept to a minimum in order to reduce the conductor material required and to avoid extra pole height for sufficient clearance above ground level. It is also desirable that tension in the conductor should be low to avoid the mechanical failure of conductor and to permit the use of less strong supports. However, low conductor tension and minimum sag are not possible. It is because low sag means a tight wire and high tension, whereas a low tension means a loose wire and increased sag. Therefore, in actual practice, a compromise in made between the sag and tension.

CALCULATION OF SAG

A conductor is suspended between two supports *'A'* and *'B'* as shown in Fig.-6.1. The lowest point on the conductor is *'O'* and the sag is *'d'*. When the conductor is suspended between two supports at the same level, it takes the shape of catenary. However, if the sag is very small compared with the span, then sag-span curve is like a parabola. The tension at any point on the conductor acts tangentially. Thus tension *'T'* at the lowest point *'O'* acts horizontally as shown. The horizontal component of tension is constant throughout the length of the wire. The tension at supports is approximately equal to the horizontal tension acting at any point on the wire.

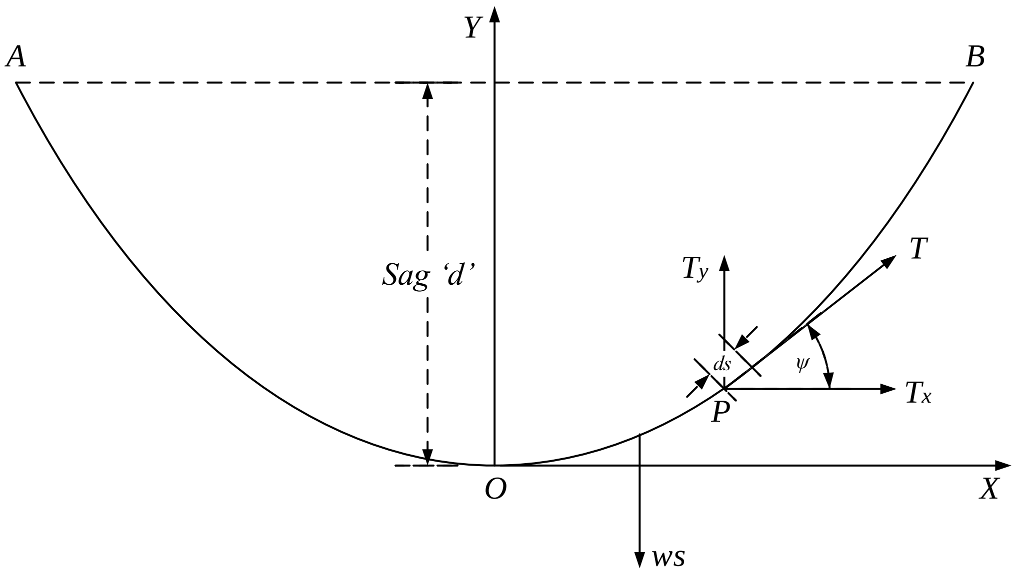


FIG.-6.1 SPAN OF TRANSMISSION LINE SHOWING THE CONDUCTOR SAG AND TENSION (SUPPORTS AT SAME LEVEL)

Let us consider an elemental length of the conductor *'ds'* at point *'P'* on the conductor at the length of *'s'* from the center point *'O' (minimum point of the conductor)*. We can write the vertical component and horizontal component of tension acting on the elemental length as follows.

$T_x = H$ and $T_y = ws$ where *'w'* is the weight of the conductor per unit length of the conductor. At point *'P'*

$$\tan\psi = \frac{dy}{dx} = \frac{T_y}{T_x} = \frac{ws}{H} \tag{6.1}$$

For the elemental length of the conductor we can write

$$ds = \sqrt{dx^2 + dy^2} \Rightarrow \frac{ds}{dx} = \sqrt{1 + \left(\frac{dy}{dx}\right)^2} = \sqrt{1 + \left(\frac{ws}{H}\right)^2} \tag{6.2}$$

Integrating and solving for constant we get

$$s = \frac{H}{w} Sinh \frac{wx}{H} \tag{6.3}$$

Thus from(6.1) and (6.3) we get after solving for constant

$$y = \frac{H}{w}\left(Cosh \frac{wx}{H} - 1 \right) \tag{6.4}$$

(6.4) is the equation of catenary. At point *'P'* the tension *'T'* is given by

$$T = \sqrt{T_x^2 + T_y^2} = \sqrt{H^2 + (ws)^2} \tag{6.5}$$

Using (6.3) in (6.5) we get

$$T = HCosh\frac{wx}{H} \tag{6.6}$$

If the span length is '*2l*' then half span is '*l*', hence the length of the conductor in half span, sag and tension can be given by (6.7)

$$S = \frac{H}{w}Sinh\frac{wl}{H} \tag{6.7a}$$

$$Sag'd' = y_A - y_B = \frac{H}{w}\left(Cosh\frac{wl}{H} - 1\right) \tag{6.7b}$$

$$T = T_A = T_B = HCosh\frac{wl}{H} \tag{6.7c}$$

(6.7) can be approximated to

$$s = l + \frac{w^2\ell^3}{6T^2} \tag{6.8a}$$

$$y = \frac{w\ell^2}{2T} = d \tag{6.8b}$$

$$\frac{T}{H} = 1 + \frac{(w\ell)^2}{2H^2} \tag{6.8c}$$

Substituting for $l = \frac{L}{2}$ in (6.8)

$$s = \frac{L}{2} + \frac{w^2L^3}{48T^2} \tag{6.8a}$$

$$d = y = \frac{wL^2}{8T} \tag{6.8b}$$

$$T = H\left(1 + \frac{w^2L^2}{8H^2}\right) \tag{6.8c}$$

In hilly areas, we generally come across conductors suspended between supports at unequal levels as shown in Fig.-6.2. Where '*h*' is the difference between the two supports.

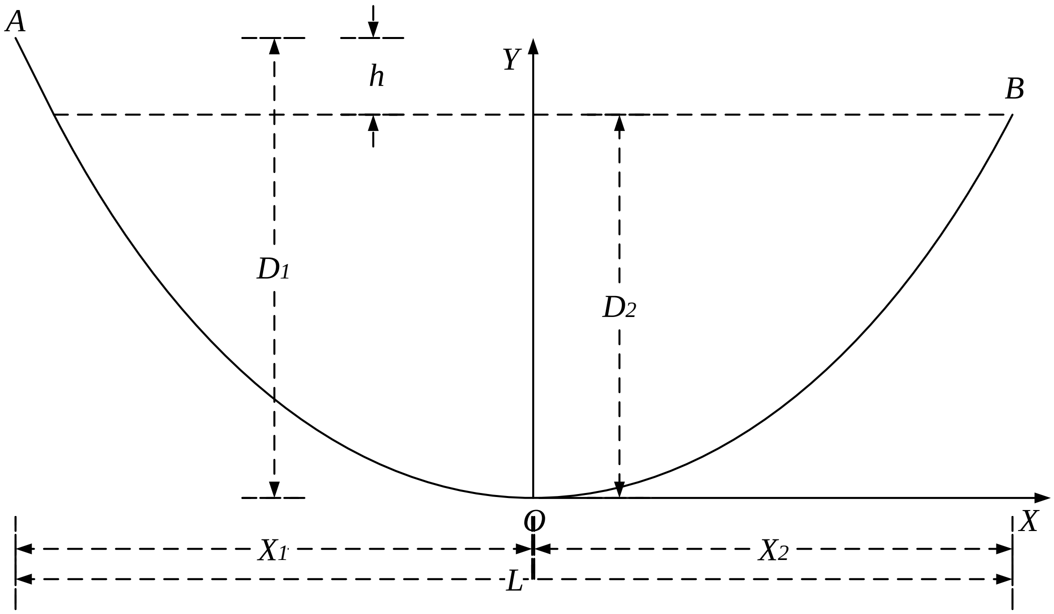


FIG.-6.2 SPAN OF TRANSMISSION LINE SHOWING THE CONDUCTOR SAG AND TENSION (SUPPORTS AT DIFFERENT LEVEL)

For such case the sag calculated from two supports are given by

$$D_1 = \frac{wx^2{}_1}{2T} \tag{6.9a}$$

$$D_2 = \frac{wx^2{}_2}{2T} \tag{6.9b}$$

$$h = D_1 - D_2 = \frac{w}{2T}\left(x_1^2 - x_2^2\right) \tag{6.9c}$$

$$\because (x_1 + x_2) = L$$

$$h = \frac{wL}{2T}(x_1 - x_2) \tag{6.10}$$

Where

$$x_1 = \frac{L}{2} + \frac{Th}{wL} \text{ and } x_2 = \frac{L}{2} - \frac{Th}{wL}$$

EFFECT OF WIND AND ICE

The above formulae for sag are true only in still air and at normal temperature when the conductor is acted by its weight only. However, in actual practice, a conductor may have ice coating and simultaneously subjected to wind pressure. The weight of ice acts vertically downwards i.e. in the same direction as the weight of conductor. The force due to the wind is assumed to act horizontally i.e. at right angle to the projected surface of the conductor. Hence, the total force on the conductor is the vector sum of horizontal and vertical forces as given below.

$w=\sqrt{(w_c+w_i)^2+w_w^2}$, where $'w_c','w_i'\&'w_w'$ are the weight of the conductor, weight of the ice coating on the surface of the conductor and wind pressure acting on the surface of the conductor respectively.

The transmission line may not have equal span throughout its length. In such case the effective span length can be calculated by using (6.11) or (6.12).

$$L_{eq}=\sqrt{\frac{L^3_1+L^3_2+L^3_3+........+L^3_n}{L_1+L_2+L_3+.......+L_n}} \tag{6.11}$$

$$L_{eq}=L_{avg}+\frac{2}{3}\left(L_{\max}-L_{avg}\right) \tag{6.12}$$

STRINGING CHARTS

There are two factors which vary the sag and tension. These are elasticity and temperature. For use in the field work of stringing the conductors, temperature-sag and temperature-tension charts are plotted for the given conductor and loading conditions. Such curves are called stringing charts. These charts are very helpful while stringing overhead lines.

The conductor length and sag at temperature $'\theta_1'$ is given by $s_1=\ell+\frac{w^2\ell^3}{6A^2f_1^2}$ and $d_1=\frac{w\ell^2}{2Af_1}$. Where $'f_1'$ is the stress tension per cross section area of the conductor.

If temperature is increased from $\theta_1\rightarrow\theta_2$ then the sag and tension changes as follows:

$$s_2=s_1-\left(\frac{f_1-f_2}{E}\right)+(\theta_2-\theta_1)\alpha\ell$$

$$s_2=\ell+\frac{{w_2}^2\ell^3}{6f^2{}_2A^2}$$

$'\alpha'$-temperature coefficient of thermal expansion

IMPORTANT CONSIDERATION IN MECHANICAL DESIGN

Mechanical factors of safety to be used in transmission line design should depend to some extent on the importance of continuity of operation in the line under consideration. In general, the strength of the line should be such as to provide against the worst probable weather conditions. We now discuss some important points in the mechanical design of overhead transmission lines.

Tower height: Tower height depends upon the length of span. With long spans, relatively few towers are required but they must be tall and correspondingly costly. It is not usually possible to determine the tower height and span length on the basis of direct construction costs because the lightning hazards increase greatly as the height of the conductors above ground is increased. This is one reason that horizontal spacing is favored in spite of the wider right of way required.

Conductor clearance to ground: The conductor clearance to ground at the time of greatest sag should not be less than some specified distance (usually between 6 and 12 m), depending on the voltage, on the nature of the country and on the local laws. The greatest sag may occur on the hottest day of summer on account of the expansion of the wire or it may occur in winter owing to the formation of a heavy coating of ice on the wires. Special provisions must be made for melting ice from the power lines.

Sag and tension: When laying overhead transmission lines, it is necessary to allow a reasonable factor of safety in respect of the tension to which the conductor is subjected. The tension is governed by the effects of wind, ice loading and temperature variations. The relationship between tension and sag is dependent on the loading conditions and temperature variations. For example, the tension increases when the temperature decreases and there is a corresponding decrease in the sag. Icing-up of the line and wind loading will cause stretching of the conductor by an amount dependent on the line tension.

In planning the sag, tension and clearance to ground of a given span, a maximum stress is selected. It is then aimed to have this stress developed at the worst probable weather conditions (i.e. minimum expected temperature, maximum ice loading and maximum wind). Wind loading increases the sag in the direction of resultant loading but decreases the vertical component. Therefore, in clearance calculations, the effect of wind should not be included unless horizontal clearance is important.

Conductor spacing: Spacing of conductors should be such so as to provide safety against flash-over when the wires are swinging in the wind. The proper spacing is a function of span length, voltage and weather conditions. The use of horizontal spacing eliminates the danger caused by unequal ice loading. Small wires or wires of light material are subjected to more swinging by the wind than heavy conductors. Therefore, light wires should be given greater spacing.

Conductor vibration: Wind exerts pressure on the exposed surface of the conductor. If the wind velocity is small, the swinging of conductors is harmless provided the clearance is sufficiently large so that conductors do not approach within the sparking distance of each other. A completely different type of vibration, called dancing, is caused by the action of fairly strong wind on a wire covered with ice, when the ice coating happens to take a form which makes a good air-foil section. Then the whole span may sail up like a kite until it reaches the limit of its slack, stops with a jerk and falls or sails back. The harmful effects of these vibrations occur at the clamps or supports where the conductor suffers fatigue and breaks eventually. In order to protect the conductors, Vibration Dampers are used.

CHAPTER-7
UNDERGROUND CABLES

INTRODUCTION

In high populated cities, bulk amount of power transfer through overhead transmission lines is impractical due to safety hazards. Further it is impossible to construct transmission towers in some places. In such places insulated conductors are laid underground known as underground cables. Underground cables have different technical requirements than overhead lines and have different environmental impacts. Due to their different physical, environmental, and construction needs, underground transmission generally costs more and may be more complicated to construct than overhead lines. The design and construction of underground transmission lines differ from overhead lines because of two significant technical challenges that need to be overcome. These are:

- Providing sufficient insulation so that cables can be within inches of grounded material; and
- Dissipating the heat produced during the operation of the electrical cables.

The basic construction of underground cables is as shown in Fig.-7.1. It consists of current carrying conductor surrounded by a suitable layer of insulation and finally a protective coating known as sheath made of lead.

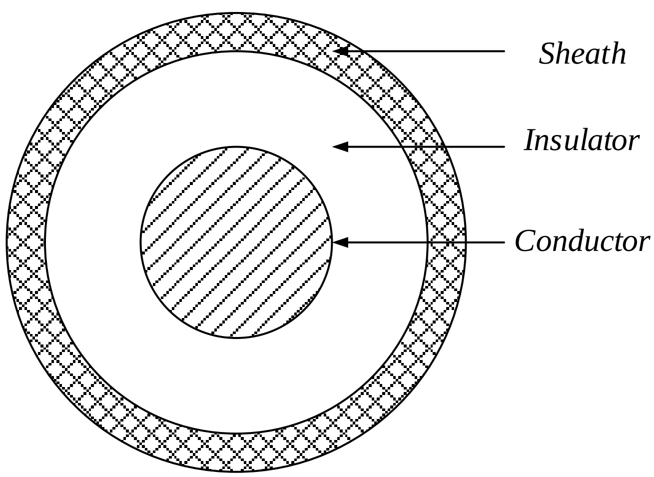


FIG.-7.1 BASIC CONSTRUCTION OF UNDERGROUND CABLES

Based on its application and construction there are various types of underground cables. They are described here briefly. The details of these cables can be referred from the Bureau of

Indian Standard as BIS has set the guidelines for the manufacturing of cables as per applications and criteria for safety.

XLPE CABLES

Extra-high voltage cables over 66-kV rating may be categorized into OF (Oil Filled), POF (Pipe Oil Filled) and CV (Cross-Linked Polyethylene Insulated PVC Sheathed, i.e., XLPE) cables, XLPE cable has made a remarkable progress since its first application 50 years ago, with respect to the material, structure, manufacturing technology and quality control technology. Because XLPE cable is characterized by its ease of maintenance, the cable rapidly proliferated domestically in the 1960s when its application began, currently constituting the majority of domestic power cables having voltage ratings of 66-kV and higher. Moreover, since the late 1990s when 500-kV XLPE cables have been put into actual use, studies have been made focusing on simplifying the installation process for joints as well as reducing their sizes, and new joints that utilize new structures and materials have been developed for practical application.

UNDERGROUND DISTRIBUTION CABLE

Underground distribution cables range from 6.6 kV to 33 kV in voltage rating, and XLPE cables that employ crosslinked polyethylene as insulator are generally used. It may be said that the history of XLPE cable is the history of countermeasures against water tree, a process of insulation deterioration due to water absorption. Water tree is a phenomenon in which water penetrates into insulation under the influence of electric fields forming a dendritic (tree-like) array of voids filled with water, thereby degrading the insulation performance. Moreover, water-impervious XLPE cables were developed and applied in the late 1980s centering on the 22- kV and 33-kV XLPE cables, with the aim of improving the reliability further by completely preventing entry of water into the cables. The water-impervious tape consisted of a laminated lead tape which is laminated with a lead foil and plastics to improve the extensibility, making it possible for the tape to follow the thermal expansion and contraction of the cable. This laminated lead layer was bonded on the inside of the cable sheath, constituting a waterimpervious cable.

HIGH-PRESSURE, FLUID-FILLED PIPE-TYPE CABLE

A high-pressure, fluid-filled (HPFF) pipe-type of underground transmission line, consists of a steel pipe that contains three high-voltage conductors. Each conductor is made of copper or aluminum; insulated with high-quality, oil-impregnated kraft paper insulation; and covered with metal shielding (usually lead) and skid wires (for protection during construction). Inside steel pipes, three conductors are surrounded by a dielectric oil which is maintained at 200 pounds per square inch (psi). This fluid acts as an insulator and does not conduct electricity. The pressurized dielectric fluid prevents electrical discharges in the conductors' insulation. An electrical discharge can cause the line to fail. The fluid also transfers heat away from the conductors. The fluid is usually static and removes heat by conduction. In some situations the fluid is pumped through the pipe and cooled through the use of a heat exchanger. Cables with pumped fluids require aboveground pumping stations, usually located within substations. The pumping stations monitor the pressure and temperature of the fluid. There is a radiator-type device that moves the heat from the underground cables to the atmosphere. The oil is also monitored for any degradation or trouble with the cable materials.

HIGH-PRESSURE, GAS-FILLED PIPE-TYPE CABLE

The high-pressure, gas-filled (HPGF) pipe-type of underground transmission line is a variation of the HPFF pipe-type, described above. Instead of a dielectric oil, pressurized nitrogen gas is used to insulate the conductors. Nitrogen gas is less effective than dielectric fluids at suppressing electrical discharges and cooling. To compensate for this, the conductors' insulation is about 20 percent thicker than the insulation in fluid-filled pipes. Thicker insulation and a warmer pipe reduce the amount of current the line can safely and efficiently carry. In case of a leak or break in the cable system, the nitrogen gas is easier to deal with than the dielectric oil in the surrounding environment.

Cables have a much lower inductance than overhead lines due to the lower spacing between conductor and earth, but have a correspondingly higher capacitance, and hence a much higher charging current. High voltage cables are generally single cored, and hence have their separate insulation and mechanical protection by sheaths. In the older paper insulated cables, the sheath was of extruded lead. The presence of the sheath introduces certain difficulties as currents are induced in the sheath as well. This is due to fact that the sheaths of the conductors cross the magnetic fields set up by the conductor currents. At all points along the cable, the magnetic field is not the same, Hence different voltages are induced at different points on the sheath. This causes eddy currents to flow in the sheaths. These eddy currents depend mainly on (a) the frequency of operation, (b) the distance between cables, (c) the mean radius of the sheath, and (d) the resistivity of the sheath material.

Dielectrics used for cable insulation must have the following properties.

- High Insulation resistance
- High dielectric strength
- Good mechanical strength
- Immune to attack by acids and alkali
- Should not be too costly
- Should not be hygroscopic (tending to absorb water), or if hygroscopic should be enclosed in a water tight covering.

CAPACITANCE IN A SINGLE-CORE CABLE

Let us consider a single core cable as shown in Fig.-7.2.

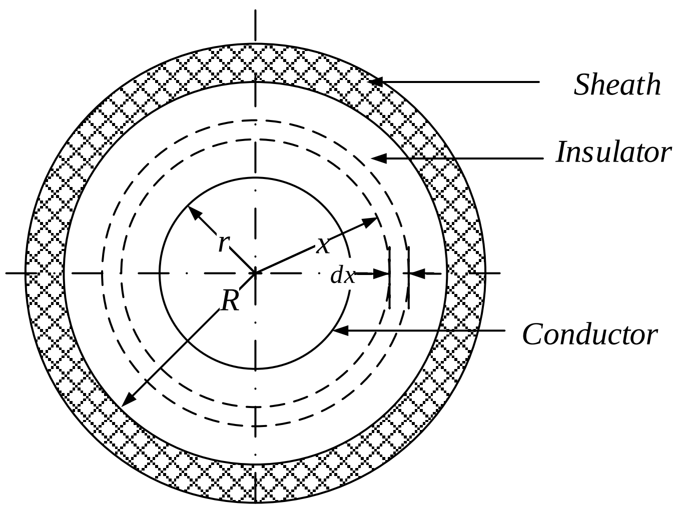


FIG.-7.2 CAPACITANCE CALCULATION OF SINGLE PHASE CABLE

Where,

r = radius of core (m)

R = inner radius of earthed sheath (m)

q = charge/unit length of cable (C/m)

D = electric flux density = charge density (C/m^2)

k = permittivity of free space

Let us consider an elemental cylinder of radius x and thickness dx, and of length unity along the cable.

$$g = \frac{q}{2\pi k x} \text{ (V/m)} \qquad (7.1)$$

$$V = \int_r^R g dx = \frac{q}{2\pi k} \ln\left(\frac{R}{r}\right) \qquad (7.2)$$

Hence from (7.1) and (7.2) we obtain

$$g = \frac{V}{x \ln\left(\frac{R}{r}\right)} \qquad (7.3a)$$

The electrical stress shall be maximum at the surface of the conductor i.e. at $x = r$ and minimum at the inner surface of the sheath i.e. $x = R$. So that we can write:

$$g_{\max} = \frac{V}{r \ln\left(\frac{R}{r}\right)} \qquad (7.3b)$$

$$g_{\min} = \frac{V}{R \ln\left(\frac{R}{r}\right)} \qquad (7.3c)$$

The maximum stress should be minimum so that the cable can work satisfactorily without rupturing the insulation. To achieve this we can differentiate (7.3b) w.r.t. r and make it equal to zero.

$$\frac{dg_{\max}}{dr} = \frac{d}{dr}\left(\frac{V}{r \ln\left(\frac{R}{r}\right)}\right) = 0 \qquad (7.3d)$$

Solving (7.3b) we get

$$\frac{R}{r} = e = 2.718 \qquad (7.3e)$$

Thus if the overall diameter of the cable is kept fixed, then *R/r* = *e* is the condition for minimum $g_{\max}$. This value of radius of conductor will generally be larger than would be required for current carrying capacity. Since the radius of the conductor that would be given from the above expression is larger than is necessary for current carrying capacity, this value of radius may be achieved by using aluminum or hollow conductors.

The stress can be written as

$$g = \frac{q}{2\pi k x} = \frac{q}{2\pi k_0 k_r x} = \frac{18 \,\mathrm{X}\, 10^9 q}{k_r x} \text{ (V/m)} \qquad (7.4)$$

The capacitance of the cable is then given by

$$C = \frac{q}{V} = \frac{k_r}{18\,\mathrm{X}\,10^9 \ln\left(\frac{R}{r}\right)} \text{ (F/m)} \tag{7.5}$$

$$C = \frac{0.024k_r}{\ln\left(\frac{R}{r}\right)} \text{ (µF/km)} \tag{7.6}$$

CAPACITANCE OF THREE-CORE BELTED TYPE CABLES

In the case of a 3-core cable as shown in Fig.7.3, the 3-cores are individually insulated with paper insulation. The filler spaces between the core insulation is also filled up with insulation, but depriving these of voids is much more difficult. Belt insulation is used on top of all three core insulations, and the lead sheath is extruded over this. Over the lead sheath, there is generally bitumen to prevent damage. In buried cables, additional protection is necessary to prevent damage. There are two types of armouring used for these cables.

- Steel tape armouring - the steel tape is usually wound in two layers with opposite directions of lay
- Steel wire armouring - the steel wires are laid in one or two layers.

The capacitance between the conductors to neutral of 3-core belted cables cannot be obtained by a simple derivation as for the single core cable. Simon's expression can be used to obtain this value. The capacitance per unit length to neutral is given by

$$C = \frac{0.03k_r}{\log_{10}\left[\left(0.52\left(\frac{t}{T}\right)^2 - 1.7\left(\frac{t}{T}\right) + 3.84\right)\left(\frac{T+t}{d}\right) + 1\right]} \text{ (µF/km)} \tag{7.7}$$

Where,

t = thickness of belt insulation

T = thickness of conductor insulation

d = diameter of conductor

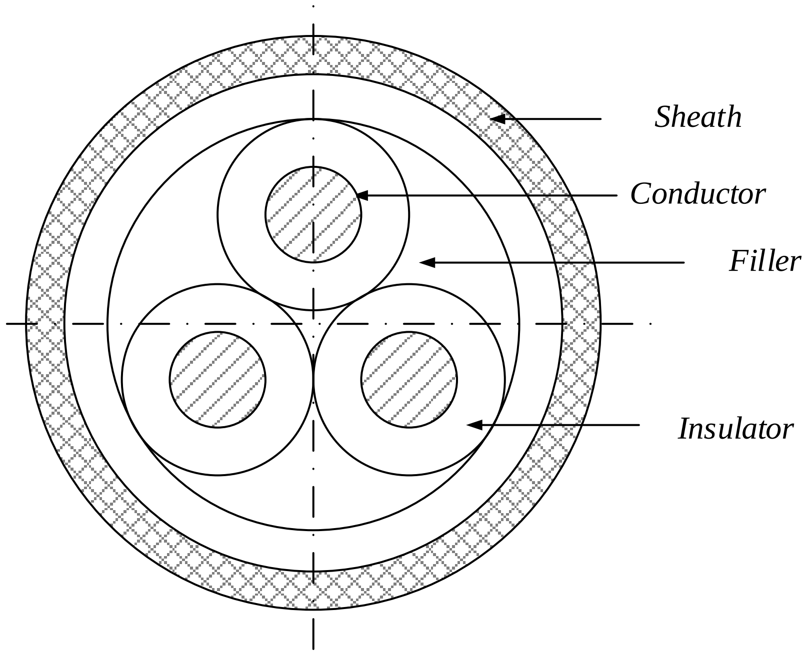


FIG.-7.3 THREE-CORE BELTED TYPE CABLES

MEASUREMENT OF CAPACITANCE OF 3-CORE CABLES

In three-core cables, capacitance does not have a single value, but can be lumped as shown in Fig.-7.4.

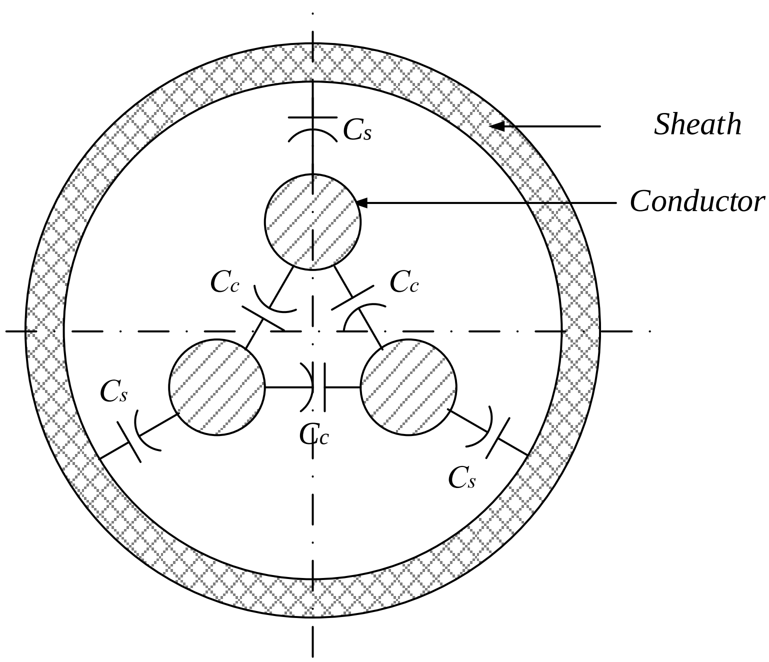


FIG.-7.4 CAPACITANCE OF 3-CORE CABLES

Where, C_s - Capacitance between each core and sheath and C_c - Capacitance between cores

These can be calculated as mentioned below:

Step-I: Strap the 3 cores together and measure the capacitance between this bundle and the sheath as shown in Fig.-7.5. Let this value to be C_x., So that

$$C_x = 3C_s \tag{7.8}$$

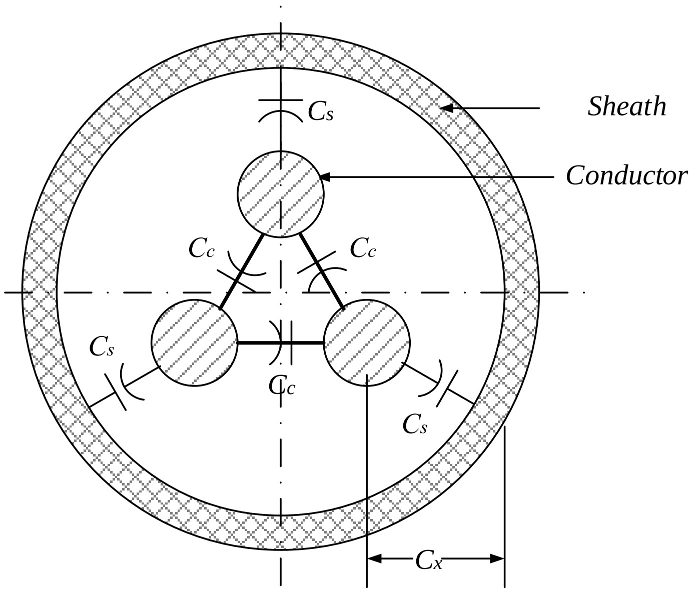


FIG.-7.5 MEASUREMENT OF CAPACITANCE OF 3-CORE CABLES *(STEP-I)*

Step-II: Connect 2 of the cores to the sheath and measure between the remaining core and the sheath as shown in Fig.-7.6. Let this value to be C_y., So that

$$C_y = C_s + 2C_c \tag{7.9}$$

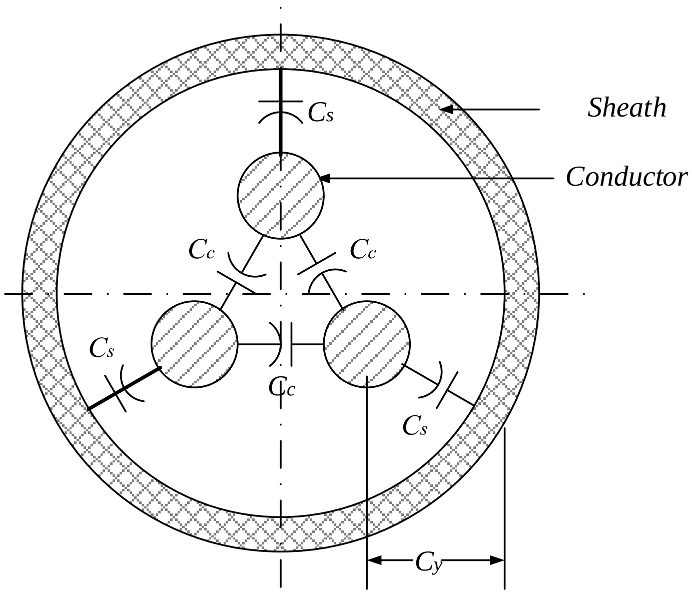


FIG.-7.6 MEASUREMENT OF CAPACITANCE OF 3-CORE CABLES *(STEP-II)*

Using (7.8) and (7.9) we derive the capacitance between the conductors and the conductor and Sheath.

$$C_s = \frac{1}{3}C_x \tag{7.10}$$

$$C_c = \frac{3C_y - C_x}{6} \tag{7.11}$$

From these the effective capacitance to neutral can be given by

$$C = C_s + 3C_c \tag{7.12}$$

$$C = \frac{9C_y - C_x}{6} \tag{7.13}$$

GRADING OF CABLES

As can be seen the dielectric is not equally stressed at all radii, in a cable of homogeneous insulation. The insulation is fully stressed only at the conductor, and further away near the sheath the insulation is unnecessarily strong and thus needlessly expensive.

The electric stress in the dielectric may be more equally distributed by one of the two following methods.

- Capacitance grading
- Intersheath grading

CAPACITANCE GRADING

In this method of grading, the insulation material consists of various layers having different permittivities. Consider a cable graded by means of 3 layers of insulation, as shown in Fig.-7.7 having permittivities k_1, k_2, k_3, respectively.

Let the outer radii of these layers by $r_1, r_2 \;\&\; r_3 = R$ respectively, and the conductor radius r. In order to secure the same value of maximum stress in each layer, the maximum stresses in the layers are equated.

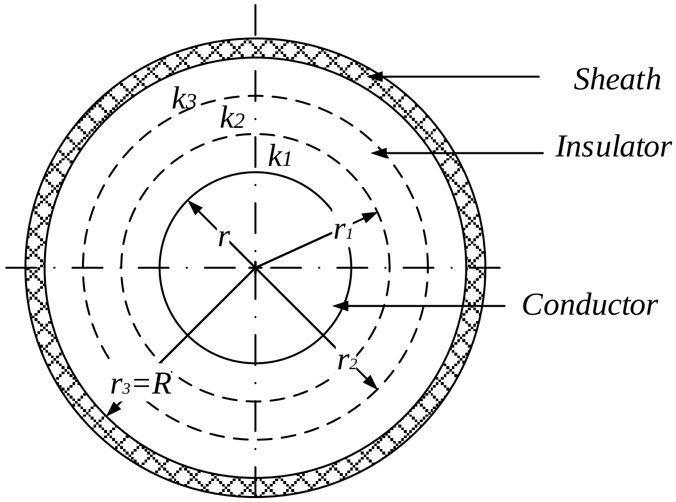


FIG.-7.7 CAPACITANCE GRADING OF CABLES

Let the voltage across the inner-most layer of insulation be V .

Case-1: Dielectric strength have same factor of safety

Let dielectric strength of three materials be G_1 , G_2 and G_3 respectively with factor of safety f .

Gradient at $x = r$ is $\frac{q}{2\pi k_1 r} = \frac{G_1}{f}$

Gradient at $x = r_1$ is $\frac{q}{2\pi k_2 r_1} = \frac{G_2}{f}$

Gradient at $x = r_2$ is $\frac{q}{2\pi k_3 r_2} = \frac{G_3}{f}$

From the above relations,

$q = 2\pi k_1 r \frac{G_1}{f} = 2\pi k_2 r_1 \frac{G_2}{f} = 2\pi k_3 r_2 \frac{G_3}{f}$ which gives $k_1 r G_1 = k_2 r_1 G_2 = k_3 r_2 G_3$

Since $r < r_1 < r_2$ it means $k_1 G_1 > k_2 G_2 > k_3 G_3$

This shows that material of highest product of dielectric strength and permittivity should be placed nearest to conductor and other layers be in descending order of product of dielectric strength and permittivity.

Case-2: All materials are subjected to same maximum stress.

Then,

$$g_{\max} = \frac{q}{2\pi k_1 r} = \frac{q}{2\pi k_2 r_1} = \frac{q}{2\pi k_3 r_2}$$

$$k_1 r = k_2 r_1 = k_3 r_2$$

Hence $k_1 > k_2 > k_3$, thus total operating voltage of the cable becomes

$$V = g_{\max}\left(r \ln\frac{r_1}{r} + r_1 \ln\frac{r_2}{r_1} + r_2 \ln\frac{R}{r_2}\right)$$

Hence by grading the insulation, without increasing the overall diameter of the cable, the operating voltage can be raised. A difficulty with this method is that we cannot obtain a wide range of permittivities in practice, as paper insulation has permittivities limited to the range 2.8 to 4.0.

In the above analysis, it has been assumed that the maximum permissible stress is the same for all three dielectrics used. If the maximum stress in the three sections are different, then the maximum stresses should be reached at the same time for the most economical operation of the insulation.

INTERSHEATH GRADING

In this type grading method, a single insulating material is used but separated into two or more layers by thin metallic intersheaths maintained at appropriate potentials by being connected to tappings on the winding of an auxiliary transformer supplying the cable as shown in Fig.-7.8.

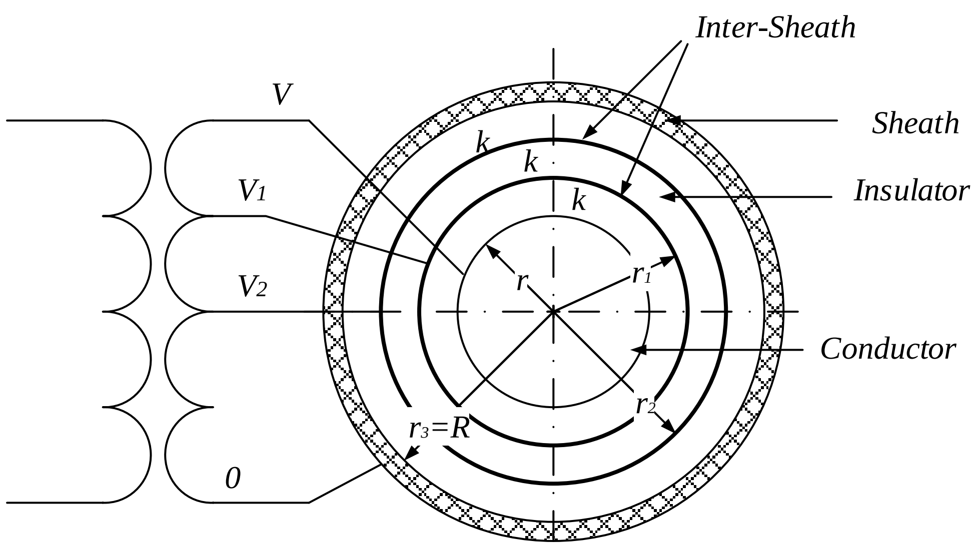


FIG.-7.8 INTERSHEATH GRADING

The intersheaths are relatively flimsy, and are meant to carry only the charging current. Since there is a definite potential difference between the inner and outer radii of each sheath, we can treat each section separately as a single core cable.

As can be seen from the diagram there are three layers of insulation separated by two intersheaths maintained at voltage $V_1 \& V_2$, the conductor is at voltage V. Thus we can write at the surface of different intersheaths

$$g_{\max 1} = \frac{V_1}{r \ln\left(\frac{r_1}{r}\right)}, \; g_{\max 2} = \frac{V_2}{r_1 \ln\left(\frac{r_2}{r_1}\right)}$$

Hence for grading purpose we need to have $g_{\max 1} = g_{\max 2}$ or $\frac{V_1}{r \ln\left(\frac{r_1}{r}\right)} == \frac{V_2}{r_1 \ln\left(\frac{r_2}{r_1}\right)}$

Since the cable insulation now consists of a number of capacitors in series, formed by the respective intersheaths, all potential differences $V_1 \& V_2$ are in phase.

$$V = V_1 + V_2$$

In practice if there are *n* layers having same thickness then for uniform stress the voltage across m^{th} layer is given by

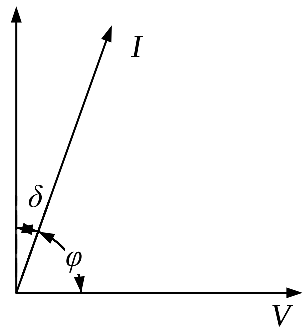
$$V_m = \frac{V}{M}\left[r + (m-1)t\right] \ln \frac{r + mt}{r + (m-1)t}$$

POWER LOSS IN THE CABLE

Power loss in the cable can occur due to a variety of reasons. They may be caused by the conductor current passing through the resistance of the conductor - conductor loss (also sometimes called the copper loss on account of the fact that conductors were mainly made out of copper), dielectric losses caused by the voltage across the insulation, sheath losses caused by the induced currents in the sheath, and inter-sheath losses caused by circulating currents in loops formed between sheaths of different phases. The dielectric loss is voltage dependent, while the rest is current dependent.

DIELECTRIC LOSS

For a perfect dielectric, the power factor is zero. Since the cable is not a perfect dielectric, the power factor is not zero. The current leads the voltage by an angle of less than 90^o, and hence there is a power loss. Refer to Fig.-



As because $I = \omega VC$, the dielectric loss is given by

$$P = VICos\phi = VISin\delta = \omega V^2 CSin\delta$$

Where If C is the capacitance of the cable, and V is the applied voltage.

CONDUCTOR LOSS

The conductor loss is given by

$$P_C = I^2 R_c$$

Where R_c is the resistance of the conductor and I is the current in the cable.

SHEATH LOSS

The losses occurring in the sheath of a cable is usually obtained by the empirical formula of Arnold. Arnold's formula for the sheath loss is given by

$$P_{sh} = 7.7 \text{ X } 10^{-3} \frac{I^2}{R_{sh}} \left(\frac{r_m}{d} \right)^2 \text{ (W)}$$

Where r_m = mean radius of sheath, d = distance between cables (centre to centre), R_{sh} = resistance of full length of cable, I = current in cable

The sheath loss is usually about 2 to 5 % of the conductor loss.

INTERSHEATH LOSS

The Intersheath losses are caused by the induced emf between the sheaths causing a circulating current. This loss is thus present only when the sheaths of adjacent cables are connected together. The sheaths need to be connected together in practice, as otherwise sparking could occur causing damage to the sheaths. The intersheath loss can be calculated as follows.

$$P_{ish} = I_{ish}^2 R_{sh} = \frac{I^2 \omega^2 M_{sh}^2}{R_{sh}^2 + \omega^2 M_{sh}} R_{sh}$$

Where The mutual inductance between a core of one cable and the sheath of an adjacent cable $M_{sh} = \frac{\mu}{2\pi} \ln\left(\frac{d}{r}\right)$

The voltage induced $E_{ish} = I\omega M_{sh}$ and

The induced current

$$I_{ish} = \frac{E_{ish}}{\sqrt{\left[R_{sh}^2 + \omega^2 M_{sh}^2\right]}} = \frac{I\omega M_{sh}}{\sqrt{\left[R_{sh}^2 + \omega^2 M_{sh}^2\right]}}$$

Generally, the sheath resistance $R_{sh} \rangle\rangle \omega M_{sh}$ so that $P_{ish} = \frac{I^2 \omega^2 M_{sh}^2}{R_{sh}}$

The intersheath loss is larger than the sheath loss and may range from 10% to 50% of the copper loss. Thus the total power loss (exclusive of the dielectric loss) is given as

$$P_{Loss(total)} = P_C + P_{sh} + P_{ish} \tag{7.14}$$

We may express the total loss in terms of an effective resistance as

$$P_{Loss(total)} = I^2 R_{eff}$$

Since the sheath loss is usually very small, the effective conductor resistance can be written as

CHAPTER-8
DISTRIBUTION SYSTEM

Electrical distribution systems are an essential part of the electrical power system. In order to transfer electrical power from an alternating-current or a direct-current source to the place where it will be used, some type of distribution network must be utilized. The method used to distribute power from where it is produced to where it is used can be quite simple. More complex power distribution systems are used, to transfer electrical power from the power plant to industries, homes, and commercial buildings. Distribution systems usually employ such equipment as transformers, circuit breakers, and protective devices. The original electrical distribution system developed by Thomas Edison was an underground direct current (DC) system.

In general, the distribution system is the electrical system between the sub-station fed by the transmission system and the consumer end. It generally consists of feeders, distributors. The single line diagram of a typical distribution system is shown in Fig.-8.1. Basically we can say, that part of power system which distributes electric power for local use is known as distribution system.

Feeders: A feeder is a conductor which connects the sub-station (or localised generating station) to the area where power is to be distributed. Generally, no tappings are taken from the feeder so that current in it remains the same throughout. The main consideration in the design of a feeder is the current carrying capacity.

Distributor: A distributor is a conductor from which tappings are taken for supply to the consumers. The current through a distributor is not constant because tappings are taken at various places along its length.

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

A distribution system may be classified according to;

According to nature of current, distribution system may be classified as

- d.c. distribution system
- a.c. distribution system.

Now-a-days, a.c. system is universally adopted for distribution of electric power as it is simpler and more economical than direct current method.

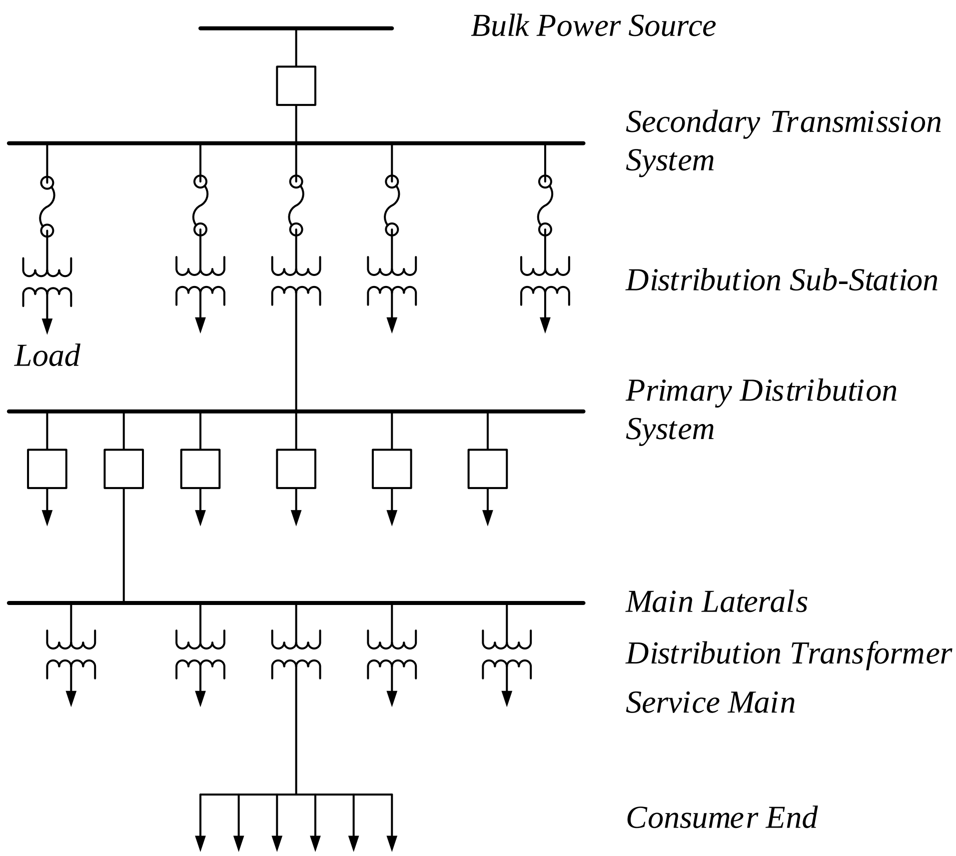


FIG.-8.1 A TYPICAL ELECTRIC POWER DISTRIBUTION SYSTEM

According to scheme of connection, the distribution system may be classified as

- Radial system
- Ring main system
- Inter-connected system.

Each scheme has its own advantages and disadvantages.

A.C. DISTRIBUTION

Now-a-days electrical energy is generated, transmitted and distributed in the form of alternating current. One important reason for the widespread use of alternating current in preference to direct current is the fact that alternating voltage can be conveniently changed in magnitude by means of a transformer. Transformer has made it possible to transmit a.c. power at high voltage and utilize it at a safe potential. High transmission and distribution voltages have greatly reduced the current in the conductors and the resulting line losses.

There is no definite line between transmission and distribution according to voltage or bulk capacity. However, in general, the a.c. distribution system is the electrical system between the step-down substation fed by the transmission system and the consumers' meters. The a.c. distribution system is classified into (i) primary distribution system and (ii) secondary distribution system.

Primary distribution system: It is that part of a.c. distribution system which operates at voltages somewhat higher than general utilization and handles large blocks of electrical energy than the average low-voltage consumer uses. The voltage used for primary distribution depends upon the amount of power to be conveyed and the distance of the substation required to be fed. The most commonly used primary distribution voltages are 11 kV, 66 kV and 33 kV. Due to economic considerations, primary distribution is carried out by 3-phase, 3-wire system.

Electric power from the generating station is transmitted at high voltage to the substation located in or near the city. At this substation, voltage is stepped down to 11 kV with the help of step-down transformer. Power is supplied to various substations for distribution or to big consumers at this voltage. This forms the high voltage distribution or primary distribution.

Secondary distribution system: It is that part of a.c. distribution system which includes the range of voltages at which the ultimate consumer utilises the electrical energy delivered to him. The secondary distribution employs 400/230 V, 3-phase, 4-wire system.

The primary distribution circuit delivers power to various substations, called distribution sub-stations. The substations are situated near the consumers' localities and contain step-down transformers. At each distribution substation, the voltage is stepped down to 400 V and power is delivered by 3-phase,4-wire a.c. system. The voltage between any two phases is 400 V and between any phase and neutral is 230 V. The single phase domestic loads are connected between any one phase and the neutral, whereas 3-phase 400 V motor, power transformer loads are connected across 3-phase lines directly.

D.C. DISTRIBUTION

It is a common knowledge that electric power is almost exclusively generated, transmitted and distributed as a.c. However, for certain applications, d.c. supply is absolutely necessary. For instance, d.c. supply is required for the operation of variable speed machinery (i.e., d.c. motors), for electro-chemical work and for congested areas where storage battery reserves are necessary. For this purpose, a.c. power is converted into d.c. power at the substation by using converting machinery e.g., mercury arc rectifiers, rotary converters and motor-generator sets. The d.c. supply from the substation may be obtained in the form of (i) 2-wire or (ii) 3-wire for distribution.

2-wire d.c. system: As the name implies, this system of distribution consists of two wires. One is the outgoing or positive wire and the other is the return or negative wire. The loads such as lamps, motors etc. are connected in parallel between the two wires. This system is never used for transmission purposes due to low efficiency but may be employed for distribution of d.c. power.

3-wire d.c. system: It consists of two outers and a middle or neutral wire which is earthed at the substation. The voltage between the outers is twice the voltage between either outer and neutral wire. The principal advantage of this system is that it makes available two voltages at the consumer terminals viz., V between any outer and the neutral and $2V$ between the outers. Loads requiring high voltage (e.g., motors) are connected across the outers, whereas lamps and heating circuits requiring less voltage are connected between either outer and the neutral.

Radial System: In this system, separate feeders radiate from a single substation and feed the distributors at one end only. A single line diagram of a radial distribution system is shown in Fig.-8.2. The radial system is employed at low voltage and the substation is located at the center of the load.

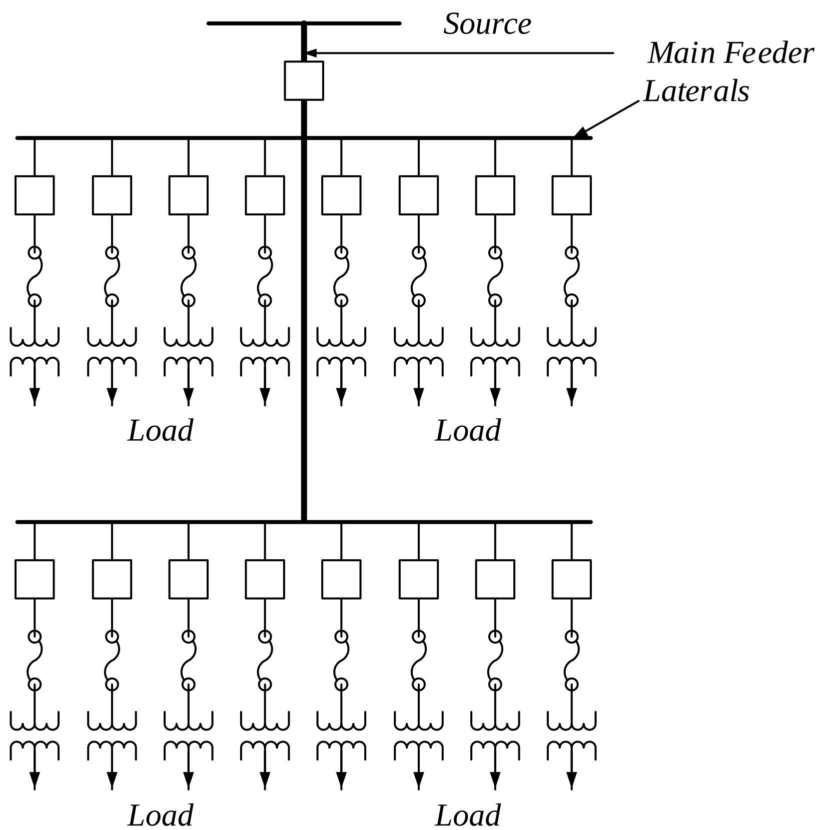


FIG.-8.2 RADIAL DISTRIBUTION SYSTEM

This is the simplest distribution circuit and has the lowest initial cost. However, it suffers from the following drawbacks.

- The end of the distributor nearest to the feeding point will be heavily loaded.
- The consumers are dependent on a single feeder and single distributor. Therefore, any fault on the feeder or distributor cuts off supply to the consumers who are on the side of the fault away from the substation.
- The consumers at the distant end of the distributor would be subjected to serious voltage fluctuations when the load on the distributor changes.

Due to these limitations, this system is used for short distances only. The radial system can be extended by introducing more laterals and sub-laterals.

Ring main system: In this system, the primaries of distribution transformers form a loop. The loop circuit starts from the substation bus-bars, makes a loop through the area to be served, and returns to the substation. The single line diagram of ring main system is shown in Fig.-8.3.

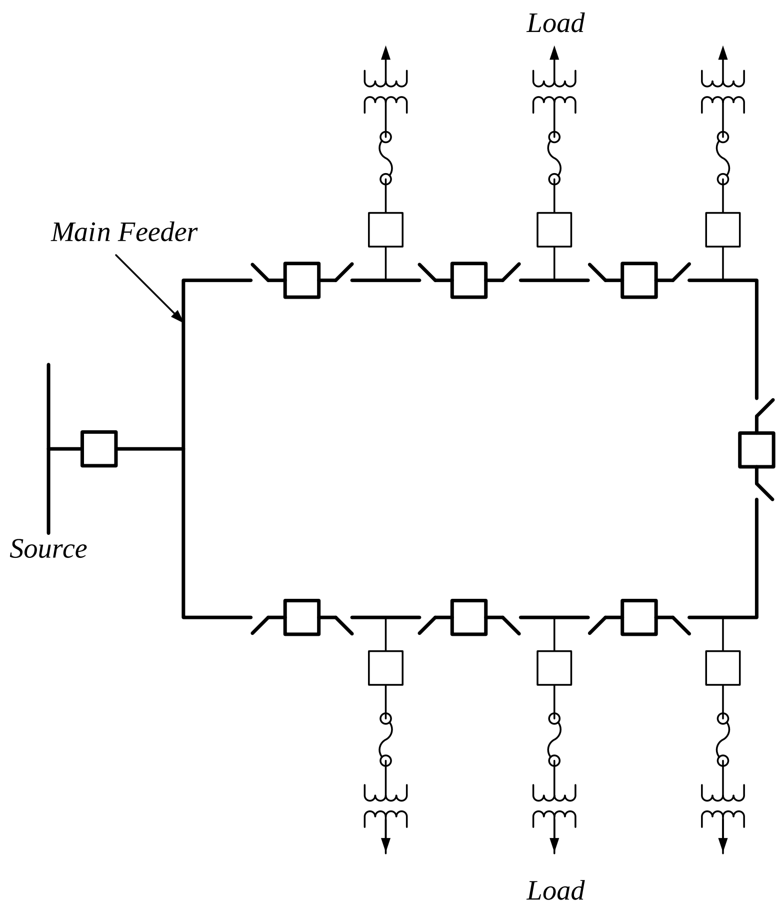


FIG.-8.3 RING MAIN SYSTEM

The ring main system has the following advantages.

- There are less voltage fluctuations at consumer's terminals.
- The system is very reliable as each distributor is fed via two feeders. In the event of fault on any section of the feeder, the continuity of supply is maintained.

For example, suppose that fault occurs at any section of the feeder. Then the faulted section the feeder can be isolated for repairs and at the same time continuity of supply is maintained to all the consumers via the other feeder.

Interconnected system: When the feeder ring is energized by two or more than two source, it is called inter-connected system. The single line diagram of interconnected system is shown in Fig.-8.4.

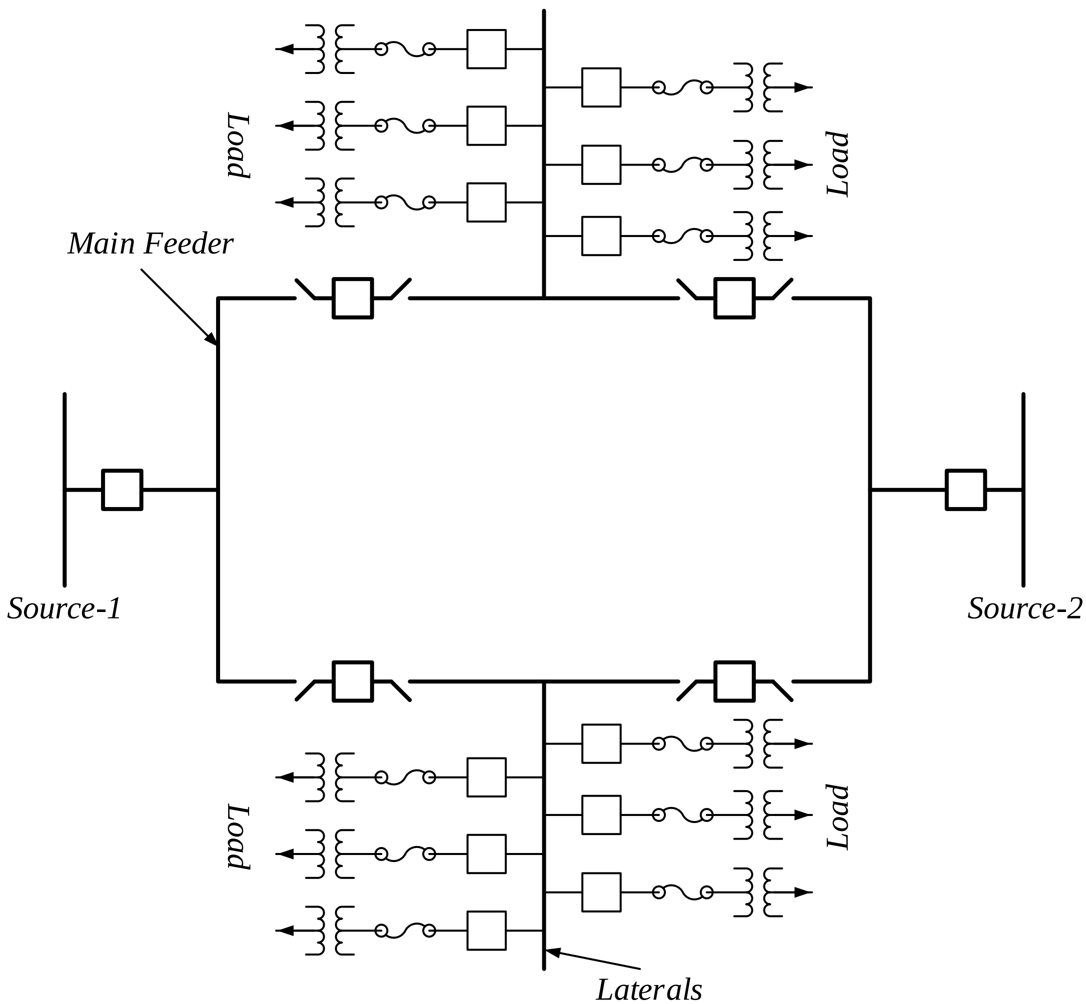


FIG.-8.4 INTERCONNECTED SYSTEM

The interconnected system has the following advantages.

- It increases the service reliability.

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

VOLTAGE DROP CALCULATION

The voltage drop in distribution system is calculated by following Ohm,s Law. Let us consider a simple dc radial distribution system as shown in Fig.-8.5.

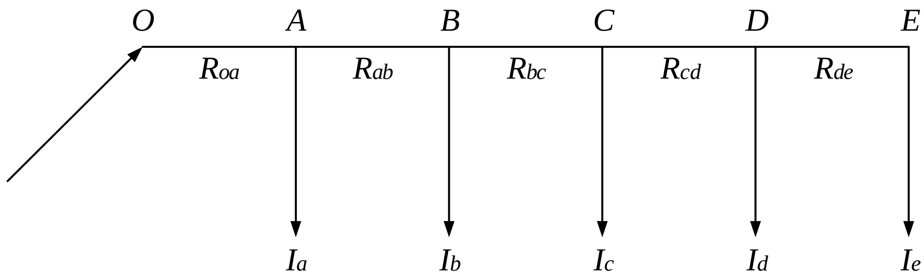


FIG.-8.5 A RADIAL DC DISTRIBUTOR SYSTEM HAVING CONCENTRATED LOAD

The system have concentrated load $I_a, I_b, I_c, I_d \,\&\, I_e$ at load point $A, B, C, D \,\&\, E$ respectively. The resistance of different section has been shown in the Fig.-8.5. The feeder is fed at point *O*. Let the voltages at different nodes are $V_a, V_b, V_c, V_d \,\&\, V_e$ and the feeder is fed at the voltage V_o.

Hence the voltage drop is given by

$$VD_{Total} = VD_{OA} + VD_{AB} + VD_{BC} + VD_{CD} + VD_{DE} \tag{8.1}$$

The current flowing in the section *'OA'* is

$$I_{oa} = I_a + I_b + I_c + I_d + I_e \tag{8.2a}$$

The current flowing in the section *'AB'* is

$$I_{ab} = I_b + I_c + I_d + I_e \tag{8.2b}$$

The current flowing in the section *'BC'* is

$$I_{bc} = I_c + I_d + I_e \tag{8.2c}$$

The current flowing in the section *'CD'* is

$$I_{cd} = I_d + I_e \tag{8.2d}$$

The current flowing in the section *'DE'* is

$$I_{de} = I_e \tag{8.2e}$$

The total voltage drop therefore, is given by

$$VD_{Total} = I_{oa}R_{oa} + I_{ab}R_{ab} + I_{bc}R_{bc} + I_{cd}R_{cd} + I_{de}R_{de} \tag{8.3}$$

Similarly we can determine the voltage drop for ac distribution system. In many cases the load in the system is not concentrated, it may be either uniform loading or a combination of uniform and concentrated loading. If the load is uniform then the voltage drop is calculated for a very small length of the feeder such as *dx* and then integrate it over the whole length.

REQUIREMENTS OF A DISTRIBUTION SYSTEM

A considerable amount of effort is necessary to maintain an electric power supply within the requirements of various types of consumers. Some of the requirements of a good distribution system are proper voltage, availability of power on demand and reliability.

Proper voltage: One important requirement of a distribution system is that voltage variations at consumer's terminals should be as low as possible. The changes in voltage are generally caused due to the variation of load on the system. Low voltage causes loss of revenue, inefficient lighting and possible burning out of motors. High voltage causes lamps to burn out permanently and may cause failure of other appliances. Therefore, a good distribution system should ensure that the voltage variations at consumer's terminals are within permissible limits. The statutory limit of voltage variations is ± 5% of the rated value at the consumer's terminals. Thus, if the declared voltage is 230 V, then the highest voltage of the consumer should not exceed 242 V while the lowest voltage of the consumer should not be less than 218 V.

Availability of power on demand: Power must be available to the consumers in any amount that they may require from time to time. For example, motors may be started or shut down, lights may be turned on or off, without advance warning to the electric supply company. As electrical energy cannot be stored, therefore, the distribution system must be capable of supplying load demands of the consumers. This necessitates that operating staff must continuously study load patterns to predict in advance those major load changes that follow the known schedules.

Reliability: Modern industry is almost dependent on electric power for its operation. Homes and office buildings are lighted, heated, cooled and ventilated by electric power. This calls for reliable service. Unfortunately, electric power, like everything else that is man-made, can never be absolutely reliable. However, the reliability can be improved to a considerable extent by

- Interconnected system
- Reliable automatic control system
- Providing additional reserve facilities.

DESIGN CONSIDERATIONS IN DISTRIBUTION SYSTEM

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

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

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

CHAPTER-9
NEUTRAL GROUNDING

INTRODUCTION

System grounding is the intentional connection of the neutral points of transformers, generators and rotating machinery to earth. It offers many advantages over an ungrounded system such as:

- Reduced magnitude of transient over-voltages
- Simplified ground fault location
- Improved system and equipment fault protection
- Reduced maintenance time and expense
- Greater safety for personnel
- Improved lightning protection
- Reduction in frequency of faults
- Note that solidly grounded systems offer only partial protection

The term “grounding” describes and encompasses both systems grounding and equipment grounding. The basic difference between system and equipment grounding is that system grounding involves grounding circuit conductors that are current carrying under normal operation, where equipment grounding involves grounding of all non-current carrying metallic parts that enclose the circuit conductors. A grounding electrode or several grounding electrodes tied together as a system provides the reference ground and the means for connection to earth.

The best way to obtain the system neutral for grounding purposes in three phase systems is to use source transformers or generators with Wye-connected windings. The neutral is the readily available. When the system neutral may not available, earthing transformer may be used to obtain the neutral.

ISOLATED NEUTRAL SYSTEMS

A power system not having any intentional connection to ground is referred to as an ungrounded system as shown in Fig.-9.1. A three phase system with its voltage phasor diagram is shown. However, because of the capacitive coupling between the phase conductors and ground, an ungrounded system is in reality grounded through the distributed capacitance of the system conductors to ground as shown in Fig.-9.2. When the neutral of a system is not grounded, a ground fault on one line causes full line to line voltage throughout the system, between ground and the two unfaulted phases. This voltage is 73% higher than normal as shown in Fig.-9.2. Usually the insulation between each line and ground is adequate to withstand full line to line voltage. However, if the insulation has deteriorated and the overvoltage is sustained sufficiently long, a second ground fault may occur due to insulation failure. In spite of these considerations, ungrounded systems may be used to gain an additional degree of service continuity.

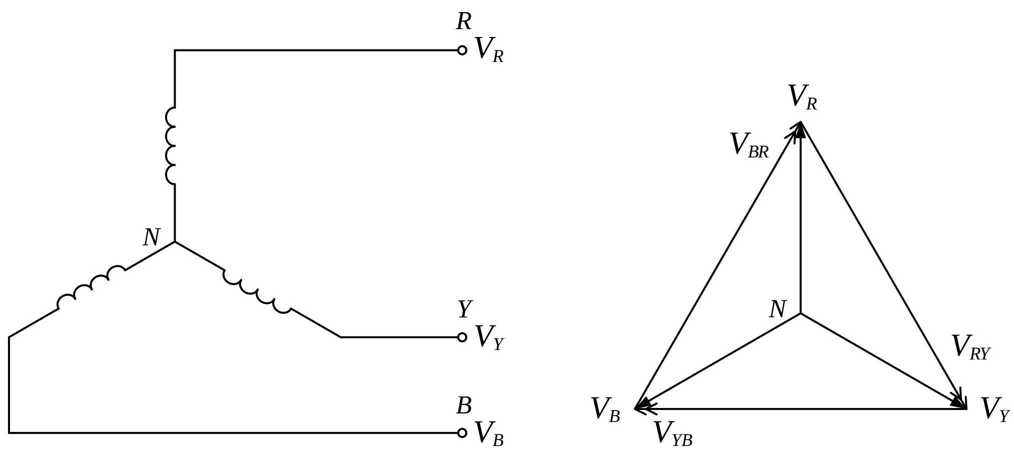


FIG.-9.1 THREE PHASE SYSTEM (UNGROUNDED) WITH ITS VOLTAGE PHASOR DIAGRAM

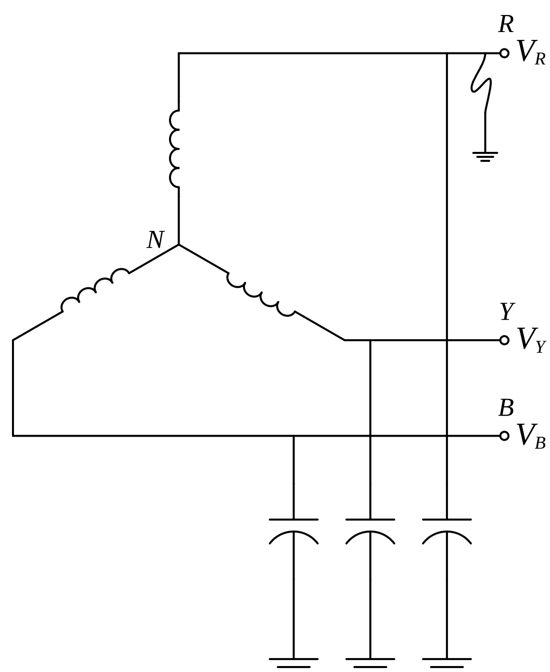


FIG.-9.2 THREE PHASE SYSTEM (UNGROUNDED) WITH ONE PHASE FAULTED WITH EARTH

The method of system grounding used has a significant effect on the continuity of power to critical loads underground fault conditions. There are three typical grounding methods.

SOLID GROUNDED NEUTRAL SYSTEMS

In a solid grounded system, the neutral points have been intentionally connected to ground with a conductor having no intentional impedance as shown in Fig.-9.3a. This reduces the problem of transient over-voltages found on the ungrounded system and aids in the location of faults.

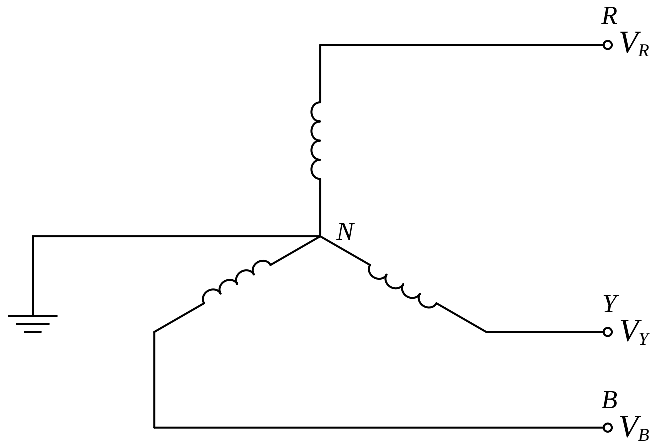


FIG.-9.3a SOLID GROUNDED THREE PHASE SYSTEM

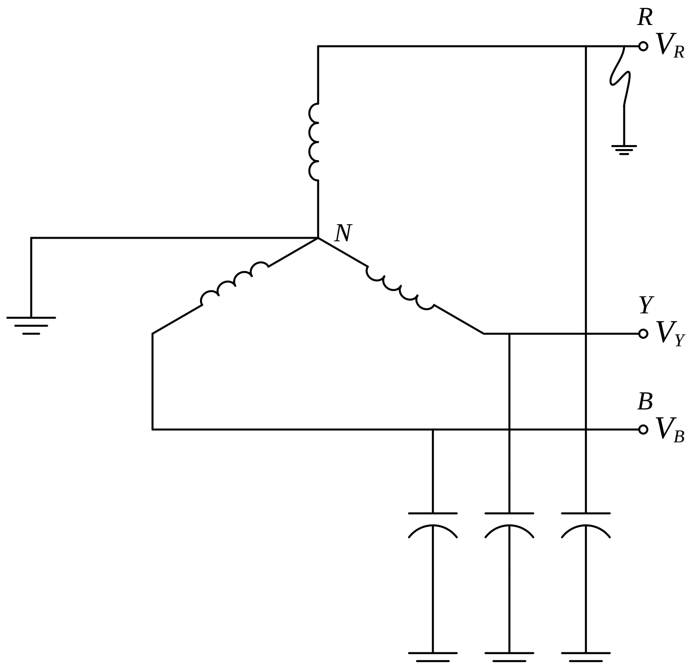


FIG.-9.3b SOLID GROUNDED THREE PHASE SYSTEM WITH ONE PHASE FAULTED WITH EARTH

The single-phase earth fault current in a solidly earthed system may exceed the three phase fault current. The magnitude of the current depends on the fault location and the fault resistance.

One way to reduce the earth fault current is to leave some of the transformer neutrals unearthed. The main advantage of solidly earthed systems is low over voltages, which makes the earthing design common at high voltage levels (HV). However, solidly grounded systems lack the current limiting ability of resistance grounding and the extra protection this provides against equipment damage and arcing ground faults.

Solid grounding facilitates the automatic clearing of ground faults by circuit protective equipment (fuses and circuit breakers) because solid grounding results in the highest magnitude of ground fault current. The higher the fault current, the higher the probability that fuses and circuit breakers will operate in the "instantaneous" range.

RESISTANCE GROUNDED NEUTRAL SYSTEMS

Resistance grounding provides protection of a transformer/generator by solving the problem of transient over-voltages thereby reducing equipment damage. It accomplishes this by allowing the magnitude of fault current to be predetermined/limited by a simple Ohms law calculation. In addition, limiting fault current to predetermined maximum values permits the designer to selectively co-ordinate the operation of protective devices, which minimizes system disruption and allows quick location of the fault. The systems with a very weak capacitive connection to earth are normally resistance earthed as shown in Fig.-9.4.

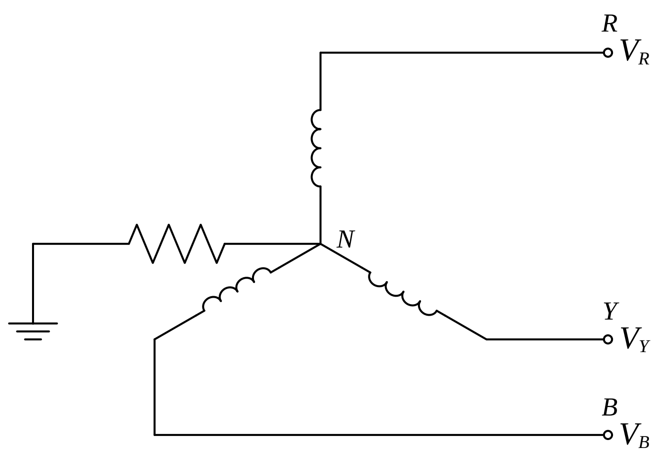


FIG.-9.4 RESISTANCE GROUNDED THREE PHASE SYSTEM

Neutral grounding resistors will have advantage by reducing magnitude of transient over-voltages, thereby reducing equipment damage, simplifying ground fault location, improving system and equipment fault protection, reducing maintenance time and expense, creating improved safety for personnel, improving lightning protection and reducing fault frequency.

There are two broad categories of resistance grounding.

- Low-resistance
- High-resistance

In both types of grounding, the resistor is connected between the generator/transformer neutral and earth ground. Low-resistance grounding of the neutral limits the ground fault current to a relatively high level (typically 50 amps or more), in order to operate protective fault-clearing relays and current transformers. These devices are then able to quickly clear the fault, usually within a few seconds. This fast response time is important, since it limits damage to equipment, prevents additional faults from occurring, provides safety for personnel and localizes the fault. The limited fault current and fast response time also prevent overheating and mechanical stress on conductors. It must be noted that the circuit must be shut down after the first ground fault occurs. Low-resistance grounding, typically 400 Amps for 10 seconds are commonly found on medium and high voltage systems.

High-resistance grounding of the neutral limits the ground fault current to a very low level (typically under 25 Amps with a continuous duty). It is typically used on low voltage systems of 600 volts or less. By limiting the ground fault current to a very low level, the fault can be tolerated on the system until it can be located and then isolated or removed at a convenient time. This permits continued production, provided a second ground fault does not occur.

Advantages of high resistance earthed systems:

- Enables high impedance fault detection in systems with weak capacitive connection to earth
- Some phase-to-earth faults is self-cleared.
- The neutral point resistance can be chosen to limit the possible over voltage transients to 2.5 times the fundamental frequency maximum voltage
- Transients are further discussed in section below.

Disadvantages:

- Generates extensive earth fault currents when combined with strong or moderate capacitive connection to earth.
- Cost involved

REACTANCE GROUNDED NEUTRAL SYSTEMS

The neutral is connected to earth through reactor. The ground fault that may flow is a function of the neutral reactance, the level of the fault current is often used as a criteria for describing the degree of grounding. In this method the ground fault current should be at least 60% of the three phase fault current to prevent serious transient over voltages. This is considerably higher than the level of fault current desirable in the system using resistor, and therefore reactance grounding is usually not considered as an alternative to the system using resistor.

This system is used when the system neutral transformer is not available (Delta connected system). In such case the reactor is used as transformer grounding to obtain the neutral .

GROUNDING THROUGH ARC-SUPPRESSION COIL (PETERSEN COIL)

An earthing reactor connected between the neutral of a system and earth and having a specially selected, relatively high value of reactance in such that the reactive current to earth under fault conditions balances the capacitance current to earth flowing from lines so that the earth current at the fault is limited to practically zero. It is also known as resonant grounding. This method of grounding is used primarily on 110 kV systems, consisting largely of overhead transmission or distribution lines. Resonance earthing makes it possible to more or less eliminate the reactive earth fault current.

Advantages of resonant earthed systems:

- Small reactive earth fault current independent of the phase to earth capacitance of the system.
- Enables high impedance fault detection.

Disadvantages

- Risk of extensive active earth fault losses
- Complicated relay protection
- High costs associated.

The IEEE Green Book, Standard 142, contains useful reference information on system grounding factors in selecting a system grounding method and equipment grounding and methods. The IEEE Orange Book, Standard 446, contains a chapter of recommended practice that is specific to grounding of emergency and standby generator systems.

CHAPTER-10
SUB-STATION

Substations are key parts of electrical generation, transmission, and distribution systems. Substations transform voltage from high to low or from low to high as necessary. Substations also dispatch electric power from generating stations to consumption centers. Electric power may flow through several substations between the generating plant and the consumer, and the voltage may be changed in several steps. Substations can be generally divided into three major types:

1. Transmission substations integrate the transmission lines into a network with multiple parallel interconnections so that power can flow freely over long distances from any generator to any consumer. This transmission grid is often called the bulk power system. Typically, transmission lines operate at voltages above 132 kV. Transmission substations often include transformation from one transmission voltage level to another.

2. Sub-transmission substations typically operate at 33 kV through 132 kV voltage levels, and transform the high voltages used for efficient long distance transmission through the grid to the sub-transmission voltage levels for more cost-effective transmission of power through supply lines to the distribution substations in the surrounding regions. These supply lines are radial feeders, each connecting the substation to a small number of distribution substations.

3. Distribution substations typically operate at 11 kV/0.4 kV voltage levels, and deliver electric energy directly to industrial and residential consumers. Distribution feeders transport power from the distribution substations to the end consumers' premises. These feeders serve a large number of premises and usually contain many branches. At the consumers' premises, distribution transformers transform the distribution voltage to the service level voltage directly used in households and industrial plants, usually from 230 V or 400 V.

A typical sub-station connection diagram is shown in Fig.-10.1. The sub-station may include the following equipment.

- Power transformer or distribution transformer as the case may be of sub-station
- Circuit breakers
- Disconnecting switches
- Isolators
- Station bus

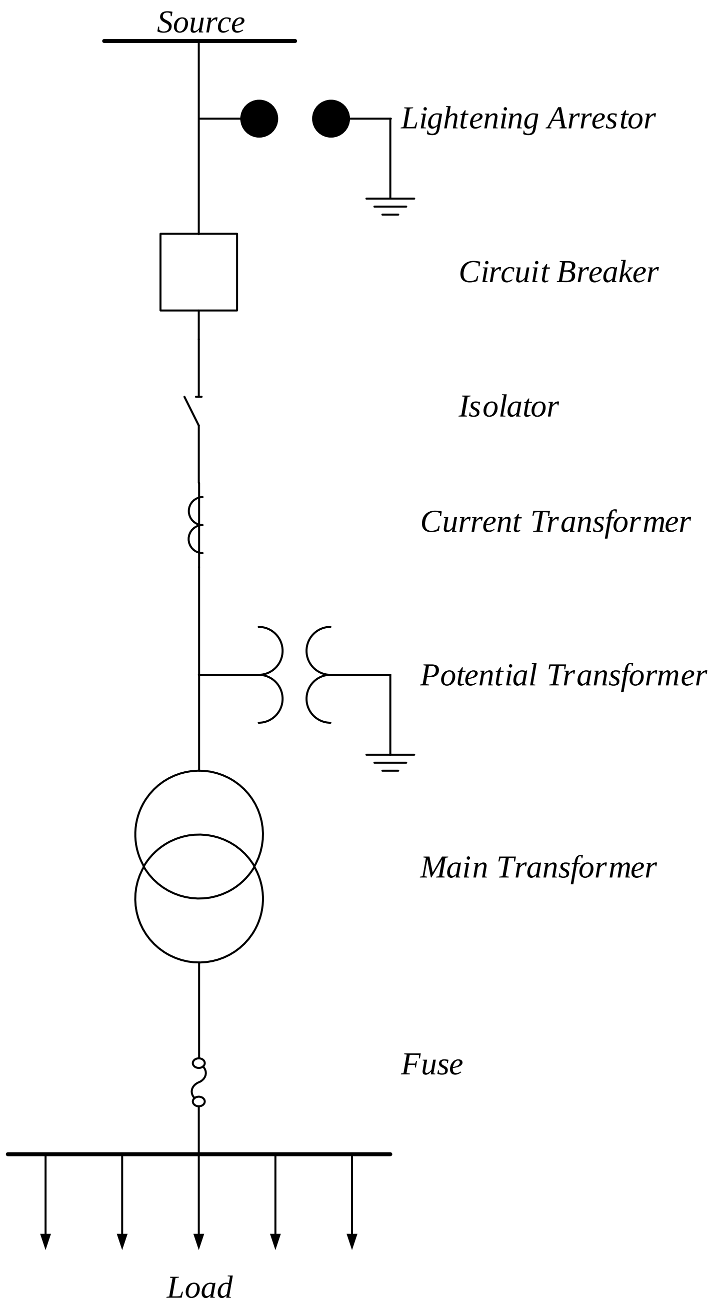


FIG.-10.1 A TYPICAL LAY-OUT OF SUB-STATION

- Current transformer
- Potential transformer
- Lightening arrestor
- Protective relays
- Station batteries
- Earthing system

TRANSFORMERS.

Transformers are an essential part of any electrical system. They come in various sizes and voltage ratings. Transformers are used for transforming power from one voltage level to another. In sub-station either power transformer or distribution transformers are used depending upon the sub-station location i.e. transmission sub-station or distribution sub-station.

CIRCUIT BREAKERS

Circuit breakers which control high voltages are also located at electrical substations. Many outdoor substations use oil-filled circuit breakers. In-this type of circuit breaker, the contacts are immersed in an insulating oil contained in a metal enclosure. Another type of high-voltage circuit breaker is the magnetic air breaker in which the contacts separate, in the air, when the power line is overloaded. Magnetic blowout coils are used to develop a magnetic field which causes the arc, that is produced when the contacts break, to be concentrated into are chutes where it is extinguished. A modification of this type is the compressed- air circuit breaker. In this type, a stream of compressed air is concentrated on the contacts when the power line is opened. The compressed air aids in extinguishing the arc, which is developed when the contacts open. It should be pointed out that large arcs are present whenever a high-voltage circuit is interrupted. This problem is not encountered to any great extent in low-voltage protective equipment.

DISCONNECTING SWITCHES

The disconnecting switches are used to disconnect electrical equipment from the power lines which supply the equipment. Ordinarily, disconnect switches are not operated when current is flowing through them. A high-voltage arcing problem would occur if disconnect switches were opened while current was flowing through them. They are opened mainly to isolate equipment from power lines for safety purposes. Most disconnect switches are the “air-break” type which is similar in construction to knife switches. These switches are available for indoor or outdoor use in both manual and motor-operated designs.

LIGHTNING ARRESTERS

The purpose of using lightning arresters on power lines is to cause the conduction to ground of excessively high voltages that are caused by lightning strikes or other system-problems. Without lightning arresters, power lines and associated equipment could become inoperable when struck by lightning. Arresters are designed to operate rapidly and repeatedly if necessary. Their response time must be more rapid than the other protective equipment used on power lines.

Lightning arresters must have a rigid connection to ground on one side. The other side of the arrester is connected to a power line. Sometimes, they are connected to transformers or the insides of switchgear. Lightning is a major cause of power-system failures and equipment damage, so lightning arresters have a very important function.

INSULATORS AND CONDUCTORS

All power transmission lines must be isolated so as not to become safety hazards. Large strings of insulators are used at substations and at other points along the power distribution system to isolate the current carrying conductors from their steel supports or any other ground mounted equipment. Insulators may be made of porcelain, rubber, or a thermoplastic material.

PROTECTIVE RELAYS

Protective relays provide an accurate and sensitive method of protecting electrical distribution equipment short circuits and other abnormal conditions. Overcurrent relays are used to cause the rapid opening of electrical power lines when the current exceeds a predetermined value. The response time of the relays is very important in protecting the equipment from damage. Some common types of faults which may be protected by relays are line-to-ground short circuits, line-to-line short circuits, double line-to-ground short circuits, and three-phase line short circuits. Each of these conditions is caused by faulty circuit conditions which draw abnormally high current (fault currents) from the power lines.

FUSES

Since electrical power lines are frequently short circuited, various protective equipment is used to prevent damage to both the power lines and the equipment. This protective equipment must be designed to handle high voltages and currents. Either fuses or circuit breakers may be used to protect high-voltage power lines. High-voltage fuses (those used for over 600 volts) are made in several ways. An expulsion-type fuse has an element which will melt and vaporize when it is overloaded, causing the power line it is connected in series with to open. Liquid fuses have a liquid-filled metal enclosure, which contains the fuse element. The liquid acts as an arc suppressing medium. When the fuse element melts due to an excessive current in a power line, the element is immersed in the liquid to extinguish the arc. This type of fuse reduces the problem of high-voltage arcing. A solid material fuse is similar to a liquid fuse except that the arc is extinguished in a chamber filled with solid material. Ordinarily, high-voltage fuses at substations are mounted adjacent to air-break disconnect switches. These switches provide a means of switching power lines and disconnecting them for repair. The fuse and switch enclosure is usually mounted near the overhead power lines at a substation.

SUBSTATION LOCATION

Distribution substations should be located as close to the load to be served as possible. In addition, future load requirement should be planned accurate. The level of distribution voltage is also a consideration. Generally, the higher the distribution voltage, the farther apart substations may be located. However, they become larger in capacity and in number of customers served as distance apart increases. The decision of substation location must be based upon system reliability and economic factors. Among these factors are the availability of land, estimated operating costs, taxes, local zoning laws, environmental factors and potential public opinion. Also considered is the fact that conductor size increases as the size of the load supplied increases. The primary voltage level affects not only the size of conductors, but also the size of regulation equipment, insulation and other equipment ratings.

SUBSTATION BUS SCHEMES

The electrical and physical connection of sub-station buses are typically governed by safety, reliability, economy, maintainability and ease of operations etc. The connection schemes for the buses are described herein. Each scheme has its own advantages and disadvantages. The students are advised to discuss these in the class room.

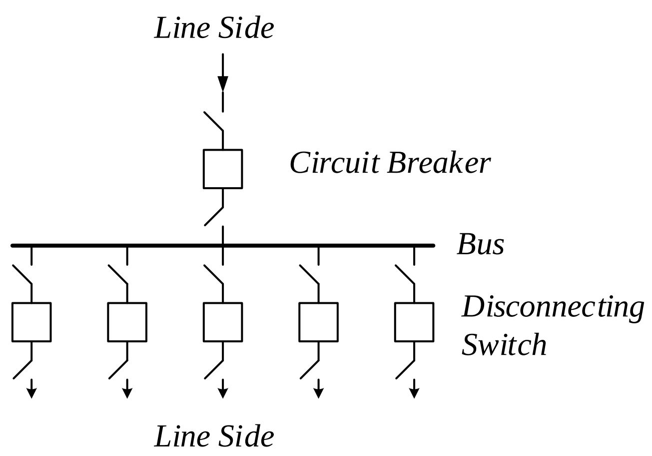


FIG.-10.2 SINGLE BUS SCHEME

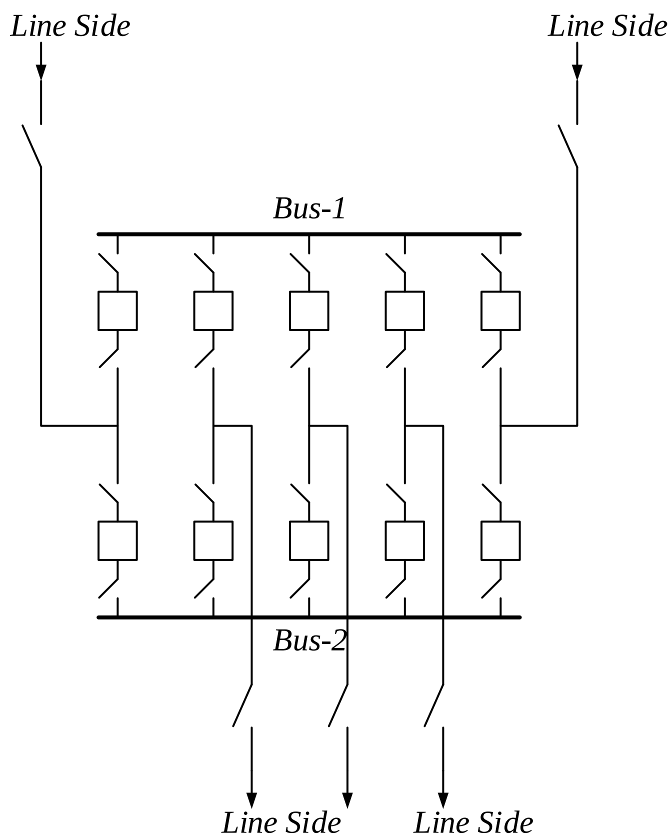


FIG.-10.3 DOUBLE BUS DOUBLE BREAKER SCHEME

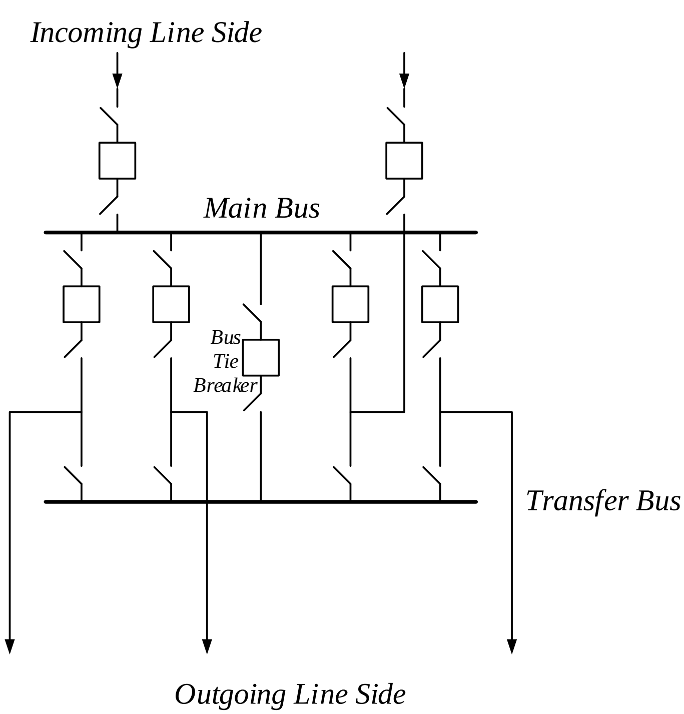


FIG.-10.4 MAIN AND TRANSFER BUS SCHEME

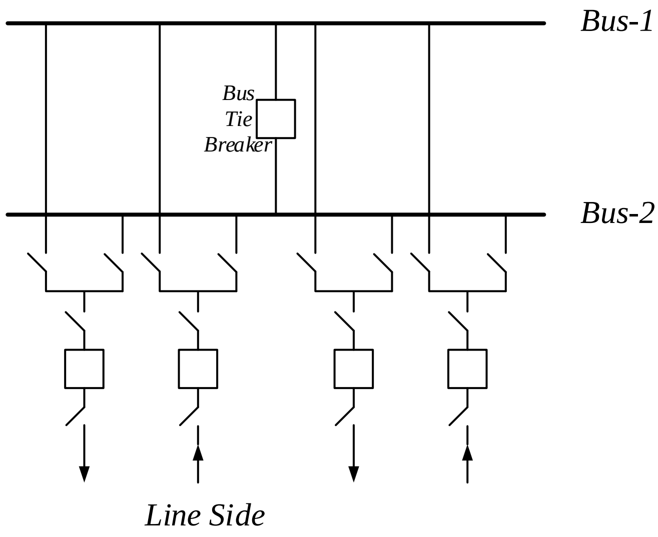


FIG.-10.5 DOUBLE BUS SINGLE BREAKER SCHEME

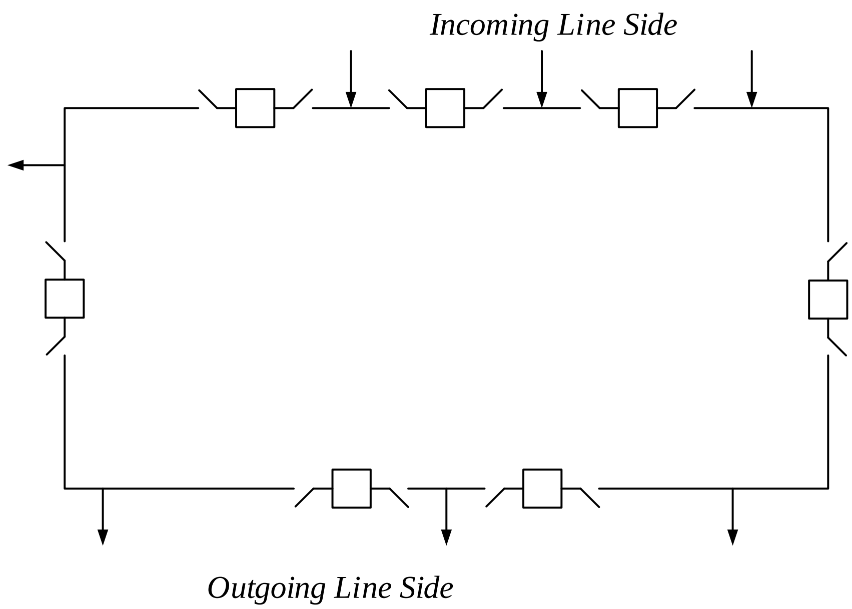


FIG.-10.6 RING BUS SCHEME

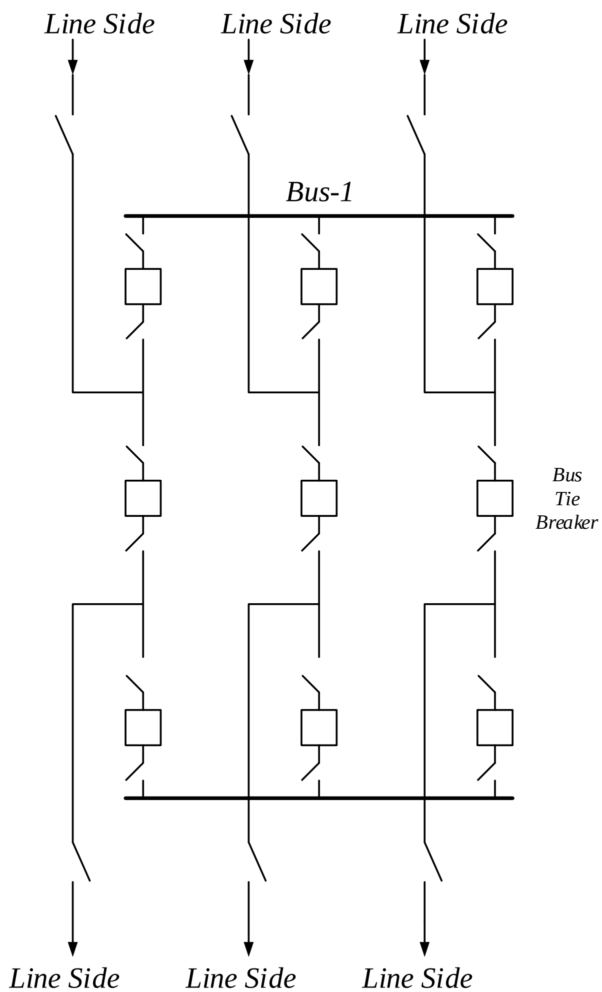


FIG.-10.7 ONE AND HALF BREAKER SCHEME

CHAPTER-11
FLEXIBLE AC TRANSMISSION SYSTEM

In chapter-3 we have derived the relation for power flow in a transmission line. We see that the power flow depends upon the magnitude of voltages at both the ends of the line, phase difference between two end voltages and the reactance of the transmission link. We also see that the parameters of the transmission line is constant, once the construction of transmission line is over. Moreover the line is operated at its rated design voltage hence the power flow through the link is limited by the magnitude of voltages i.e. operating voltage. Moreover there is thermal limit to power flow in the transmission link.

LINE COMPENSATION

As stated above the power flow in a transmission line depends upon the voltage at both the ends, the reactance of the line and phase difference between the voltages. If the power flow has to be increased or decreased then we have to control these variables. It can be controlled by

- Voltage magnitude control
- Transmission line reactance control
- Phase angle control

Once the installation of the transmission line is over its A, B, C, D parameters are constant because these depend upon the size and material of conductors and the configurations of the conductors. And hence the value of reactance and resistance are also fixed. The value of reactance X however can be controlled by providing compensation.

Since the series impedance of the transmission line consists of inductive reactance, the total series reactance can be reduced by connecting a capacitor in series. The shunt admittance of the transmission line consists of capacitive reactance, the effect of which can be compensated by connecting a shunt reactor. These processes are known as providing line compensation. The line compensation are of two types.

- Series compensation
- Shunt compensation

In series compensation as mentioned above, a suitable value of capacitor is connected in series with the transmission line as shown in Fig.-11.1. The location of this capacitor is optional and depend upon the requirement of transmission company.

FIG.-11.1 TRANSMISSION LINE WITH SERIES COMPENSATION

In shunt compensation a shunt reactor of suitable capacity is connected as a shunt element at the required bus of the transmission line as shown in Fig.-11.2.

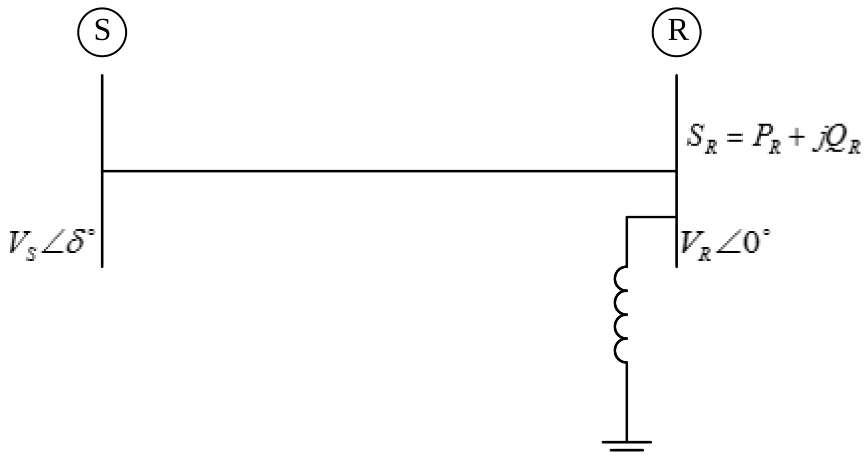


FIG.-11.2 TRANSMISSION LINE WITH SHUNT COMPENSATION

The value of series compensation and shunt compensation known as degree of compensation depend upon operational policy. It is seen that the series compensation is very much effective in controlling the power transfer over the transmission line where as the shunt compensation is most proved way for voltage control at the bus at which the compensation has been provided.

In power system most of the loads are inductive in nature resulting in reducing the voltage at which it is connected, it is well known to connect the capacitor at that voltage. It improves the power factor at that bus by supplying reactive power at the said bus. Thus Fig.-11.2 can be modified to Fig.-11.3.

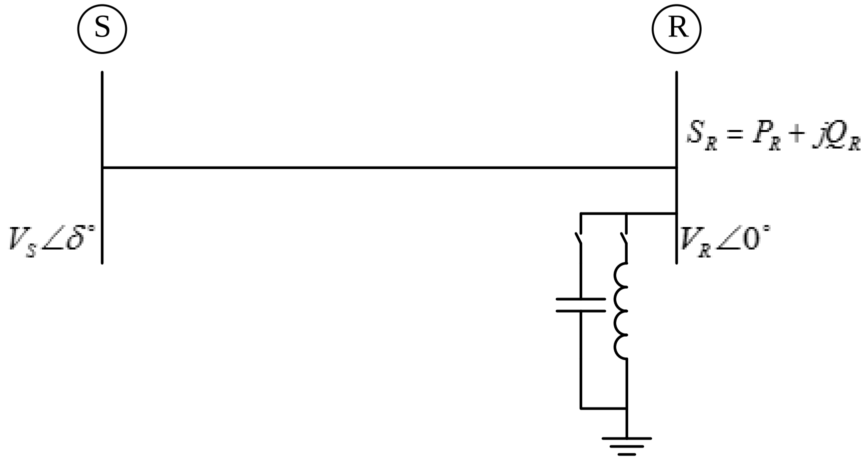


FIG.-11.3 TRANSMISSION LINE WITH SHUNT COMPENSATION

If the magnitude of voltage at the bus is less than the required magnitude then the shunt capacitor is connected. If the magnitude of voltage at the bus is more than the required magnitude then the shunt reactor is connected. Other way we can say, the shunt capacitor is used to improve the voltage and the shunt reactor is used to avoid the overvoltage.

With the insertion of compensation the circuit parameters changes and thus the operation of the power system. The line compensation provides:

- Improvement in power flow
- Power flow control
- Share of power between the transmission lines
- Voltage control
- Improved stability
- Improved security

The above described compensation are provided in steps by using capacitor bank or reactor with tappings at regular steps. To achieve required degree of compensation under all loading condition, we need to have a very flexible operation, which shall provide any degree of compensation. This led to concept of flexible transmission system. The AC transmission system, which employs to achieve a flexible operation is known as flexible AC transmission system (FACTS) and the devices used for such operation are known as FCATS devices.

The technological development in high voltage power electronics application has enabled to use FACTS devices for EHV or UHV transmission system. These devices can be divided into two categories. The first group employs reactive impedances or tap-changing transformer with thyristos switches as controlled elements. The second group uses self-commuted static converters as controlled voltage sources.

The first group of controllers are static var compensator (SVC), thyristor controlled series capacitor (TCSC) an phase shifter. These employs conventional thyristor in circuit arrangements with capacitor or reactor or tap changing transformer, such that these can represented by variable admittance in the circuit.

The second group of controllers employs self-commuted voltage sourced switching converters to realize rapidly controllable, static, synchronous ac voltage source or current source. These controllers provide superior performance characteristics and uniform applicability for transmission voltage, effective line impedance control and angle control. It also offers unique potential to exchange real power directly with ac system, in addition to providing the independently controllable reactive power compensation. The static synchronous compensator (STATCOM) and static synchronous series compensator (SSSC) are the FACTS devices in this group as counterpart to SVC and TCSC in the first group.

STATIC VAR COMPENSATOR (SVC)

The SVC is shunt connected device whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters. Basically the SVC is more effective in the bus voltage control at which it is connected rather than the power flow control in the transmission line.

The basic SVC is represented as variable impedance. The Fixed Capacitor (FC) with a thyristor Controlled Reactor (TCR) configuration of the SVC is shown in Fig.-11.4. The circuit representation is shown in Fig.-11.5.

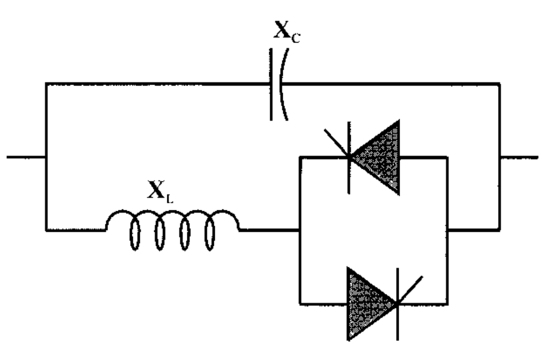


FIG.-11.4 FC-TCR CONFIGURATION OF SVC.

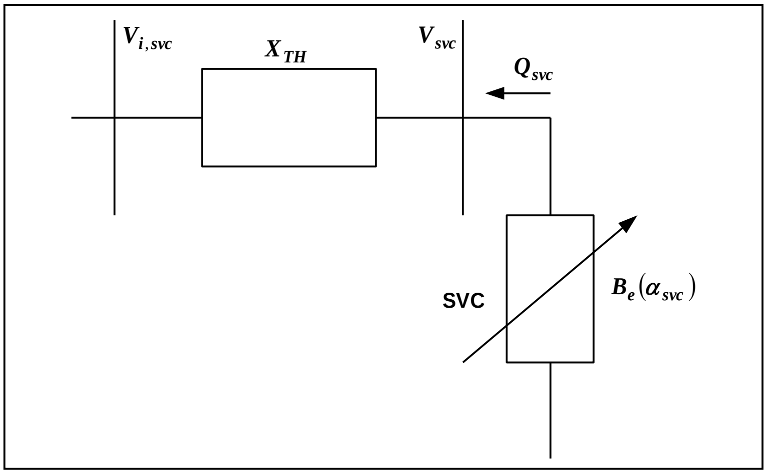


FIG.-11.5 CIRCUIT REPRESENTATION OF SVC

The controller is composed of a fixed capacitor (X_C), fixed reactor (X_L) and a bi-directional thyristor valve, composed of two thyristors. The fixed reactor and bi-directional valve can be modeled as an equivalent variable inductance using Fourier analysis on the inductor current waveform. This model is given in terms of the equivalent susceptance B_e, rather than the corresponding reactance equations, because an admittance model is numerically more stable than the corresponding impedance model.

The variables are the current I_{svc}, the reactive power Q_{svc}, the firing angle α_{svc}, the equivalent susceptance B_e and the voltage reference $V_{svc_{ref}}$. The equivalent susceptance B_e is a function of the firing angle α_{svc} and act either in capacitive or in inductive mode.

THYRISTOR CONTROLLED SERIES CAPACITOR (TCSC)

The thyristor controlled series capacitor (TCSC) is a capacitive reactance compensator, which consists of a series capacitor bank shunted by a thyristor controlled reactor in order to provide a smoothly variable series capacitive reactance. Basically TCSC is more suitable device to control the power flow in the transmission line.

The same FC-TCR configuration shown above can be used as TCSC, however it is connected in series with the transmission line. In the FC-TCR scheme the degree of compensation in the capacitive region (the admittance of the TCR is kept below that of parallel connected capacitor) is increased or decreased by increasing or decreasing the thyristor conduction period and thereby the current in the TCR. The minimum series compensation is reached when the TCR is off. The TCR may be designed to have the capability to limit the voltage across the capacitor during the faults and other system contingencies of similar effect.

In the thyristor switched capacitor scheme, the degree of series compensation is controlled by increasing or decreasing the number of capacitor bank in series. To accomplish this, each capacitor bank is inserted or bypassed by a thyristor valve. To minimize switching transients and utilize natural commutation, the operation of the thyristor is coordinated with voltage and current zero crossings.

STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

The functional single line diagram of a STATCOM is given in Fig.-11.6. The VSC is connected to the ac system bus through a coupling transformer. The reactive power is absorbed or supplied by VSC to the system if $|V_{ac}|<|V_{bus}|$ or $|V_{ac}|>|V_{bus}|$ respectively. The real power is absorbed or supplied by VSC to the system if $\angle V_{ac}<\angle V_{bus}$ or $\angle V_{ac}>\angle V_{bus}$ respectively. The output voltage 'V_{ac}' depends upon the firing angle and conduction time of thyristor of VSC, which depends upon the P_{ref}, Q_{ref}. The STATCOM is connected in shunt with the transmission line. For real power transfer the dc capacitor is replaced by an external energy source.

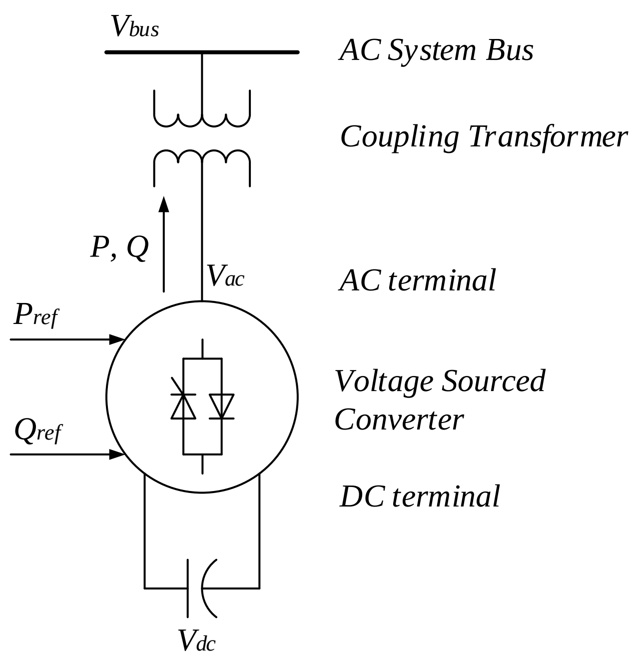


FIG.-11.6 FUNCTIONAL DIAGRAM OF STATCOM

STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC)

The static synchronous series compensator (SSSC) is a series controller and employs the same configuration shown in Fig.-11.6. It has the same operation as above but it is connected in series with the transmission line. It inject a voltage in series with the line voltage profile and thus improves the power transfer. The basic connection is shown in Fig.-11.7. It is generally operated without an external energy source thus it can only inject a variable voltage which is 90^0 leading or lagging the current.

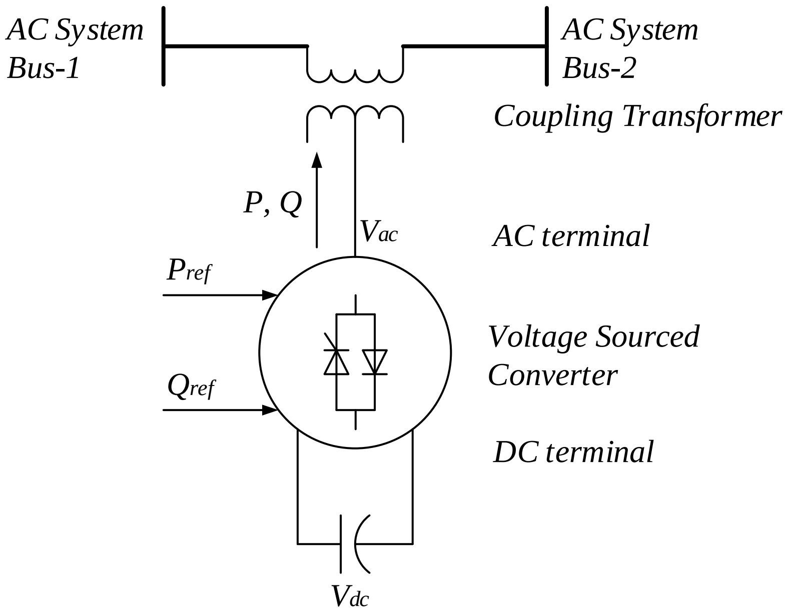


FIG.-11.7 FUNCTIONAL DIAGRAM OF SSSC

UNIFIED POWER FLOW CONTROLLER (UPFC)

We have seen that the STATCOM is a shunt controller and it either delivers or absorbs the reactive power bus controls the voltage magnitude at the bus at which it is connected. The SSSC is a series controller and used to control the power transfer through the transmission line by controlling the series impedance.

The Unified power flow controller (UPFC) is combination of STATCOM and SSSC which are coupled via dc link to allow the bidirectional flow of real power between the series output terminal of the SSSC and the shunt output terminal of the STATCOM. It is controlled to provide concurrent real and reactive series line compensation without any external energy source. The UPFC is able to control the voltage magnitude, line impedance and the phase angle between the two end voltages. The UPFC functional diagram is given in Fig.-11.8.

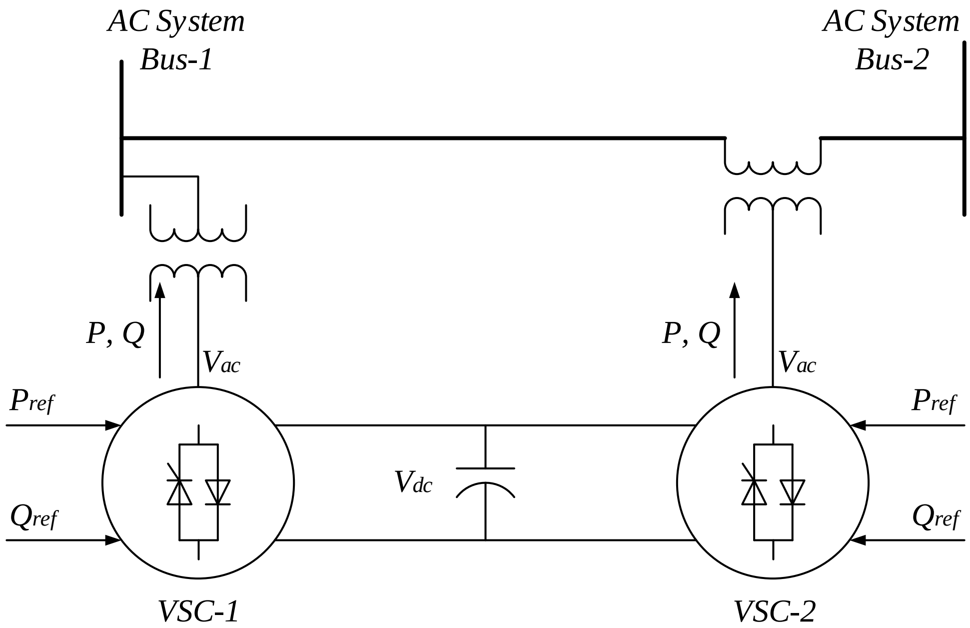


FIG.-11.8 FUNCTIONAL DIAGRAM OF UPFC

COMPARISON OF SVC AND STATCOM

A comparison between SVC and STATCOM is given below.

Sl. No.	SVC	STATCOM
1	It acts as a variable susceptance.	It acts as a voltage source behind a reactance.
2	It is sensitive to transmission system harmonics.	It is insensitive to transmission system harmonics.
3	It has smaller dynamic range.	It has large dynamic range.
4	Its performance is slow.	It has faster response
5	It operates generally in capacitive region.	It operates generally both in inductive and capacitive region.
6	It has difficulty in operating during weak AC system.	It can maintain stable voltage in weak AC system.
7		It can be used for small amount of energy storage.

In this chapter a brief introduction on flexible ac transmission system (FACTS) and the devices used in FACTS are described. However there are more number of devices, which comes into the category of FCATS devices. They are as follows:

- Thyristor switched capacitor
- Thyristor switched reactor
- Thyristor controlled capacitor
- Thyristor controlled reactor
- Thyristor controlled/switched series capacitor
- Thyristor controlled/switched series reactor
- Thyristor controlled/switched phase shifting transformer
- Thyristor controlled/switched voltage regulator
- Interline power flow controller etc.

The application of each devices is specific as per requirement of the power system parameter and variables, or the state of the power system and the control strategy of its operating company.

CONCLUSION

This class note has been prepared for the use by the students as a supplement to this course. It must be remembered that there cannot be any alternative to the conventional class rooms teaching and learning with chalk and black board. The students are advised to attend the classes and go through this notes along with the progress of the subject in the classes. In the meantime the students must refer the prescribed text books and reference books. The author wishes best of luck to the students.