SRI CHANDRASEKHARENDRA SARASWATHI VISWA MAHA VIDYALAYA

(Deemed to be University under section 3 Of UGC Act 1956)

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

Subject: Generation Transmission and Distribution **Code: BEEF184T50**

Unit Details

1. Generation and distribution systems
2. Line parameters and corona
3. Performance of over head line
4. Underground cables and insulator
5. Mechanical design and HVDC transmission

Name of the Course **: Generation Transmission and Distribution**

Name of the unit **: Generation and distribution systems**

Topic – Title **: Overview of various power plants**

Aim and Objective

To study the overview of the hydro, thermal and nuclear power plants along with Bio mass plant and feeder networks also.

Pre-requisites

Present scenario in fossil fuel in the world and nuclear energy concepts.

Pre – Test MCQ

1. Commercial source of energy are
a. Solar, wind and Bio Mass
b. Fossil fuels, hydro, nuclear
c. Wood, agriculture waste
d. None of the above
Ans: b

2. In India largest thermal power plant is at
a. Kota
b. Sarui
c. Chandrapur
d. Neyveli
Ans: c

3. Main source of production of Bio gas is
a. Human waste
b. Cow dung
c. Live stock waste
d. All
Ans: d

4. India's first nuclear power plant is installed at
a. Tarapure
b. Kota
c. Kalpakkam
d. None
Ans: a

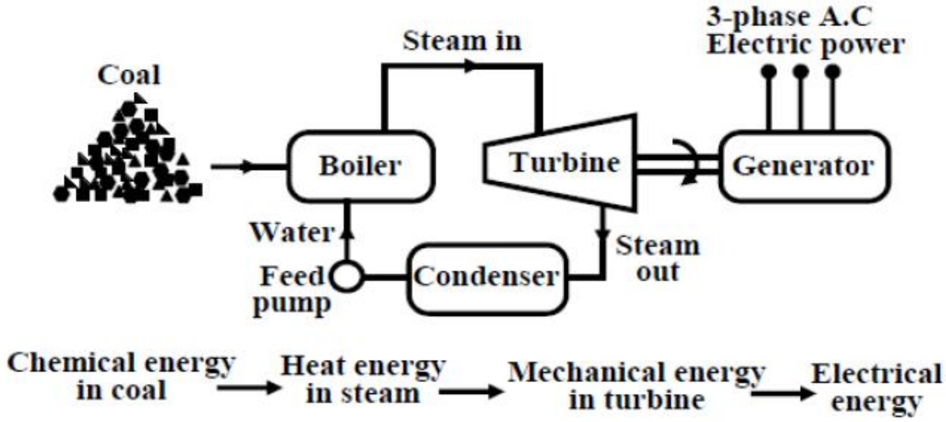
5. In fuel cell ______________ energy converted to electrical energy
a. Mechanical
b. Chemical
c. Heat
d. Sound
Ans: b

Theory

Thermal plant

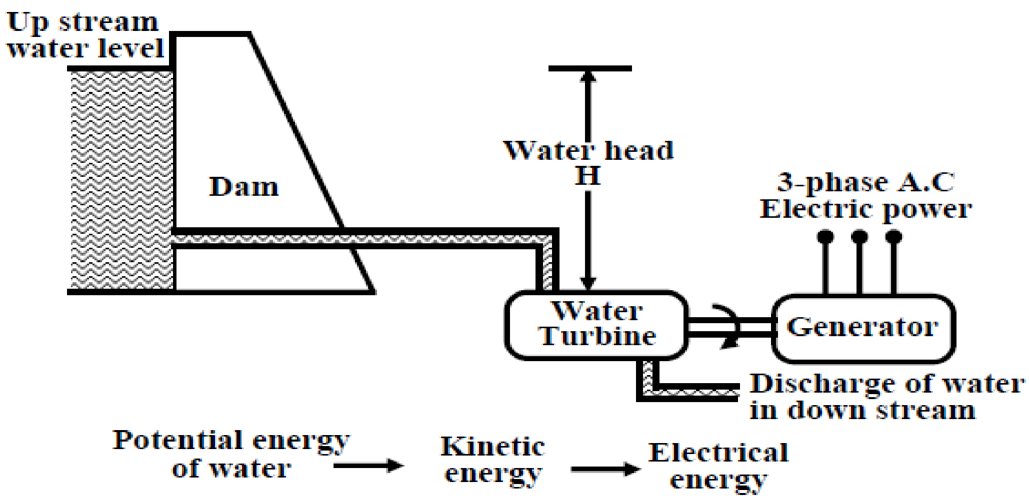
We have seen in the previous section that to generate voltage at 50 Hz we have to run the generator at some fixed rpm by some external agency. A turbine is used to rotate the generator. Turbine may be of two types, namely steam turbine and water turbine. In a thermal power station coal is burnt to produce steam which in turn, drives the steam turbine hence the generator (turbo set). In figure 2.2 the elementary features of a thermal power plant is shown.

In a thermal power plant coil is burnt to produce high temperature and high pressure steam in a boiler. The steam is passed through a steam turbine to produce rotational motion. The generator, mechanically coupled to the turbine, thus rotates producing electricity. Chemical energy stored in coal after a couple of transformations produces electrical energy at the generator terminals as depicted in the figure. Thus proximity of a generating station nearer to a coal reserve and water sources will be most economical as the cost of transporting coal gets reduced. In our country coal is available in abundance and naturally thermal power plants are most popular. However, these plants pollute the atmosphere because of burning of coals. Stringent conditions (such as use of more chimney heights along with the compulsory use of electrostatic precipitator) are put by regulatory authorities to see that the effects of pollution is minimized. A large amount of ash is produced every day in a thermal plant and effective handling of the ash adds to the running cost of the plant. Nonetheless 57% of the generation in out country is from thermal plants. The speed of alternator used in thermal plants is 3000 rpm which means 2-pole alternators are used in such plants.



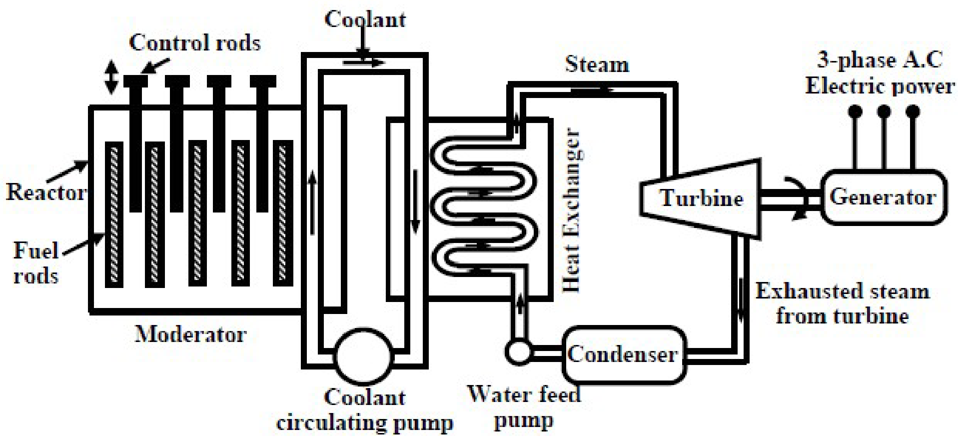
Hydel plant

In a hydel power station, water head is used to drive water turbine coupled to the generator. Water head may be available in hilly region naturally in the form of water reservoir (lakes etc.) at the hill tops. The potential energy of water can be used to drive the turbo generator set installed at the base of the hills through piping called *pen stock*. Water head may also be created artificially by constructing dams on a suitable river. In contrast to a thermal plant, hydel power plants are eco-friendly, neat and clean as no fuel is to be burnt to produce electricity. While running cost of such plants are low, the initial installation cost is rather high compared to a thermal plants due to massive civil construction necessary. Also sites to be selected for such plants depend upon natural availability of water reservoirs at hill tops or availability of suitable rivers for constructing dams. Water turbines generally operate at low rpm, so number of poles of the alternator are high. For example a 20-pole alternator the rpm of the turbine is only 300 rpm.



Nuclear Plant

The initial investment required to install a nuclear power station is quite high but running cost is low. Although, nuclear plants produce electricity without causing air pollution, it remains a dormant source of radiation hazards due to leakage in the reactor. Also the used fuel rods are to be carefully handled and disposed off as they still remain radioactive.



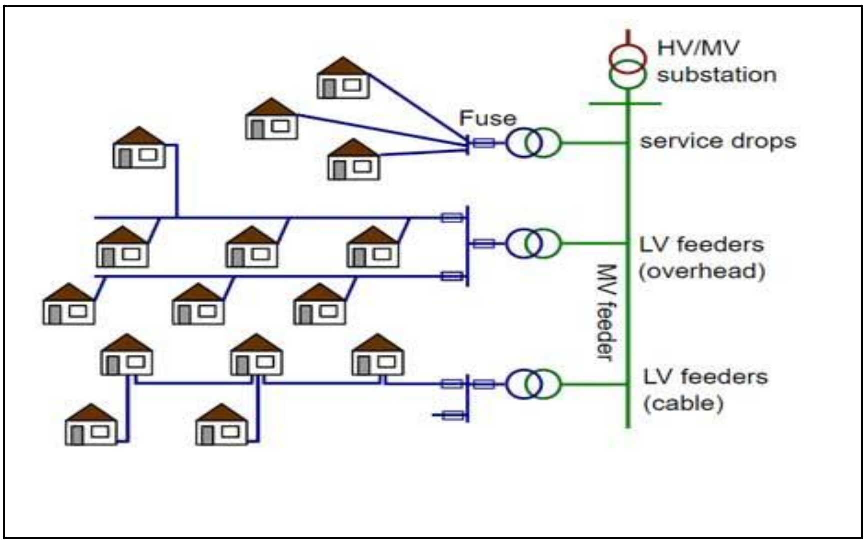
An **electric power distribution** system can be classified according to its **feeder connection schemes or topologies** as follows -

- Radial distribution system
- Parallel feeders distribution
- Ring main distribution system
- Interconnected distribution

There are few other **variations of distribution feeder systems**, but we'll stick to these four basic and commonly used systems.

Radial Distribution System

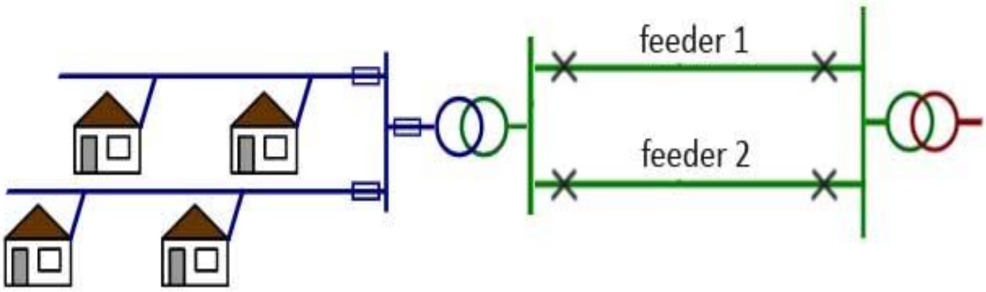
This system is used only when substation or generating station is located at the center of the consumers. In this system, different feeders radiate from a substation or a generating station and feed the distributors at one end. Thus, the main **characteristic of a radial distribution system** is that the power flow is in only one direction. Single line diagram of a typical radial distribution system is as shown in the figure below. It is the simplest system and has the lowest initial cost.



Although this system is simplest and least expensive, it is not highly reliable. A major **drawback of a radial distribution system** is, a fault in the feeder will result in supply failure to associated consumers as there won't be any alternative feeder to feed distributors.

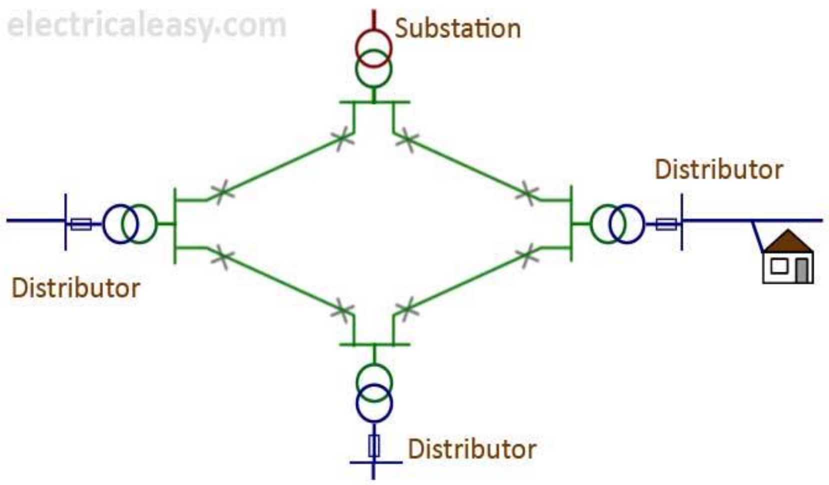
Parallel Feeders Distribution System

The above-mentioned disadvantage of a radial system can be minimized by introducing parallel feeders. The initial cost of this system is much more as the number of feeders is doubled. Such system may be used where reliability of the supply is important or for load sharing where the load is higher. (Reference: EEP - Distribution Feeder Systems)



Ring Main Distribution System

A similar level of system reliability to that of the parallel feeders can be achieved by using **ring distribution system**. Here, each distribution transformer is fed with two feeders but in different paths. The feeders in this system form a loop which starts from the substation bus-bars, runs through the load area feeding distribution transformers and returns to the substation bus-bars. The following figure shows a typical single line diagram of a ring main distribution system.



Ring main distribution system is the most preferred due to its following advantages.

Advantages Of Ring Main Distribution System

- There are fewer voltage fluctuations at consumer's terminal.

- The system is very reliable as each distribution transformer is fed with two feeders. That means, in the event of a fault in any section of the feeder, the continuity of the supply is ensured from the alternative path.

Interconnected Distribution System

When a ring main feeder is energized by two or more substations or generating stations, it is called as an interconnected distribution system. This system ensures reliability in an event of transmission failure. Also, any area fed from one generating stations during peak load hours can be fed from the other generating station or substation for meeting power requirements from increased load.

MCQ – Post Test

1. Modern steam turbines are
a. Impulse turbine
b. Reaction turbine
c. Impulse – reaction turbine
d. None
Ans: c

2. Economizer is used to heat
a. Air
b. Feed water
c. Flue gas
d. All the above
Ans:b

3. The efficiency of chimney is roughly
a. 80 %
b. 40 %
c. 20 %
d. 0.25 %
Ans: d

4. Reheat factor in stream turbine depends on
a. Exit pressure
b. Stage efficiency
c. Initial pressure & temperature
d. All the above
Ans: c

5. The value of reheat factor varies from
a. 0.5 – 0.6
b. 0.9 – 0.95
c. 1.02 – 1.06
d. 1.2 above
Ans: c

Summary

The overview of the power plant generation of different types discussed and methodology of generations arrived at.

References

1. C.L.Wadhva, Generation Distribution and Utilization of Electrical Energy, New Age International Publishers ltd.-New Delhi
2. V.K Mehta, Principle of Power Systems, S.Chand Publishers, New Delhi

Assignment

Explain the difference between hydro & thermal power plants in all aspects of study.

Name of the Course **: Generation Transmission and Distribution**

Name of the unit **: Line parameters and corona**

Topic – Title **: Inductance and capacitance of the transmission line**

Aim and Objective

To study the line parameters, inductance and capacitance of the transmission line along with corona effects on line and to minimise the corona loss. Spacing of conductors in bundled way.

Pre-requisites

Basic Electromagnetic properties, R,L,C parameter concepts.

Pre – Test MCQ

1. GMD of transmission line is used to evaluate
   a. Inductance of line
   b. Capacitance of line
   c. Inductance and capacitance of line
   d. None

   Ans: a

2. Transmission lines are transposed to
   a. Reduce copper loss
   b. Reduce skin effect
   c. To Prevent interference from telephone line
   d. To prevent short circuit between lines

   Ans: c

3. Which of the system transmission line has more initial cost?
   a. Overhead lines
   b. Under Ground Cable
   c. Bothe are same
   d. None

   Ans: b

4. Which is the material not used on transmission lines
   a. Copper
   b. Tungsten
   c. Aluminium
   d. Steel

   Ans: b

5. LT Cable are up to
   a. 1 kv
   b. 5 kv
   c. 10 kv
   d. 33kv

   Ans: a

Theory

Line parameters

An electric transmission line can be represented by a series combination of resistance, inductance and shunt combination of conductance and capacitance. These parameters are symbolized as *R*, *L*, *G* and *C* respectively. Of these *R* and *G* are least important in the sense that they do not affect much the total equivalent impedance of the line and hence the transmission capacity.

They are of course very much important when transmission efficiency and economy are to be evaluated as they completely determine the real transmission line losses.

The resistance of a conductor is given by

$$R = \frac{\text{Power loss in conductor}}{I^2} \text{ ohms}$$

where *R* is the effective resistance of the conductor and *I* the current flowing through the conductor. The effective resistance is equal to the d.c. resistance of the conductor only if the current is uniformly distributed throughout the section of the conductor. The difference in the d.c. resistance and effective resistance to frequencies less than 50 Hz is less than 1% for copper

conductors of section less than 350,000 circular mils. The loss on the overhead lines is due to (*i*) ohmic loss in the power conductors, (*ii*) corona loss and (*iii*) leakage at the insulators which

support the lines at the towers. This leakage loss is different from the leakage in cables as in cables the leakage is uniformly distributed along its length, whereas the leakage on overhead lines is limited only to the insulators. This could be represented as conductance uniformly distributed along the line. Since the corona loss and the leakage over the insulators is negligibly small under normal operating conditions, the conductance between the conductors of an overhead line is assumed to be zero.

A current carrying conductor produces a magnetic field which is in the form of closed circular loops around the conductor. The relation of the magnetic field direction to the current direction can be easily remembered by means of the right hand rule. With the thumb pointing in the direction of the current, the fingers of the right hand encircling the wire point in the direction of the magnetic field. According to Biot-Savart's law, the magnetic flux density at any point *P* as produced by a current carrying element shown in Fig. 2.1 is given by

$$dB = \frac{\mu}{4\pi}\frac{Idl \sin\theta}{r^2}$$

where dB = infinitesimal flux density at point P,

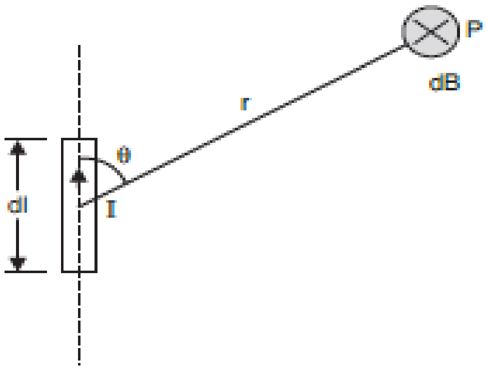
I = current in the element,

dl = length of element,

r = radius vector.

In order to determine the magnetic flux density B due to a long, straight or curved conductor, we assume that the conductor is made up of infinitesimal lengths dl and B is given by

$$B = \frac{\mu I}{4\pi}\int\frac{\sin\theta}{r^2}\,dl$$



The integration is carried out over the length of the conductor. If relation (2.3) is made use of in evaluating the magnetic flux density B at any point due to an infinite conductor, it is given by

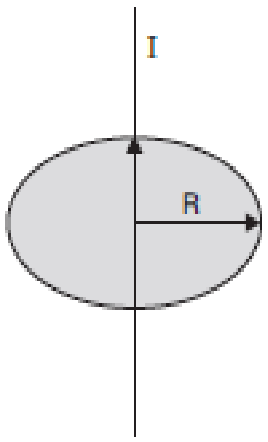
$$B = \frac{\mu I}{2\pi R}$$

where R = radial distance of the point from the conductor. The direction of the flux density is normal to the plane containing the conductor and the radius vector R. If B is now integrated around a path of radius R enclosing the wire once, we have

$$\oint Bdl = \frac{\mu I}{2\pi R}\oint dl$$

$$= \frac{\mu I}{2\pi R}.2\pi R = \mu I$$

$$\oint Hdl = I \text{ as } H = \frac{B}{\mu}$$



In words it states that the line integral of *H* around a single closed path is equal to the current enclosed. This is known as Ampere's law. If the path of integration encloses *N* number of turns of wire, each with a current *I* in the same direction, then

$$\int Hdl = NI$$

These relations are very much useful in evaluating the flux linkages and hence the inductance of a given system of conductors. Variation of the current in the conductors causes a change in the number of flux linkages. According to Faraday's laws of electromagnetic induction, this change in flux linkages induces a voltage in the conductors which is proportional to the rate of change of flux linkages.

An inductor is a device which stores energy in a magnetic field. By definition, the inductance *L* of an inductor is the ratio of its total magnetic flux linkages to the current *I* through the inductor or

$$L = \frac{N\psi_m}{I} = \frac{\lambda}{I}$$

This definition is satisfactory for a medium for which the permeability is constant. However, the permeability of ferrous media is not constant and for such cases the inductance is defined as the ratio of the infinitesimal change in flux linkage to the infinitesimal change in current producing it, *i.e.*,

$$L = \frac{d\lambda}{dI}$$

The unit of inductance is the henry. Mutual inductance between two circuits is defined as the flux linkages of one circuit due to the current in the second circuit per ampere of current in the second circuit. If the current *I*2 produces 12 flux linkages with circuit 1, the mutual inductance is

$$M_{12} = \frac{\lambda_{12}}{I_2} \text{ henries}$$

The phasor voltage drop in circuit 1 caused by the flux linkages of circuit 2 is

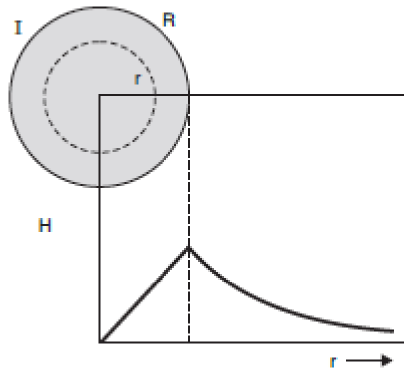
$$V_1 = j\omega M_{12} I_2 = j\omega\lambda_{12} \text{ volts.}$$

Let us consider a long current carrying conductor with radius *R* as shown in Fig. 2.3. We will consider here that the current is uniformly distributed across the section of the conductor. The flux linkages here will be both due to internal flux and external flux. The magnetic field intensity due to the current distribution inside the conductor is calculated as follows:

Consider a cylinder with radius $r < R$. The current enclosed by the cylinder will be

$$I' = I\left(\frac{r}{R}\right)^2.$$

where *I* is the current through the conductor.



Therefore, the magnetic field intensity at a distance *r* due to this current, using Ampere's Law,

$$H_r = \frac{I'}{2\pi r} = I\left(\frac{r}{R}\right)^2 \frac{1}{2\pi r} = \frac{Ir}{2\pi R^2}$$

which means that the magnetic field intensity inside the conductor is directly proportional to the distance from the centre of the conductor.

Now consider a cylinder with radius $r > R$. Applying Ampere's Law,

$$H = \frac{I}{2\pi r}$$

which means *H* is inversely proportional to *r* outside the conductor. The variation of *H* as a function of *r* is shown in Fig. 2.3. It can be shown that the magnetic field density (energy volume density)

$$W_e = \frac{1}{2}\mu H^2$$

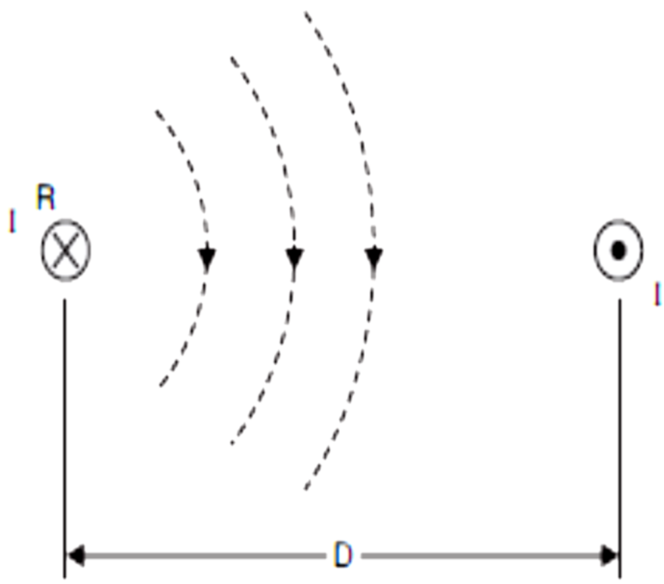
From this and the distribution of magnetic field intensity as shown in Figure, the following observations are made:

(*i*) Although the volume of the conductor is comparatively small, the field densities are of high magnitude, and the magnetic field energy stored in the conductor is not small.

(*ii*) The presence of the earth will affect the magnetic field geometry insignificantly.

By definition inductance is the flux linkages per ampere (Fig. 2.4). So the objective is to find out the flux linkages to this system of conductors. Now there are two flux linkages: (*i*) due to internal flux, and (*ii*) due to external flux.

Internal flux linkages: In order to determine the internal flux linkages, we start with the magnetic field intensity H at any distance $r < R$.



$$H = \frac{Ir}{2\pi R^2}$$

$$B = \mu H = \mu_0 H = \frac{\mu_0 I}{2\pi R^2} \cdot r \quad (\text{as } \mu_r = 1) \text{ for conductors.}$$

This flux density as we see is varying with r. We can assume this to be constant over an infinitesimal distance dr. The flux lines are in the form of circles concentric to the conductor.

Therefore, the flux lines passing through the concentric cylindrical shells of radii r and r +

where l is the length of wire.

In case the inductance per unit is desired, $l = 1$ metre.

$$d\phi = Bdr$$
$$= \frac{\mu_0 I}{2\pi R^2} rdr$$

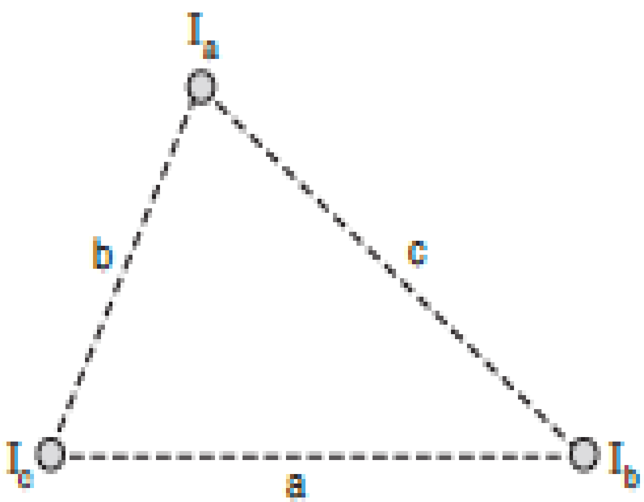
Now flux linkages = Flux × No. of turns.

Here since only a part of the conductor ($r < R$) is being enclosed by the flux lines $d\phi$,

$$\therefore \quad d\lambda = d\phi \left(\frac{r^2}{R^2}\right)$$
$$= \frac{\mu_0 I}{2\pi R^2} rdr \frac{r^2}{R^2}$$

$$\therefore \quad \text{Total internal flux linkages } \lambda = \int_0^R d\lambda$$
$$= \frac{\mu_0 I}{2\pi R^4} \int_0^R r^3 dr$$
$$= \frac{\mu_0 I}{8\pi}$$

From this it is clear that the flux linkage due to internal flux is independent of the size of the conductor. Consider a single circuit 3 phase system having three conductors *a*, *b* and *c* carrying currents *Ia*, *Ib* and *Ic* respectively. The three conductors are unsymmetrically placed *i.e.*, $a \neq b \neq c$ and each has a radius of *R* metres. The flux linkage of conductor *a* due to *Ia*, *Ib* and *Ic* from equation



$$\lambda_a = 2 \times 10^{-7}\left[I_a \ln\frac{1}{R'} + I_b \ln\frac{1}{c} + I_c \ln\frac{1}{b}\right]$$

Similarly,

$$\lambda_b = 2 \times 10^{-7}\left[I_a \ln\frac{1}{c} + I_b \ln\frac{1}{R'} + I_c \ln\frac{1}{a}\right]$$

$$\lambda_c = 2 \times 10^{-7}\left[I_a \ln\frac{1}{b} + I_b \ln\frac{1}{a} + I_c \ln\frac{1}{R'}\right]$$

Now taking I_a as reference

$$I_b = k^2 I_a \text{ and } I_c = kI_a$$

where $k = (-0.5 + j0.866)$

Substituting these values of I_b and I_c in the expression for λ_a,

$$\lambda_a = 2 \times 10^{-7}\left[I_a \ln\frac{1}{R'} + I_a(-0.5 - j0.866)\ln\frac{1}{c} + I_a(-0.5 + j0.866)\ln\frac{1}{b}\right]$$

$$\therefore \qquad L_a = \frac{\lambda_a}{I_a} = 2 \times 10^{-7}\left[\ln\frac{1}{R'} - \ln\frac{1}{\sqrt{bc}} - j\frac{\sqrt{3}}{2}\ln\frac{b}{c}\right]$$

Similarly,

$$L_b = 2 \times 10^{-7}\left[\ln\frac{1}{R'} - \ln\frac{1}{\sqrt{ac}} - j\frac{\sqrt{3}}{2}\ln\frac{c}{a}\right]$$

and

$$L_c = 2 \times 10^{-7}\left[\ln\frac{1}{R'} - \ln\frac{1}{\sqrt{ab}} - j\frac{\sqrt{3}}{2}\ln\frac{a}{b}\right]$$

It is clear from the expressions for inductances of conductors *a*, *b* and *c* that the three inductances are unequal and they contain imaginary term which is due to the mutual inductance.

In case the transmission line is transposed *i.e.*, each conductor takes all the three positions of the conductors, each position for one third length of the line as shown in Figure. The average value of the inductance

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

$$= \frac{1}{3}\left[2 \times 10^{-7}\left(3\ln\frac{1}{R'} - \ln\frac{1}{abc} - j\frac{\sqrt{3}}{2}\ln 1\right)\right]$$

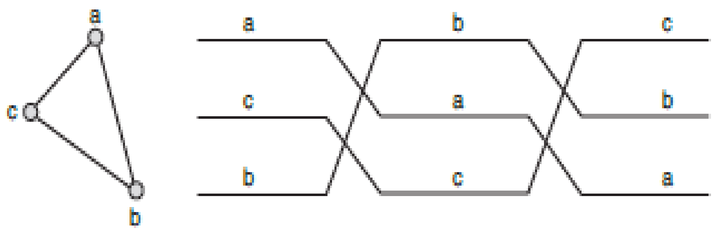
$$= 2 \times 10^{-7} \ln\frac{\sqrt[3]{abc}}{R'} \text{ Henry/metre}$$

For symmetrical spacing $a = b = c = d$,

$$L = 2 \times 10^{-7} \ln\frac{d}{R'} \text{ Henry/metre.}$$

By transposition of conductors is meant the exchanging of position of the power conductors at regular intervals along the line, so that each conductor occupies the original position of every other conductor over an equal distance.

A complete transposition cycle is shown in Figure, If the spacing is unsymmetrical, even though the system operates under balanced condition, voltage drops of different magnitude will be there in the three conductors due to unequal inductance of the three phases. Also, due to unsymmetrical spacing, the magnetic field external to the conductors is not zero, thereby causing induced voltages in adjacent electrical circuits, particularly telephone lines, that may result in telephone interference. To reduce this effect to a minimum the conductors are transposed as shown in Figure. It is enough to transpose either power line or the communication lines. Under balanced operating condition, the magnetic field linking an adjacent telephone line is shifted 120° in time phase with each rotation of the conductor positions in the transposition cycle. Over the length of the one complete transposition cycle of power line, the net voltage induced in the telephone line is zero as it is the sum of three induced voltages which are displaced by 120° in time phase. Under unbalanced conditions, of course, where power currents flow in the earth or in overhead ground wires (zero sequence currents), voltages will be induced in communication lines and interference will take place.



Modern power lines are normally not transposed. The transposition, however, may be affected at the intermediate switching station. It is to be noted that the difference in the inductances of the three phases is negligibly small due to asymmetrical spacing and the inductance of the untransposed line is taken equal to the average value of the inductance of one phase of the same line correctly transposed.

For transmission lines operating at high voltages normally stranded conductors are used. These conductors are known as composite conductors as they compose of two or more elements or strands electrically in parallel. The conductors used for transmission lines are stranded copper conductors, hollow copper conductors, ACSR conductors, copper weld and copper weld-copper conductors. By using different proportion of steel and aluminium strands different tensile and current carrying capacity conductors can be obtained. By the use of a filler such as a paper, between the outer aluminium strands and the inner steel strands, a conductor of large diameter can be obtained for use in high voltages. This type of conductor is known as expanded ACSR. Sometimes hollow conductors are used to increase the effective diameter of the conductor so as to reduce corona loss and hence radio interference level. A typical hollow copper conductor (Anaconda) consists of a twisted copper '*I*' beam as a core about which strands of copper wire are wound. The '*I*' beam is twisted in a direction opposite to that of the inner layer of strands.

Aluminium conductor steel reinforced (ACSR) which combine the lightness, electrical conductivity and rustlessness of aluminium with the high tensile strength of steel are now employed as overhead conductors on every kind of system, low voltage distribution to the most important long distance transmission lines of the world. The reasons for this can be summarised as follows:

1. Aluminium conductor steel reinforced (ACSR) are normally cheaper than copper conductors of equal resistance and this economy is obtained without sacrifice of efficiency, of reliability or of length of useful life.

2. The superior mechanical strength of ACSR can be utilized by using spans of larger lengths which results in smaller number of supports for a particular length of transmission.

3. A reduction in the number of supports involves a corresponding reduction in the total cost of insulators, foundations' erection and incidentally the costs of maintenance, replacements and stores are similarly reduced.

4. The increase in span length is beneficial in another way. It is well known that the vast majority of shut downs in the operation of an overhead line arise at points of supports, due to faulty insulators, flash-overs by birds and so on. Hence a reduction in the number of points of supports will correspondingly reduce the risk of outages.

5. Corona losses are reduced because of the larger diameter of the conductor.

6. These conductors are corrosion resistant and are useful under unfavourable conditions of industrial atmosphere and severe condition of exposure such as may occur on the sea coast.

The conductivity of an aluminium conductor steel reinforced is taken as that of the aluminium portion alone and though the steel core may add slightly to the current carrying capacity, this is usually neglected. The specific resistance of hard drawn aluminium is approximately 1.6 times that of normal hard drawn copper and the sectional area of an aluminium conductor must, therefore, be 1.6 times that of the equivalent copper. In order to obtain the overall diameter of a stranded conductor, multiply the wire diameter (diameter of one strand) *D* by the appropriate constant in the table below.

For voltages in excess of 230 kV, it is in fact not possible to use a round single conductor. Instead of going in for a hollow conductor it is preferable to use more than one conductor per phase which is known as bundling of conductors. A bundle conductor is a conductor made up of two or more sub-conductors and is used as one phase conductor. It is found that the increase in transmission capacity justifies economically the use of two conductor bundles on 220 kV lines.

The following are the advantages in using bundle conductors:

1. Reduced reactance.
2. Reduced voltage gradient.
3. Reduced corona loss.
4. Reduced radio interference.
5. Reduced surge impedance.

The reactance of the bundle conductors is reduced because the self GMD of the conductors is increased and as we know reactance = *K* ln GMD/GMR and as GMR is increased the reactance is reduced.

Theoretically, there is an optimum sub-conductor spacing for bundle conductors that will give minimum gradient on the surface of a sub-conductor and hence highest disruptive voltage. For a two conductor bundle, the equation for maximum gradient at the surface of a sub-conductor is

$$g = \frac{V\left(1+\frac{2r}{s}\right)}{2r \ln \frac{d}{\sqrt{rs}}}$$

When direct current flows in the conductor, the current is uniformly distributed across the section of the conductor whereas flow of alternating current is non-uniform, with the outer filaments of the conductor carrying more current than the filaments closer to the centre. This results in a higher resistance to alternating current than to direct current and is commonly known as skin effect. This effect is more, the more is the frequency of supply and the size of the conductor. A conductor could be considered as composed of very thin filaments. The inner filaments carrying currents give rise to flux which links the inner filaments only where as the flux due to current carrying outer filaments enclose both the inner as well as the outer filaments (Art. 2.4). The flux linkages per ampere to inner strands is more as compared to outer strands.

Hence the inductance/impedance of the inner strands is greater than those of outer strands which results in more current in the outer strands as compared to the inner strands. This non uniformity of flux linkage is the main cause of skin effect.

The alternating magnetic flux in a conductor caused by the current flowing in a neighbouring conductor gives rise to circulating currents which cause an apparent increase in the resistance of a conductor. This phenomenon is called proximity effect. In a two-wire system more lines of flux link elements farther apart than the elements nearest each other. Therefore, the inductance of the elements farther apart is more as compared to the elements near each other and the current density is less in the elements farther apart than the current density in the elements near each other. The effective resistance is, therefore, increased due to nonuniform distribution of current. The proximity effect is pronounced in case of cables where the distance between the conductors is small whereas for overhead lines with usual spacing the proximity effect is negligibly small.

Corono Effect

Corona phenomenon is the ionization of air surrounding the power conductor. Free electrons are normally present in free space because of radioactivity and cosmic rays. As the potential between the conductors is increased, the gradient around the surface of the conductor increases.

Assume that the spacing between the conductors is large as compared with the diameter of the conductors. The free electrons will move with certain velocity depending upon the field strength.

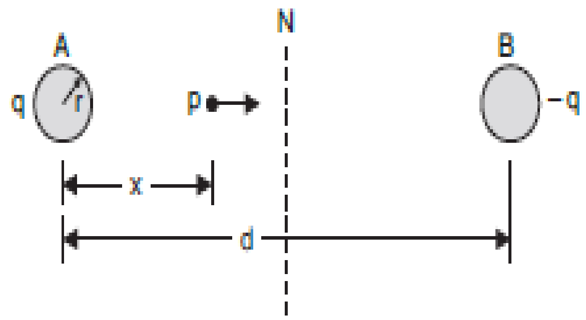
These electrons will collide with the molecules of air and in case the speed is large, they will dislodge electrons from these molecules, thereby the number of electrons will increase. The process of ionization is thus cumulative and ultimately forms an electron avalanche. This results in ionization of the air surrounding the conductor. In case the ratio of spacing between conductors to the radius of the conductor is less than 15, flash over will occur between the conductors before corona phenomenon occurs. Usually for overhead lines this ratio is far more than this number and hence flash-over can be regarded as impossible.

Corona phenomenon is, therefore, defined as a self-sustained electric discharge in which the field intensified ionization is localized only over a portion of the distance between the electrodes.

When a voltage higher than the critical voltage is applied between two parallel polished wires, the glow is quite even. After operation for a short time, reddish beads or tufts form along the wire, while around the surface of the wire there is a bluish white glow. If the conductors are examined through a stroboscope, so that one wire is always seen when at a given half of the wave, it is noticed that the reddish tufts or beads are formed when the conductor is negative and a smoother bluish white glow when the conductor is positive. The a.c. corona, viewed through a stroboscope, has the same appearance as direct current corona. As corona phenomenon is initiated, a hissing noise is heard and ozone gas is formed which can be detected by its characteristic odour.

Let r be the radius of each conductor and d the distance of separation such that $d >> r$. Since it is a single-phase transmission line, let q be the charge per unit length on one of the conductors and hence $-q$ on the other. If the operating voltage is V, the potential of conductor A with respect to neutral plane N will be $V/2$ and that of B will be $-V/2$. Consider a point P at a distance x where we want to find the electric field intensity. Bring a unit positive charge at P.

The field due to A will be repulsive and that due to B will be attractive; thereby the electric field intensity at P due to both the line charges will be additive and it will be



$$E_x = \frac{q}{2\pi\varepsilon_0 x} + \frac{q}{2\pi\varepsilon_0 (d-x)} = \frac{q}{2\pi\varepsilon_0}\left[\frac{1}{x} + \frac{1}{d-x}\right]$$

The potential difference between the conductors

$$V = -\int_{d-r}^{r} E_x dx = \int_{r}^{d-r} \frac{q}{2\pi\varepsilon_0}\left[\frac{1}{x} + \frac{1}{d-x}\right] dx$$

$$= \frac{q}{2\pi\varepsilon_0}\Big[\ln x - \ln (d-x)\Big]_r^{d-r}$$

$$= \frac{q}{2\pi\varepsilon_0} \cdot 2 \ln \frac{d-r}{r} = \frac{q}{\pi\varepsilon_0} \ln \frac{d-r}{r}$$

Since r is very small as compared to d, $d - r \simeq d$.

$\therefore$ $$V = \frac{q}{\pi\varepsilon_0} \ln \frac{d}{r}$$

Now gradient at any point x from the centre of the conductor A is given by

$$E_x = \frac{q}{2\pi\varepsilon_0}\left[\frac{1}{x} + \frac{1}{d-x}\right]$$

$$= \frac{q}{2\pi\varepsilon_0} \cdot \frac{d}{x(d-x)}$$

Substituting for q from the above equation,

$$q = \frac{\pi\varepsilon_0 V}{\ln \frac{d}{r}}$$

$$E_x = \frac{\pi\varepsilon_0 V}{\ln \frac{d}{r}} \cdot \frac{1}{2\pi\varepsilon_0} \cdot \frac{d}{x(d-x)}$$

$$= \frac{V}{2 \ln \frac{d}{r}} \cdot \frac{d}{x(d-x)}$$

$$= \frac{V' d}{x(d-x) \ln \frac{d}{r}}$$

Here V' is the line to neutral voltage of the system. In case of 3-phase system

$$V' = \frac{V_L}{\sqrt{3}}$$

where *VL* is the line to line voltage.

From the expression for the gradient it is clear that for a given transmission system the gradient increases as *x* decreases *i.e.*, the gradient is maximum when *x* = *r*, the surface of the conductor, and this value is given by

$$g_{max} = E_r = E_{max} = \frac{V' d}{r(d-r) \ln \frac{d}{r}}$$

$$\simeq \frac{V'}{r \ln \frac{d}{r}}$$

$$V' = r g_{max} \ln \frac{d}{r}$$

Critical disruptive voltage is defined as the voltage at which complete disruption of dielectric occurs. This voltage corresponds to the gradient at the surface equal to the breakdown strength of air. This dielectric strength is normally denoted by *g*0 and is equal to 30 kV/cm peak at NTP *i.e.*, 25°C and 76 cm of Hg.

At any other temperature and pressure

$$g_0' = g_0 \cdot \delta$$

Where g is the air density correction factor and is given by

$$\delta = \frac{3.92b}{273 + t}$$

where *b* is the barometric pressure in cm of Hg and *t* the temperature in °C.

Therefore, the critical disruptive voltage is given by

$$V' = r g_0 \, \delta \ln \frac{d}{r} \text{ kV}$$

In deriving the above expression, an assumption is made that the conductor is solid and the surface is smooth. For higher voltages ACSR conductors are used. The cross-section of such a conductor is a series of arcs of circles each of much smaller diameter than the conductor as a whole. The potential gradient for such a conductor will, in consequence, be greater than for the equivalent smooth conductor, so that the breakdown voltage for a stranded conductor will be somewhat less than for a smooth conductor. The irregularities on the surface of such a conductor are increased further because of the deposition of dust and dirt on its surface and the breakdown voltage is further reduced. An average value for the ratio of breakdown voltage for such a conductor and a smooth conductor lies between 0.85 to unity and is denoted by *m*0. Suitable values of *m*0 are given below:

Polished wires	1.0
Roughened or weathered wires	0.98 to 0.93
Seven strand cable	0.87 to 0.83
Large cables with more than seven strands	0.90 approx.

The final expression for the critical disruptive voltage after taking into account the atmospheric conditions and the surface of the conductor is given by

$$V' = r g_0 \delta m_0 \ln \frac{d}{r} \text{ kV}$$

When the voltage applied corresponds to the critical disruptive voltage, corona phenomenon starts but it is not visible because the charged ions in the air must receive some finite energy to cause further ionization by collisions. For a radial field, it must reach a gradient *gv* at the surface of the conductor to cause a gradient *g*0, a finite distance away from the surface of the conductor. The distance between *gv* and *g*0 is called the energy distance. According to Peek this distance is equal to (*r* + 0.301 *r*) for two parallel conductors and (*r* + 0.308 *r*) for co-axial conductors. From this it is clear that *gv* is not constant as *g*0 is, and is a function of the size of the conductor.

$$g_v = g_0\delta\left(1+\frac{0.3}{\sqrt{r\delta}}\right) \text{ kV/cm for two wires in parallel.}$$

Also if V_v is the critical visual disruptive voltage, then

$$V_v = g_v r \ln\frac{d}{r}$$

or

$$g_v = \frac{V_v}{r\ln\frac{d}{r}} = g_0\delta\left(1+\frac{0.3}{\sqrt{r\delta}}\right)$$

or

$$V_v = rg_0\delta\left[1+\frac{0.3}{\sqrt{r\delta}}\right]\ln\frac{d}{r} \text{ kV}$$

In case the irregularity factor is taken into account,

$$V_v = g_0 m_v\, \delta r\left[1+\frac{0.3}{\sqrt{r\delta}}\right]\ln\frac{d}{r}$$

$$= 21.1 m_v\, \delta r\left[1+\frac{0.3}{\sqrt{r\delta}}\right]\ln\frac{d}{r} \text{ kV r.m.s.}$$

where *r* is the radius in cms. The irregularity factor *mv* has the following values:

mv = 1.0 for polished wires = 0.98 to 0.93 for rough conductor exposed to atmospheric severities = 0.72 for local corona on stranded conductors.

Since the surface of the conductor is irregular, the corona does not start simultaneously on the whole surface but it takes place at different points of the conductor which are pointed and this is known as local corona. For this *mv* = 0.72 and for decided corona or general corona *mv* = 0.82.

MCQ – Post Test

1. The presence of earth in case of overhead lines
   a. Increase the capacitance
   b. Increase the inductance
   c. Decrease the capacitance
   d. Decrease the inductance
   Ans: a

2. If earth effect is taken into account then the capacitance of line to ground
   a. Decrease
   b. Increase
   c. Remains same
   d. Becomes infinitive
   Ans: b

3. Which of the voltage system is in high tension cable
   a. Upto 11 kv
   b. 11 -20 kv
   c. Above 33 kv
   d. All the above
   Ans: a

4. Operation voltage of super tension cable is
   a. Upto 11 kv
   b. 11 -33 kv
   c. 33 – 66 kv
   d. Above 66 kv
   Ans: b

5. Extra HT cable is upto
   a. 11 kv
   b. 33 kv
   c. 66 kv
   d. 66 kv above
   Ans: c

Summary

The overview of L, C, R in transmission system well studied along with conductor spacing in transmission system, Corona effect also studied along with proximity effect.

Reference

1. C.L.Wadhva, Generation Distribution and Utilization of Electrical Energy, New Age International Publishers ltd.-New Delhi
2. V.K Mehta, Principle of Power Systems, S.Chand Publishers, New Delhi

Audio / video resources

https://www.youtube.com/watch?v=m-jeQgXAqJA

Assignment

1. Explain corona effect along with influencing factors.
2. Explain the capacitive effect of conductors in bundled way.

Name of the Course **: Generation Transmission and Distribution**

Name of the unit **: Performance of Over Head Line**

Topic – Title **: Efficiency of transmission line and shunt & series compensation**

Aim and Objective

Efficiency of short, medium and long transmission lines and series & shunt compensation effects also in the study.

Pre-requisites

Outline of transmission lines and L, C effects in transmission lines

Pre – Test MCQ

1. The power transmission will be maximum when
   a. Corona loss minimum
   b. Receiving voltage minimum
   c. Reactance is high
   d. Sending end voltage high
   Ans: a

2. Corona discharge occurs were in
   a. Humid
   b. Hot
   c. Cold
   d. All
   Ans:a

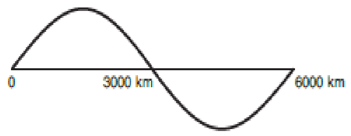
3. Receive end voltage is rising than sending voltage is called
   a. Raman effect
   b. Skin effect
   c. Corona effect
   d. Ferrantie effect
   Ans: d

4. Proximity effect is based on
   a. Magnetic Flux
   b. Voltage
   c. Current
   d. Power
   Ans: a

5. What is the value of shunt capacitance in medium line
   a. High
   b. Medium
   c. Zero
   d. All the above
   Ans: b

Theory

A transmission line is a set of conductors being run from one place to another supported on transmission towers. Such lines, therefore, have four distributed parameters, series resistance and inductance, and shunt capacitance and conductance. It will be shown later on in this chapter that the voltages and currents vary harmonically along the line with respect to the distance of the point under consideration. This observation is very important in representing the lines of different lengths. It is to be noted that the electrical power is being transmitted over the overhead lines at approximately the speed of light. In order to get one full wave variation of voltage or current on the line the length of the line for 50 Hz supply will be given by



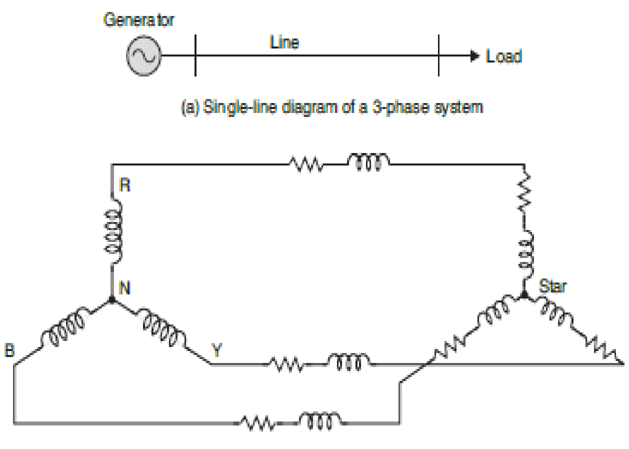
$$f \cdot \lambda = v$$

where *f* is frequency of supply, u the wavelength *i.e.*, the length of the line in this case and *v* the velocity of the wave *i.e.*, the velocity of light. Substituting for *f* = 50 and *v* = 3 × 108 m/sec.,

$$\lambda = \frac{v}{f} = \frac{3 \times 10^8}{50} = 6 \times 10^6 \text{ metres}$$

$$= 6000 \text{ km.}$$

This means that if the length of the line is 6000 km the voltage or current wave at the two ends of the line will be as shown in Figure.



(a) Single-line diagram of a 3-phase system

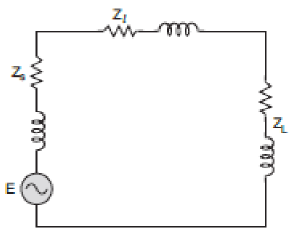
(b) 3-phase diagram of (a)

For line lengths less than about 160 km, the voltage or current variation on the line is not much and it can be said that for line length of about 160 km the parameters could be assumed to be lumped and not distributed. Such lines are known as electrically short transmission lines. In power systems these electrically short transmission lines are again categorised as short transmission lines and medium transmission lines. The lines up to about 80 km are termed as short transmission lines where the effect of shunt capacitance is neglected and the lines above 80 km and below 160 km length are termed as medium length lines. For medium length lines the shunt capacitance can be assumed to be lumped at the middle of the line or half of the shunt capacitance may be considered to be lumped at each end of the line. The two representations of medium length lines are termed as nominal-*T* and nominal- respectively. For line lengths more than 160 km the parameters are distributed and rigorous calculations are required to be made except in certain cases where lines up to 250 km can be analysed using nominal-representation.

A typical 3-phase system is shown in Fig. A 3-phase star load is connected to the generator through a 3-phase transmission system. The 3-phase system is normally balanced system irrespective of the fact that the conductors are not transposed, as the untransposed conductors introduce slight dissymmetry which can be ignored for all practical purposes.

It is known that the sum of all the currents in a balanced polyphase network is zero and, therefore, the current through the wire connected between the star point of the load and neutral of the system is zero. This means that the star point of the load and neutral of the system are at the same potential.

A 3-phase balanced system can, therefore, be analysed on single-phase basis in which the neutral wire is of zero impedance. The equivalent single-phase representation of Fig. is shown in Fig.



The equivalent circuit and vector diagram for a short transmission line are shown in Fig. The vector diagram is drawn taking *Ir*, the receiving end current, as the reference. From the vector diagram,

From the vector diagram,

$$V_s \cos\phi_s = V_r \cos\phi_r + I_r R$$

$$V_s \sin\phi_s = V_r \sin\phi_r + I_r X$$

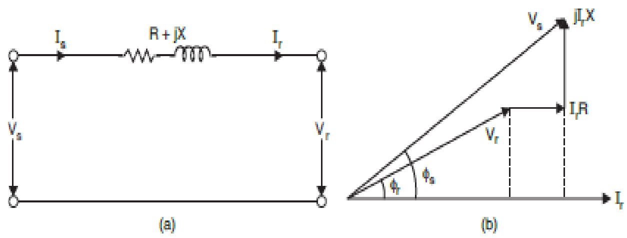
Squaring and adding equations (4.2*a*) and (4.2*b*),

$$V_s^2 = V_r^2 + 2I_r R V_r \cos\phi_r + 2I_r X V_r \sin\phi_r + I_r^2(R^2 + X^2)$$

$$V_s = V_r \sqrt{1 + \frac{2I_r R \cos\phi_r}{V_r} + \frac{2I_r X \sin\phi_r}{V_r} + \frac{I_r^{\,2}}{V_r^{\,2}}(R^2 + X^2)}$$

In practice the last term under the square root sign is generally negligible;

$$V_s = V_r \left\{1 + \left(\frac{2I_r R}{V_r}\cos\phi_r + \frac{2I_r X}{V_r}\sin\phi_r\right)\right\}^{1/2}$$



The terms within the simple brackets is small as compared to unity. Using binomial expansion and limiting only to second term,

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

Here *Vs* is the sending end voltage corresponding to a particular load current and power factor condition. It can be seen from the equivalent circuit of short line that the receiving end voltage under no load *Vr′*is the same as the sending end voltage under full load condition, *i.e.*,

$$V_r' = V_s$$

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

$$= \left(\frac{I_r R}{V_r}\cos\phi_r + \frac{I_r X}{V_r}\sin\phi_r\right) \times 100$$

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

$$= v_r \cos\phi_r + v_x \sin\phi_r$$

where *vr* and *vx* are the per unit values of resistance and reactance of the line. It will be shown later on in this chapter that in a four terminal passive network the voltage and current on the receiving end and sending end are related by the following pair of equations:

$$V_s = AV_r + BI_r$$
$$I_s = CV_r + DI_r$$

where *A, B, C, D* are called the constants of the network. The transmission line is also a fourterminal network and it is now desired to find these constants for short transmission line. Before these constants are determined it is desirable to understand what these constants are. From equation (4.8),

$$A = \left.\frac{V_s}{V_r}\right|_{I_r = 0}$$

This means *A* is the voltage impressed at the sending end per volt at the receiving end when receiving end is open. It is dimensionless.

$$B = \left.\frac{V_s}{I_r}\right|_{V_r = 0}$$

B is the voltage impressed at the sending end to have one ampere at the short circuited receiving end. This is known as transfer impedance in network theory.

$$C = \left.\frac{I_s}{V_r}\right|_{I_r = 0}$$

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

$$D = \left.\frac{I_s}{I_r}\right|_{V_r = 0}$$

D is the current at the sending end for one ampere of current at the short circuited receiving end. The constants *A, B, C* and *D* are related for a passive network as follows:

$AD – BC = 1$

This relation provides a good check on the values of these constants. The sending end voltage and current can be written from the equivalent network as

$$V_s = V_r + I_r Z$$
$$I_s = I_r$$

Comparing the coefficients of equations, the constants for short transmission line are

$A = 1$
$B = Z$
$C = 0$
$D = 1$

Checking the values of *A, B, C* and *D* with the relation

$AD – BC = 1$
$1 . 1 – Z . 0 = 1$

So, the values calculated are correct for a short transmission line. The *ABCD* constants can be used for calculation of regulation of the line as follows:

Normally the quantities *P, Ir* and cos*r* at the receiving end are given and of course the *ABCD* constant. Then determine sending end voltage using relation

$$V_s = AV_r + BI_r$$

To determine *Vr′* the no load voltage at the receiving end, equation (4.8) is made use of

$$V_r' = \frac{V_s}{A}, \text{ when } I_r = 0$$
$$\% \text{ regulation} = \frac{V_s / A - V_r}{V_r} \times 100$$

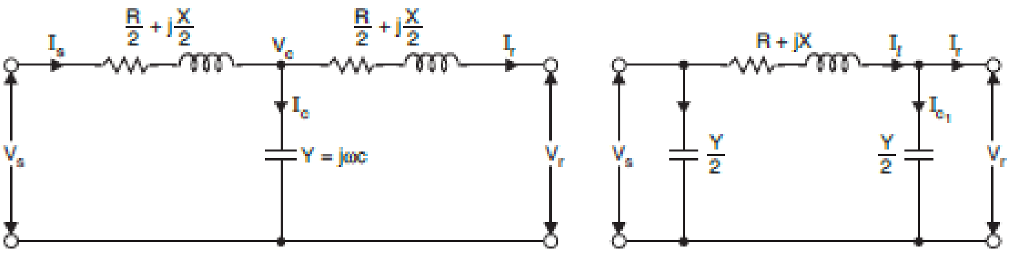
is thus evaluated.
To determine % of transmission, the following relation is made use of:

$$\% \eta = \frac{\text{Power received at the receiving end}}{\text{Power received at the receiving end + losses}} \times 100$$
$$= \frac{P}{P + 3I_r^2 R} \times 100$$

where *R* is the resistance per phase of the line.

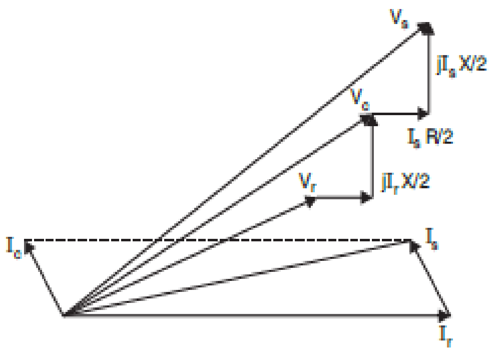
It has been mentioned previously that transmission lines with lengths between 80 km and 160 km are categorised as medium length lines where the parameters are assumed to be lumped. The shunt capacitance is either assumed to be concentrated at the middle of the line or half of the total capacitance is concentrated at each end of the line. The two configurations are known as nominal-*T* and nominal-□□respectively. The nominal circuits are shown in Figs. 4.5 (*a*) and(*b*).

It is to be noted that the two representations are approximate to the exact representation of the actual line. Also the two representations are not equivalent as can be seen by using the star-delta transformations. However, they are good enough for practical purposes and do not involve much error.



(a) Nominal-T (b) Nominal-π

The vector diagram for lagging power factor load is shown in Fig.. While analysing the medium length lines using nominal-*T*, it is preferable to take receiving end current as the reference vector as the calculations become relatively easier as compared to taking *Vr* as the reference.



For calculating regulation of the line refer to Fig. 4.5(*a*). The objective first is to calculate *Vs* which is done as follows:

$$V_c = (|V_r|\cos\phi_r + j.|V_r|\sin\phi_r) + I_r\left(\frac{R}{2} + j\frac{X}{2}\right)$$

$$I_c = j\omega C V_c$$

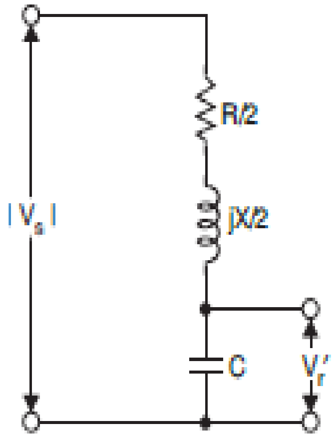
$$I_s = I_c + I_r = I_r + j\omega C V_c$$

$$V_s = V_c + I_s\left(\frac{R}{2} + j\frac{X}{2}\right)$$

$$= (|V_r|\cos\phi_r + j|V_r|\sin\phi_r) + I_r\left(\frac{R}{2} + j\frac{X}{2}\right) + I_s\left(\frac{R}{2} + j\frac{X}{2}\right)$$

To calculate regulation it is required to calculate *Vr′* the receiving end no load voltage keeping *Vs* as calculated above fixed in magnitude. The nominal-*T* circuit for this condition reduces to the following:

$$V_r' = \frac{|V_s|\left(-\frac{j}{\omega C}\right)}{\frac{R}{2} + j\frac{X}{2} - \frac{j}{\omega C}}$$



Now the regulation for nominal-*T* can be obtained as % Regulation

$$\frac{V_r' - V_r}{V_r} \times 100$$

To determine efficiency of the line it is suggested to make use of the following formula:

$$\%\ \eta = \frac{\text{Power delivered at the receiving end}}{\text{Power delivered at the receiving end + loss}} \times 100$$

The other formula is

$$\%\ \eta = \frac{\text{Power delivered at the receiving end}}{\text{Power sent at the sending end}}$$

A small error in evaluating phase angle between sending end voltage and current will lead to inaccurate calculation of efficiency. Therefore, it is suggested to make use of the first formula.

$$\%\ \eta = \frac{P}{P + 3\frac{R}{2}(I_r^2 + I_s^2)} \times 100$$

where *P* is the 3-phase power delivered at the receiving end, *R* is the resistance per phase. In order to determine *A, B, C, D* constants for nominal-*T*.

$$V_c = V_r + I_r \frac{Z}{2}$$
$$I_c = V_c Y$$
$$I_s = I_r + I_c = I_r + V_c Y = I_r + \left(V_r + I_r \frac{Z}{2}\right) Y$$
$$V_s = V_c + I_s \frac{Z}{2} = V_r + I_r \frac{Z}{2} + \left\{I_r + \left(V_r + I_r \frac{Z}{2}\right)Y\right\} \cdot \frac{Z}{2}$$
$$= V_r \left(1 + \frac{YZ}{2}\right) + I_r \left(\frac{Z}{2} + \frac{Z}{2} + \frac{YZ^2}{4}\right)$$
$$= V_r \left(1 + \frac{YZ}{2}\right) + I_r \left(Z + \frac{YZ^2}{4}\right)$$
$$V_s = V_r \left(1 + \frac{YZ}{2}\right) + I_r Z \left(1 + \frac{YZ}{4}\right)$$
$$I_s = I_r \left(1 + \frac{YZ}{2}\right) + V_r Y$$
$$= YV_r + \left(1 + \frac{YZ}{2}\right) I_r$$

Writing down the voltage and current equation,

$$V_s = AV_r + BI_r$$
$$I_s = CV_r + DI_r$$

Comparing the coefficients of equations (4.17) to (4.20)

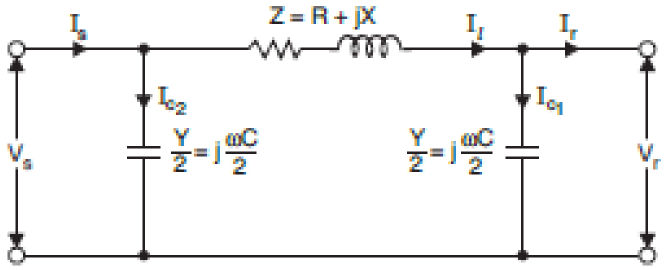
$$A = 1 + \frac{YZ}{2}$$
$$B = Z\left(1 + \frac{YZ}{4}\right)$$
$$C = Y$$
$$D = \left(1 + \frac{YZ}{2}\right)$$

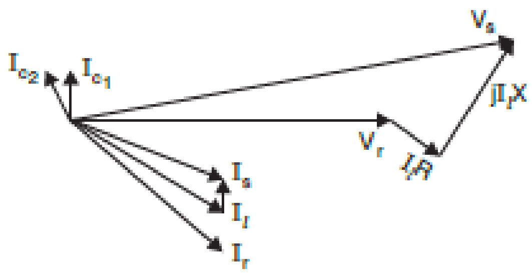
From above it is clear that $A = D$ and

$$AD - BC = \left(1 + \frac{YZ}{2}\right)^2 - YZ\left(1 + \frac{YZ}{4}\right)$$
$$= 1 + \frac{Y^2Z^2}{4} - YZ - YZ - \frac{Y^2Z^2}{4}$$
$$= 1$$

Therefore, the constants as obtained above are correct.

The circuit and its vector diagrams are shown in Figs. 4.8 (*a*) and (*b*).
For nominal-□□it is desirable to take receiving end voltage as the reference vector. Refer to Fig. 4.8 (*b*) for calculating *Vs*.





$$I_{c_1} = jV_r \frac{\omega C}{2}$$

$$I_l = |I_r| (\cos\phi_r - j\sin\phi_r) + jV_r \frac{\omega C}{2}$$

$$V_s = V_r + I_l Z$$

$$= V_r + \left\{|I_r|(\cos\phi_r - j\sin\phi_r) + jV_r \frac{\omega C}{2}\right\}(R + jX)$$

$$I_s = I_l + I_{c_2} = I_l + jV_s \frac{\omega C}{2}$$

$$I_s = |I_r| (\cos\phi_r - j\sin\phi_r) + jV_r \frac{\omega C}{2} + j\frac{\omega C}{2}\left[V_r + \left\{|I_r|(\cos\phi_r - j\sin\phi_r) + jV_r \frac{\omega C}{2}\right\}(R + jX)\right]$$

Having calculated the sending end voltage, it is required to find out no load receiving end voltage for regulation keeping sending end voltage constant in magnitude.

$$V_r' = \frac{|V_s|\left(-\frac{2j}{\omega C}\right)}{R + jX - \frac{j}{\omega C/2}}$$

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

$$\% \eta = \frac{P}{P + 3I_l^2 R} \times 100$$

To determine *A*, *B*, *C*, *D* constants for nominal-refer to Fig.(*a*).

$$I_{c_1} = V_r \frac{Y}{2}$$

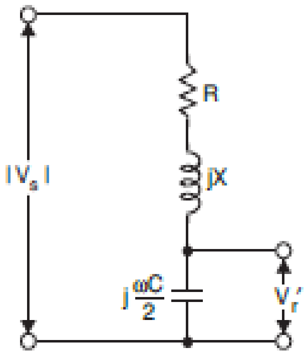
$$I_l = I_r + I_{c_1} = I_r + V_r \frac{Y}{2}$$

$$V_s = V_r + I_l Z = V_r + \left(I_r + V_r \frac{Y}{2}\right) Z$$

$$= \left(1 + \frac{YZ}{2}\right) V_r + Z I_r$$

$$I_s = I_l + I_{c_2} = I_l + V_s \frac{Y}{2} = I_r + V_r \frac{Y}{2} + \left\{V_r\left(1 + \frac{YZ}{2}\right) + ZI_r\right\}\frac{Y}{2}$$

$$= V_r\left(Y + \frac{Y^2 Z}{4}\right) + \left(1 + \frac{YZ}{2}\right) I_r$$



Comparing the coefficients of equations,

$$A = 1 + \frac{YZ}{2}$$
$$B = Z$$
$$C = Y\left(1 + \frac{YZ}{4}\right)$$
$$D = \left(1 + \frac{YZ}{2}\right)$$

From above it is clear that

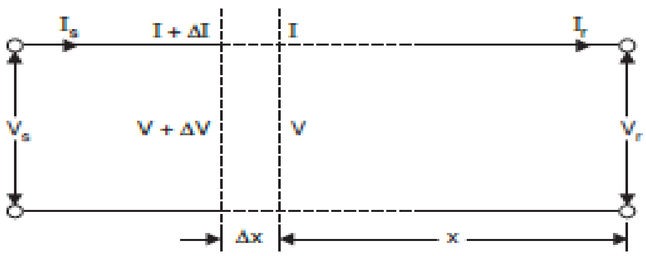
$$A = D$$

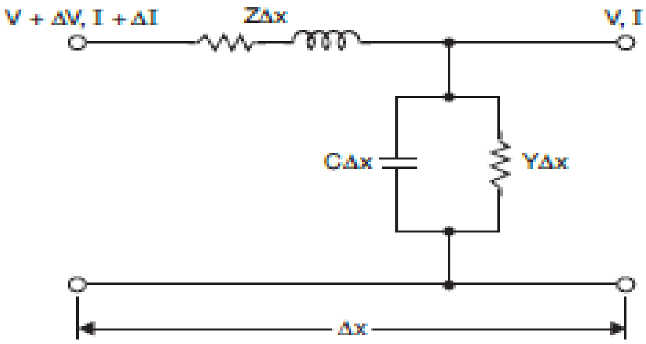
$$AD - BC = 1 + \frac{Y^2Z^2}{4} + YZ - YZ - \frac{Y^2Z^2}{4} = 1$$

which means that the values of *A*, *B*, *C* and *D* are correct.

So far electrically short transmission lines less than 160 km in length have been considered wherein the parameters are assumed to be lumped. In case the lines are more than 160 km long, for accurate solutions the parameters must be taken as distributed uniformly along the length as a result of which the voltages and currents will vary from point to point on the line. Consider for analysis.

z = series impedance per unit length
y = shunt admittance per unit length
l = length of the line
$Z = zl$ = total series impedance
$Y = yl$ = total shunt admittance
For clearity the elemental length dx is redrawn .
For analysis we shall take the receiving end as the reference for measuring distances.
Take an elemental length dx of the line at a distance of x from the receiving end. Say the voltage and current at a distance x are V and I respectively.





$$\Delta V = Iz\,\Delta x$$

$$\Delta I = Vy\,\Delta x$$

From equation (4.26)

$$\frac{\Delta V}{\Delta x} = Iz$$

$$\frac{\Delta I}{\Delta x} = Vy$$

which in the limit when $\Delta x \to 0$ reduce to

$$\frac{dV}{dx} = Iz$$

$$\frac{dI}{dx} = Vy$$

Differentiating equation (4.28), we get

$$\frac{d^2V}{dx^2} = z\frac{dI}{dx} = z\,.\,y\,.\,V$$

or

$$\frac{d^2V}{dx^2} - zyV = 0$$

The solution of this equation is

$$V = A\exp(\sqrt{yz}\,.x) + B\exp(-\sqrt{yz}\,.x)$$

Now, from equations (4.28) and (4.31) let

$$Z_c = \sqrt{\frac{z}{y}} \text{ and } \gamma = \sqrt{yz} = \alpha + j\beta$$

where Z_c is known as characteristic impedance and γ the propagation constant.

The equations (4.31) and (4.32) are rewritten as

$$V = Ae^{\gamma x} + Be^{-\gamma x}$$

$$I = \frac{I}{Z_c}(Ae^{\gamma x} - Be^{-\gamma x})$$

Two constants are to be determined, hence two boundary conditions should be known. As mentioned previously the receiving end voltage and current are known.

$\therefore$ At $x = 0$,

$$V = V_r \quad \text{and} \quad I = I_r$$

Substituting these values in equations (4.33) and (4.34),

$$V_r = A + B$$

$$I_r = \frac{1}{Z_c}(A - B)$$

$$A = \frac{V_r + I_r Z_c}{2} \text{ and } B = \frac{V_r - I_r Z_c}{2}$$

Substituting the values of A and B in equations (4.33) and (4.34), we obtain

$$V = \frac{V_r + I_r Z_c}{2} e^{\gamma x} + \frac{V_r - I_r Z_c}{2} e^{-\gamma x}$$

and

$$I = \frac{1}{Z_c}\left[\frac{V_r + I_r Z_c}{2} e^{\gamma x} - \frac{V_r - I_r Z_c}{2} e^{-\gamma x}\right]$$

As mentioned previously *V* and *I* are the voltage and current at any point distant *x* from the receiving end. It can be seen very easily from the above expression that *V* and *I* (magnitude and phase) are functions of the distance *x*, receiving end voltage *Vr* and current *Ir* and the parameters of the line, which means they vary as we move from receiving end towards the sending end.

Before we proceed further to determine the equivalent circuit for a long transmission line it looks imperative to understand the physical significance of the voltage and current equations.

$$Z_c = \sqrt{\frac{z}{y}} = \sqrt{\frac{r + j\omega L}{g + j\omega C}}$$

For a lossless line $r = 0$, $g = 0$,

$$Z_c = \sqrt{\frac{L}{C}}$$

a pure resistance, and this is known as surge impedance of the line. When dealing with high frequencies or surges normally the losses are neglected and, therefore, the characteristic impedance becomes the surge impedance. Surge impedance loading of a line is the power transmitted when the line is terminated through a resistance equal to surge impedance. The approximate value of surge impedance for overhead lines is 400 ohms and that for cables is about 40 ohms. The phase angle of *Zc* for transmission lines is usually between 0° and –15°.

A line terminated in its characteristic impedance is called a flat line or an infinite line. The latter term arises from the fact that a line of infinite length cannot have a reflected wave. The lower value of surge impedance in case of cables is due to the relatively large capacitance and low inductance of the cables.

$$V = \frac{V_r + I_r Z_c}{2} e^{\alpha x} . e^{j\beta x} + \frac{V_r - I_r Z_c}{2} e^{-\alpha x} . e^{-j\beta x}$$

The first term in the above expression is called the incident voltage wave as its value increases as *x* is increased. Since we are taking receiving end as the reference and as *x* increases the value of voltage increases that means a voltage wave decreases in magnitude as it travels from the sending end towards the receiving end, that is why this part of the voltage in the above expression is called incident voltage. For similar reason the second part is called the reflected voltage. At any point along the line, voltage is the sum of these two components *i.e.*, sums of incident and reflected voltages. As the current expression is similar to the voltage, the current can also be considered as sum of incident and reflected current waves. The equations for voltage and currents can be rearranged as follows:

$$V = V_r \cdot \frac{e^{\gamma x} + e^{-\gamma x}}{2} + I_r Z_c \frac{e^{\gamma x} - e^{-\gamma x}}{2}$$

$$= V_r \cosh \gamma x + I_r Z_c \sinh \gamma x$$

and

$$I = \frac{1}{Z_c}\left[V_r \frac{e^{\gamma x} - e^{-\gamma x}}{2} + I_r Z_c \frac{e^{\gamma x} + e^{-\gamma x}}{2}\right]$$

$$= \frac{1}{Z_c}[V_r \sinh \gamma x + I_r Z_c \cosh \gamma x]$$

$$= \frac{V_r}{Z_c} \sinh \gamma x + I_r \cosh \gamma x$$

Rewriting these equations for $x = l$, where $V = V_s$ and $I = I_s$

$$V_s = V_r \cosh \gamma l + I_r Z_c \sinh \gamma l$$

$$I_s = V_r \frac{\sinh \gamma l}{Z_c} + I_r \cosh \gamma l$$

These two equations relate the sending end voltage and current with the receiving end quantities. We have said previously that these quantities are related by the general equations.

$$V_s = AV_r + BI_r$$
$$I_s = CV_r + DI_r$$

where *A*, *B*, *C* and *D* are such that $A = D$ and $AD - BC = 1$ Comparing the coefficients of the equations and respectively,

$$A = \cosh \gamma l$$

$$B = Z_c \sinh \gamma l$$

$$C = \frac{\sinh \gamma l}{Z_c}$$

and

$$D = \cosh \gamma l$$

From this it is clear that

$$A = D = \cosh \gamma l$$

and

$$AD - BC = \cosh^2 \gamma l - Z_c \sinh \gamma l \cdot \frac{\sinh \gamma l}{Z_c} = 1.$$

When a long line is operating under no load or light load condition, the receiving end voltage is greater than the sending end voltage. This is known as Ferranti-effect. This phenomenon can be explained with the following reasonings:

(*i*) Assume no load condition. The equation (4.37)

$$V = \frac{V_r + I_r Z_c}{2} e^{\alpha x} e^{j\beta x} + \frac{V_r + I_r Z_c}{2} e^{-\alpha x} e^{-j\beta x}$$

reduces to:

$$V_s = \frac{V_r}{2} e^{\alpha l} e^{j\beta l} + \frac{V_r}{2} e^{-\alpha l} e^{-j\beta l}$$

when $x = l$ and $I_r = 0$.

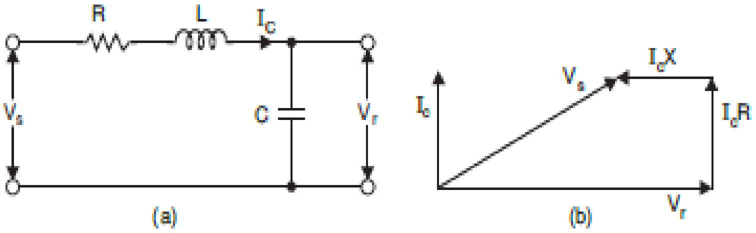
At $l = 0$

$$V_r = \frac{V_r}{2} + \frac{V_r}{2}$$

As *l* increases, the incident component of sending end voltage increases exponentially and turns the vector anti-clockwise through an angle *l*, whereas the reflected part of sending end voltage decreases by the same amount and is rotated clockwise through the same angle *l*. The sum of these two components of sending end voltage gives a voltage which is smaller than *Vr*.

(*ii*) A simple explanation of Ferranti-effect can be given by approximating the distributed parameters of the line by lumped impedance as shown in Fig. (*a*).

Since usually the capacitive reactance of the line is quite large as compared to the inductive reactance, under no load or lightly loaded condition the line current is of leading p.f. The phasor diagram is given below for this operating condition.



The charging current produces drop in the reactance of the line which is in phase opposition to the receiving end voltage and hence the sending end voltage becomes smaller than the receiving end voltage.

Yet another way of explaining the Ferranti-effect is based on the net reactive power flow on the line. It is known that if the reactive power generated at a point is more than the reactive power absorbed, the voltage at that point becomes higher than the normal value and vice versa. The inductive reactance of the line is a sink for the reactive power whereas the shunt capacitances generate reactive power. In fact, if the line loading corresponds to the surge impedance loading, the voltage is same everywhere as the reactive power absorbed then equals the reactive power generated by the line. The SIL, therefore, gives definite meaning to the terms lightly loaded or fully loaded lines. If the loading is less than SIL, the reactive power generated is more than absorbed, therefore, the receiving end voltage is greater than the sending end voltage. This explains, therefore, the phenomenon due to Ferranti-effect.

MCQ – Post Test

1. Performance of medium lines done by
   a. Reactance diagram
   b. Neglecting line inductance
   c. Neglecting line capacitance
   d. Per phase basis
   Ans: d

2. The conductors of the overhead lines are
   a. Stranded
   b. Solid
   c. Both
   d. None of the above
   Ans: a
3. In transmission line cross arm made of
   a. Steel
   b. Wood
   c. RCC
   d. Steel or wood
   Ans: d
4. Spacing between phase conductors of a 220kv line is approximately
   a. 2 m
   b. 3.5 m
   c. 6 m
   d. 8.5 m
   Ans: c
5. Minimum clearance between ground and 220 kv line is ___________
   a. 1 m
   b. 7 m
   c. 10 m
   d. 5 m
   Ans: b

Summary

Performance and efficiency in short, medium and long transmission lines are compared and compensatory (series, shunt) circuits are analysed.

References

1. C.L.Wadhva, Generation Distribution and Utilization of Electrical Energy, New Age International Publishers ltd.-New Delhi
2. V.K Mehta, Principle of Power Systems, S.Chand Publishers, New Delhi

Assignment

1. Explain Ferrantie effect with phasor diagram.
2. Find ABCD parameters of 3ph 80 km 50hz line with series impedance (0.15 + j0.78) Ω./km and shunt admittance of j5 * 10^{-6} Ω./km.
3. Determine efficiency and Π equivalent of the above problem and surge impedance and propagation constant also.

Name of the Course **: Generation Transmission and Distribution**

Name of the unit **: Under Ground Cables and Insulators**

Topic – Title **: Study of grading of cables and insulators**

Aim and Objective

Study of grading of cables and insulators in detail.

Pre-requisites

Dielectric properties of cables and insulators properties (chemical and mechanical).

Pre – Test MCQ

1. Voltage in single phase supply to residential
   a. 110
   b. 230
   c. 440
   d. All the above
   Ans: b

2. High voltage transmission line use
   a. Suspension insulator
   b. Pin insulator
   c. Any of the above
   d. None
   Ans: a

3. Insulation used in high voltage cables
   a. Rubber
   b. Paper
   c. lead
   d. Iron
   Ans: b

4. Materials commonly used for sheath of cables is
   a. Lead
   b. Rubber
   c. Copper
   d. Iron
   Ans: a

5. Which is the best voltage regulation
   a. 10 %
   b. 20 %
   c. 100 %
   d. 4 %
   Ans: d

Theory

High Voltage Cables

The dielectric material surrounds the conductor and we know that every dielectric material has certain dielectric strength which, if exceeded, will result in rupture of the dielectric. In general the disruptive failure can be prevented by designing the cable such that the maximum electric stress (which occurs at the surface of the conductor) is below that required for short time puncture of the dielectric. In case the potential gradient is taken a low value, the overall size of the cable above 11 kV becomes relatively large. Also, if the gradient is taken large to reduce the overall size of the cable the dielectric losses increase very much which may result in thermal breakdown of the cable. So a compromise between the two has to be made and normally the value of working stress is taken about one-fifth of the breakdown value for design purposes.

Electrostatic Stresses in Single Core Cable

Let r be the radius of the conductor, R the inner radius of the sheath, ϵ the permittivity of the dielectric, λ the charge per unit length, V the potential of the conductor with respect to the sheath and g the gradient at a distance x from the centre of the conductor within the dielectric material. $g = \frac{\lambda}{2\pi\varepsilon x} = E$, where E is the electric field intensity.

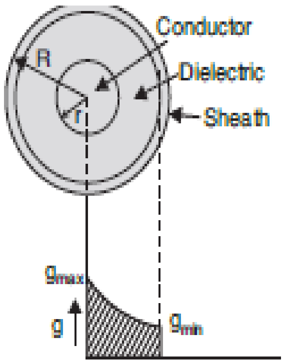


Fig. 9.1 Electric stress in a single core cable.

Now $$V = -\int_R^r E\,dx = \int_r^R \frac{\lambda}{2\pi\varepsilon x}\,dx$$

$$= \frac{\lambda}{2\pi\varepsilon} \ln \frac{R}{r}$$

Since $$g = \frac{\lambda}{2\pi\varepsilon x},$$

$\therefore$ $$g = \frac{V}{x \ln \frac{R}{r}} \qquad (9.2)$$

From the above equation (9.2) for gradient it is clear that the gradient is maximum when $x = r$ that is it is maximum at the surface of the conductor and its value is given by

$$g_{max} = \frac{V}{r \ln \frac{R}{r}}$$

and the gradient is minimum at the inner radius of the sheath where it is given by

$$g_{min} = \frac{V}{R \ln \frac{R}{r}}$$

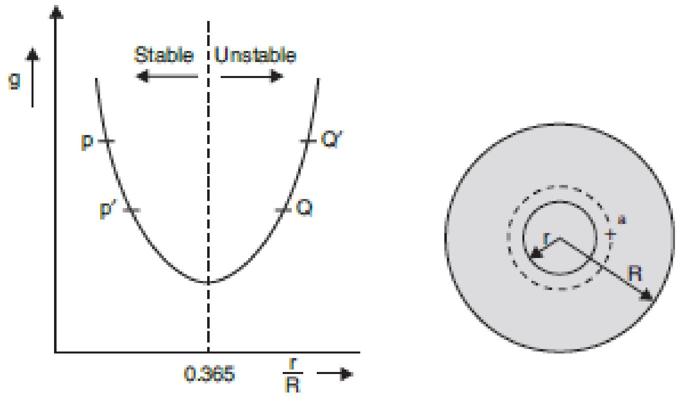
In order to keep a fixed overall size of the cable (R) for a particular operating voltage V, there is a particular value of the radius of the conductor which gives minimum gradient at the surface of the conductor. The objective here is to find the minimum value of g_{max} *i.e.*, to maximise.

$f(r) = r \ln \frac{R}{r}$ since V is fixed.

$$\frac{df(r)}{dr} = -r \cdot \frac{r}{R} \cdot \frac{R}{r^2} + \ln \frac{R}{r} = 0$$

or $$\ln \frac{R}{r} = 1$$

From this it is clear that to have minimum value of gradient at the surface of the conductor the inner radius of the sheath and the conductor radius are related by the equation. A plot of the gradient at the surface of the conductor and the ratio r/R is given in Fig.



Here study is made of the stable operation of the cable for particular ratios r/R *i.e.*, what ratio of r/R leads to stable operation of the cable and what ratios will lead to unstable operation. Say the ratio r/R corresponds to the point Q on the curve in Fig. 9.2. Now due to some manufacturing defects say a thin film of air surrounding the conductor is trapped. Let the thickness of this film be a units. Since the working dielectric strength of the insulating material is taken about 40-50 kV/cm to which now air surrounding the conductor is stressed, which will get ionized, therefore, the effective radius of the conductor will now be $(r + a)$ units and the ratio will be $(r + a)/R$. Corresponding to this ratio the operating point now shifts to Q' *i.e.*, the stress to which the dielectric material is subjected is increased and this may finally lead to rupture of the material. This situation will arise for all operating points to the right of the minimum point on the curve in Fig. Let us now take a cable with ratio r/R such that it corresponds to point P on the curve *i.e.*, left to the minimum point. Say, again due to similar reasons if the radius becomes $(r + a)$ and the ratio $(r + a)/R$ the operating point shifts to the point P' where the dielectric material is subjected to a relatively smaller electric stress than at point P. Therefore it can be seen that for all ratios r/R less than the minimum $1/e$ the cable operates satisfactorily. This means for satisfactory operation of the cable

$$\frac{r}{R} < \frac{1}{e}$$

$$\frac{R}{r} > e$$

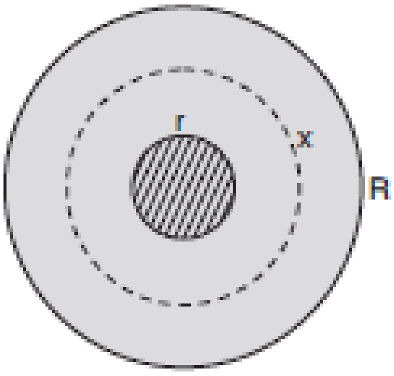
Now if this principle is used for the design of cables then we see that there will be large difference between the stress at the surface of the conductor and the stress at the inner radius of the sheath, which means the dielectric material will not be fully utilised.

By grading of a cable is meant the distribution of dielectric material such that the difference between the maximum gradient and the minimum is reduced, thereby a cable of the same size could be operated at higher voltages or for the same operating voltage a cable of relatively smaller size could be used.

There are two methods of grading:
1. Capacitance grading where more than one dielectric material is used.
2. Intersheath grading where the same dielectric material is used but potentials at certain radii are held to certain values by interposing thin metal sheaths.

Capacitance Grading

Let λ be the charge per unit length. If we have one single dielectric material the gradient at any radius *x* will be



$$g = \frac{\lambda}{2\pi\varepsilon x}$$

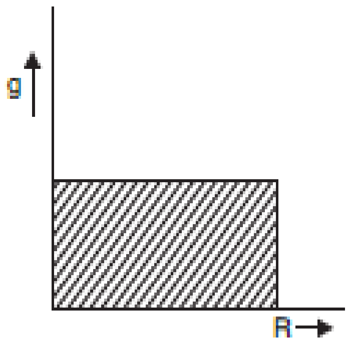
where ϵ is the permittivity of the material. If we could use an infinite number of materials with varying permittivities given by

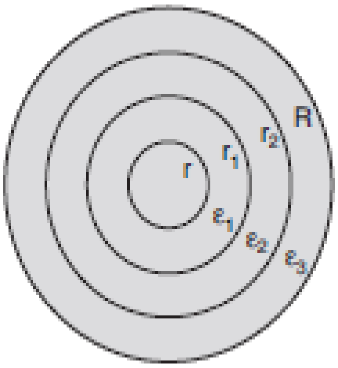
$$\varepsilon = \frac{k}{x}$$

the gradient at any radius *x* now becomes (Fig. 9.4)

$$g = \frac{\lambda}{2\pi . \frac{k}{x} . x} = \frac{\lambda}{2\pi k} = \text{constant}$$

i.e., for a particular operating voltage the overall size of the cable is minimum. This looks quite all right but practically it is impossible to have infinite number of dielectric materials with varying permittivity as given above. Normally two or three materials are used. Let there be three materials with permittivity ϵ1, ϵ2 and ϵ3 placed at radii *r*, *r*1 and *r*2 respectively.





Let the dielectric strength and working stresses of this material be *G*1, *G*2, *G*3 and *g*1, *g*2 and *g*3 respectively. The objective now is to find out the locations of these materials with respect to the conductor of the cable. We can't keep any material anywhere we like. There must be some criterion, otherwise the results of grading may be offset. There are two possibilities:

(*i*) The factor of safety for all the materials be same, thereby the working stress of the various materials different.
(*ii*) The same working stress for different materials.
(i) The gradient at the surface of the conductor will be

$$\frac{\lambda}{2\pi\varepsilon_1 r} = \frac{G_1}{f}$$

where f is the factor of safety.

The gradient at radius $r_1 = \frac{\lambda}{2\pi\varepsilon_2 r_1} = \frac{G_2}{f}$

The gradient at radius $r_2 = \frac{\lambda}{2\pi\varepsilon_3 r_2} = \frac{G_3}{f}$

From these three relations,

$$\lambda = 2\pi\varepsilon_1 r \frac{G_1}{f} = 2\pi\varepsilon_2 r_1 \frac{G_2}{f} = 2\pi\varepsilon_3 r_2 \frac{G_3}{f}$$

or $$\varepsilon_1 r G_1 = \varepsilon_2 r_1 G_2 = \varepsilon_3 r_2 G_3$$

Since $r < r_1 < r_2$, $$\varepsilon_1 G_1 > \varepsilon_2 G_2 > \varepsilon_3 G_3$$

This means the material with highest product of dielectric strength and permittivity should be placed nearest to the conductor and the other layers should be in the descending order of the product of dielectric strength and permittivity. So this is one arrangement of the dielectric materials.

(*ii*) The second alternative as is said earlier is when all the materials are subjected to the same maximum stress. With this arrangement,

$$g_{max} = \frac{\lambda}{2\pi\varepsilon_1 r} = \frac{\lambda}{2\pi\varepsilon_2 r_1} = \frac{\lambda}{2\pi\varepsilon_3 r_2}$$

or $$\varepsilon_1 r = \varepsilon_2 r_1 = \varepsilon_3 r_2$$

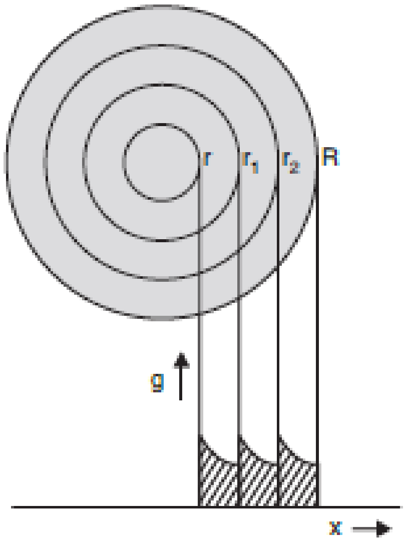
Again since $r < r_1 < r_2$,

$$\varepsilon_1 > \varepsilon_2 > \varepsilon_3$$

The dielectric material with highest permittivity should be placed nearest the conductor and other layers will be in the descending order of their permittivity. The distribution of voltage using capacitance grading (same stress) is shown in Fig. 9.6. Total operating voltage (hatched area) of the cable if *g*max is the working stress,

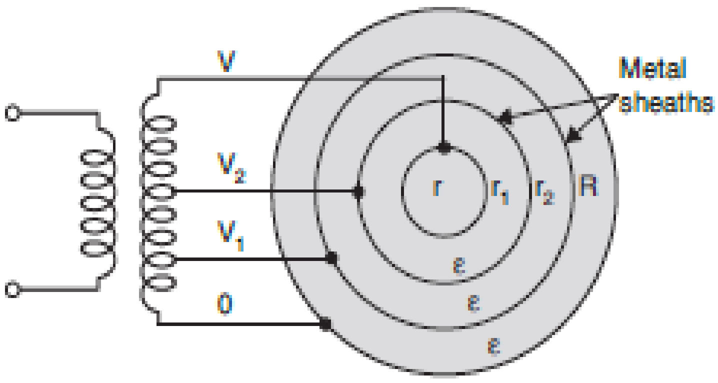
$$V = g_{max}\, r \ln \frac{r_1}{r} + g_{max}\, r_1 \ln \frac{r_2}{r_1} + g_{max}\, r_2 \ln \frac{R}{r_2}$$

$$= g_{max}\left[r \ln \frac{r_1}{r} + r_1 \ln \frac{r_2}{r_1} + r_2 \ln \frac{R}{r_2} \right] \text{ volts}$$



Intersheath Grading

An auxiliary transformer is used to maintain the metal sheath and the power conductor at certain potentials; thereby the stress distribution is forced to be different from the one which it would be without the intersheaths. The objective now here is to show that the gradient with intersheath will be smaller than the gradient without intersheath for the same overall radius and the operating voltage. Since a homogeneous material is being used the maximum value of the stress at various intersheaths is same.



Let the thickness of the materials be such that

$$\frac{r_1}{r} = \frac{r_2}{r_1} = \frac{R}{r_2} = \alpha$$

With this arrangement, the gradient at the surface of the conductor

$$g_{max} = \frac{V - V_2}{r \ln \frac{r_1}{r}}$$

Similarly gradients at radii *r*1 and *r*2 respectively are

$$\frac{V_2 - V_1}{r_1 \ln \frac{r_2}{r_1}} \text{ and } \frac{V_1}{r_2 \ln \frac{R}{r_2}}$$

Since g_{max} are same at the various radii,

$$\frac{V - V_2}{r \ln \frac{r_1}{r}} = \frac{V_2 - V_1}{r_1 \ln \frac{r_2}{r_1}} = -\frac{V_1}{r_2 \ln \frac{R}{r_2}}$$

$$\frac{V - V_2}{r \ln \alpha} = \frac{V_2 - V_1}{r_1 \ln \alpha} = \frac{V_1}{r_2 \ln \alpha}$$

$$\frac{V - V_2}{r} = \frac{V_2 - V_1}{r_1} = \frac{V_1}{r_2}$$

We want to compare the gradients under the two conditions; therefore, we must express them in terms of V, r and α. To find the gradient with intersheath we express $V1$ in terms of $V2$ and then $V2$ in terms of V.

To determine $V1$ in terms of $V2$, from equation, we have

$$\frac{V_2 - V_1}{r_1} = \frac{V_1}{r_2}$$

$$\frac{V_2}{r_1} = V_1\left[\frac{1}{r_1} + \frac{1}{r_2}\right] = V_1\left[\frac{r_1 + r_2}{r_1 r_2}\right]$$

$$V_2 = V_1\left[1 + \frac{r_1}{r_2}\right] = V_1\left[1 + \frac{1}{\alpha}\right]$$

$$V_1 = V_2\left[\frac{\alpha}{1+\alpha}\right]$$

To express $V2$ in terms of V from equation, we have

$$\frac{V - V_2}{r} = \frac{V_2 - V_1}{r_1}$$

$$V - V_2 = \frac{V_2 - V_1}{\alpha}$$

$$V - V_2 = \frac{V_2}{\alpha} - \frac{1}{\alpha}\left[V_2 \cdot \frac{\alpha}{1+\alpha}\right] = \frac{V_2}{\alpha} - \frac{V_2}{1+\alpha} = \frac{V_2}{\alpha + \alpha^2}$$

$$V = V_2 + \frac{V_2}{\alpha + \alpha^2} = V_2\left[\frac{1 + \alpha + \alpha^2}{\alpha(1+\alpha)}\right]$$

$$V_2 = V \cdot \frac{\alpha(1+\alpha)}{1 + \alpha + \alpha^2}$$

Now substituting for $V2$ in equation for gradient, we have

$$g_{max} = \frac{V - V_2}{r \ln \alpha} = \frac{V - V\dfrac{(\alpha+\alpha^2)}{(1+\alpha+\alpha^2)}}{r \ln \alpha}$$

$$= \frac{V}{r \ln \alpha} \cdot \frac{1}{1+\alpha+\alpha^2}$$

Now the gradient at the surface of the conductor without intersheath

$$g = \frac{V}{r \ln R/r} = \frac{V}{3r \ln \alpha}$$

$$\frac{g_{max}}{g} = \frac{3}{1+\alpha+\alpha^2}$$

From the geometry of the cable > 1, therefore, the gradient with intersheath is lower than without intersheath for the same overall size and operating voltage of the cable. This is what we intended to prove. This means that a cable of a particular size can be operated for higher voltages or for a particular voltage the size of the cable can be reduced. The voltage of the cable with this intersheath arrangement is given by

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

$$= g_{max} \ln \alpha \, [r + r_1 + r_2]$$

There can be other arrangements of intersheaths as well *e.g.*, the insulating material thickness between successive intersheaths is constant, *i.e.*,

$$r_1 = r + d, \; r_2 = r + 2d \text{ and } R = r + 3d$$

The grading theory is more of theoretical interest than practical for the following reasons. Capacitance grading is difficult of non-availability of materials with widely varying permittivities and secondly with time the permittivities of the materials may change as a result this may completely change the potential gradient distribution and may even lead to complete rupture of the cable dielectric material at normal working voltage.

In case of intersheath, there is possibility of damage of intersheath during laying operation and secondly since charging current flows through the intersheath which in case of a long cable may result in overheating.

For these reasons the modern practice is to avoid grading in favour of oil and gas filled cables.

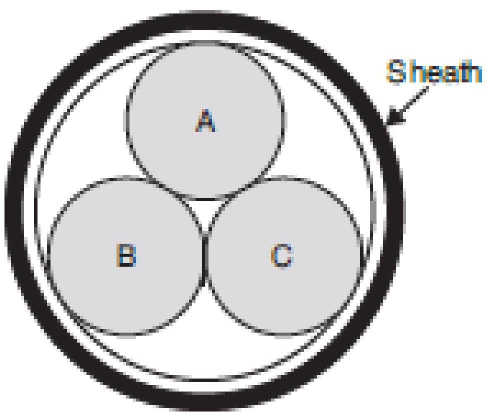
Types of Cables

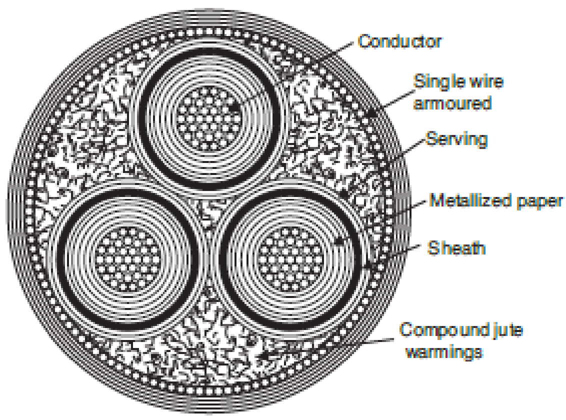
Cables are classified depending upon the material used for insulation such as paper, rubber or asbestos. Paper tapes of about 10 cms to 15 cms thickness can be wound on to a conductor in successive layers to achieve a required operating voltage and is used for voltages of 10 kV and above. In the mass-impregnation construction the paper is lapped on in its natural state and is then thoroughly dried by the combined application of heat and vacuum. It is then impregnated with insulating compound. The cable is heated in a hermetically sealed steam-heated vessel to a temperature of 120°–130°C before vacuum is applied. The compound to be used for impregnation is heated to almost 120°C in a separate vessel and is then admitted in the cable vessel. The compound fills all the pores in the paper and all the spaces in the cable assembly.

After impregnation the cable is allowed to cool down in the compound in order to minimize void formation due to shrinkage. The metal sheath is then applied. In case of pre-impregnated construction the papers are dried and impregnated before application to the conductor and after that there is no drying or impregnation process. The cables are further subdivided into solid, oil-filled or gas-filled types depending upon how the paper insulation is impregnated.

For mass impregnated cables when they are laid on a gradient, the compound used for impregnation tends to migrate from the higher to lower level. Thus voids are formed in the cable at the higher level and because of higher pressure of oil in the lower level cable, the compound will try to leak out. For voltages more than 10 kV, it is the void formation which has been responsible for breakdown.

Three-phase solid paper insulation cables are of two types: (*i*) the belted type and, (*ii*) shielded type. The belted type consists of three separately insulated conductors with an overall insulating tape enclosing all the three conductors and finally the metallic sheath is applied. The major disadvantage of belted type construction is that the electric stress is not purely radial. The existence of tangential stresses forces a leakage current (not the charging current) to flow along the layers of paper and the loss of power sets up local heating. It is to be noted that the resistance and dielectric strength of laminated paper is much less along the layers as compared to that across the layers. The local heating of the dielectric may result in breakdown of the material. The breakdown phenomenon due to tangential electric stress is shown in Fig.





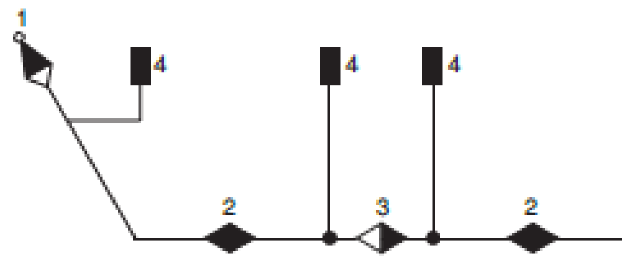
The tangential stresses are eliminated in case of the shielded construction. In this each conductor is individually insulated and covered with a thin metallic non-magnetic shielding tape. The three shields are in contact with each other and the three conductors behave as three single phase conductors. The three conductors are then cabled together with an additional shield wrapped round them. There is no belt insulation provided but it is lead covered and armoured. All the four shields and the lead sheath are at earth potential and, therefore, the electric stresses are radial only; thereby, the tangential stresses are completely eliminated.
The 3-phase shielded construction cable is shown in Fig.

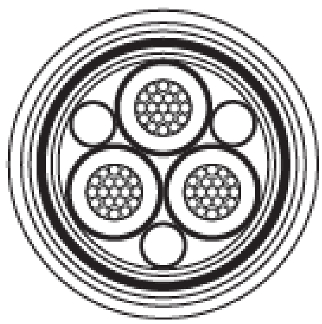
The following are the methods for elimination of void formation in the cables:

(*i*) The use of low viscosity mineral oil for the impregnation of the dielectric and the inclusion of oil channels so that any tendency of void formation (due to cyclic heating and cooling of impregnant) is eliminated.

(ii) The use of inert gas at high pressure within the metal sheath and in direct contact with the dielectric.

The first method is used in oil-filled cables. Oil ducts are provided within the cable itself and they communicate with oil tanks provided at suitable locations along the cable route so as to accommodate any changes in the oil volume during heating and cooling process.

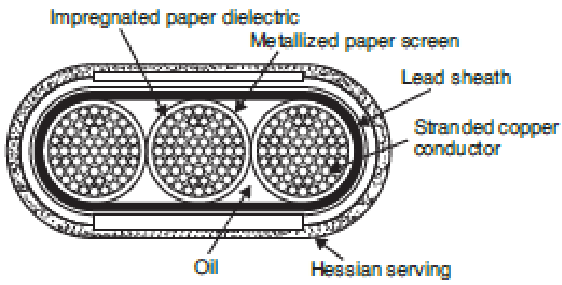


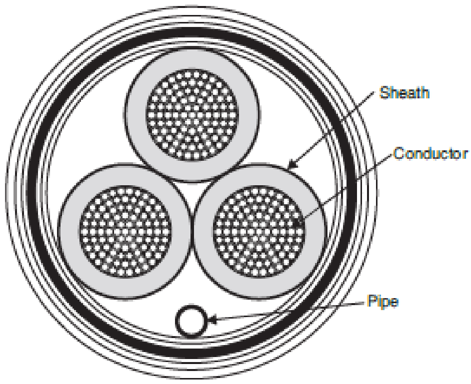


Single phase oil filled cables consist of a concentric stranded conductor built around an open helical spring core which serves as a channel for the flow of oil. The cable is insulated and sheathed in the same manner as the solid type cables. The 3-phase cables are normally of the shielded design type and consist of three oil channels composed of helical springs that extend through the cable in spaces normally occupied by filler material. Another design of three-core oil filled cable is the flat type as shown in Fig. The flat sides are reinforced with metallic tapes and binding wires so that during increase in pressure of oil, due to heating, the flat side is deformed and the section of the cable becomes slightly elliptical. Yet another construction of 3-core oil filled cables uses 3-core paper insulated cable without a lead sheath. The cable is pulled into a steel pipe which then is filled with oil.

Pumps are then used to maintain a specified oil pressure and allow it to expand and contract with the loading cycle.Leakage or oil in these cables is a very serious problem. Automatic signalling is, therefore, installed to indicate the fall in oil pressure in any of the phases. Oil filled cables require relatively smaller amount of insulation as compared to solid type for the same operating voltage and are recommended for all voltages ranging between 66 kV and 400 kV.

To obviate the disadvantages of oil filled cables in terms of expansion and contraction of oil during loading cycles, the gas filled cables are used which have a self-contained compensating arrangement within the confines of the lead sheath. The compression cable is fundamentally a solid type construction with two important modifications; (*i*) the cable cross section is noncircular and (*ii*) the sheath thickness is reduced to allow the cable to breathe more easily. The cable is then surrounded with an envelope and the space between the two is filled with an inert gas at a nominal pressure of 14 kg/cm2 which compresses the cable dielectric via the diaphragm sheath. During heating, the cable compound expands and travels radially through the dielectric and a space is provided by it by movement of the sheath, the non-circular shape becomes circular there. When the cable cools down, the gas pressure acting via the metallic sheath, forces the compound back into the paper insulation.





The gas cushion cable consists of stranded conductor, paper insulated, screened, lead sheathed, metallic reinforced and with a rubber-containing water proof covering. A continuous gas space throughout the length of the cable is provided. The inert gas introduced is at high pressure within the lead sheath and in contact with the dielectric in order to suppress gaseous ionization.

The impregnated pressure cable is similar to solid type except that provision is made for longitudinal gas flow. The cable has a mass-impregnated insulation design and is maintained under a gas pressure of 14 kg/cm2. In single core cables the sheath clearance is about 0.175 cm, and in 3-core cables about 0.075 cm. In case of 3-core cables, a lead gas channel pipe is provided which is located in the space normally occupied by the filler. The object of this pipe is to provide low resistance path between joints.

Because of the good thermal characteristic and high dielectric strength of the gas SF6, it is used for insulating the cables also. SF6 gas insulated cables can be matched to overhead lines and can be operated corresponding to their surge impedance loading. These cables can be used for transporting thousands of MVA even at UHV whereas the conventional cables are limited to 1000 MVA and 500 kV.

Types of Insulators

There are three types of insulators used for overhead lines:

(*i*) Pin type,

(*ii*) Suspension type, and

(*iii*) Strain type.

Pin type insulator consists of a single or multiple shells (petticoats or rain sheds) adapted to be mounted on a spindle to be fixed to the cross arm of the supporting structure. Multiple shells are provided in order to obtain sufficient length of leakage path so that the flash over voltage between the power conductor and the pin of the insulator is increased. The design of the shells is such that when the uppermost shell is wet due to rain the lower shells are dry and provide sufficient leakage resistance. It is desirable that the horizontal distance between the tip of the lowermost shell should be less as compared with the vertical distance between the same tip and the cross-arm, otherwise in case of an arc-over, the discharge will take place between the power conductor and cross-arm rather than power conductor and the pin of the insulator; thereby, the cross-arm will have to be replaced rather than the insulator. It is to be noted that the power conductor passes through the groove at the top of the insulator and is tied to the insulator by the annealed wire of the same material as the conductor. The pin type insulators are normally used upto 33 kV. In any case it is not desirable to use them beyond 50 kV as the cost of such insulators then increases much faster than the voltage. The cost beyond 50 kV is given by Cost $\propto Vx$ where $x > 2$.

The insulators and its pin should be sufficiently mechanically strong to withstand the resultant force due to combined effect of the weight of the conductor, wind pressure and ice loading if any per span length.

The pin type of insulators are uneconomical beyond 33 kV operating voltage. Also the replacement of these insulators is expensive. For these reasons for insulating overhead lines against higher voltages, suspension insulators are used. These insulators consist of one or more insulator units flexibly connected together and adapted to be hung for the cross arm of the supporting structure and to carry a power conductor at its lowest extremity. Such omposite units are known as string insulators. Each insulator is a single disc-shaped piece of porcelain grooved on the under surface to increase the surface leakage path between the metal cap at the top and the metal pin at the bottom of the insulator. The cap at the top is recessed so

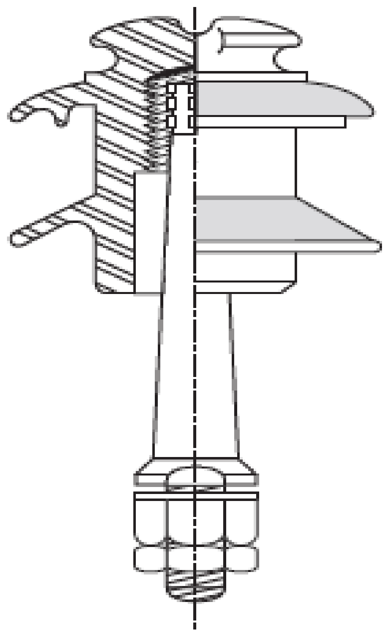
that it can take the pin of another unit and in this way a string of any required number of insulators can be built. The cap and the pin are secured to the insulator by means of cement. The standard unit is 10″× 534″in size. The diameter is taken as 10″as it gives optimum spark over to puncture voltage ratio. Increasing the diameter further increases the flash over or spark over voltage but it lowers the above ratio which is undesirable.

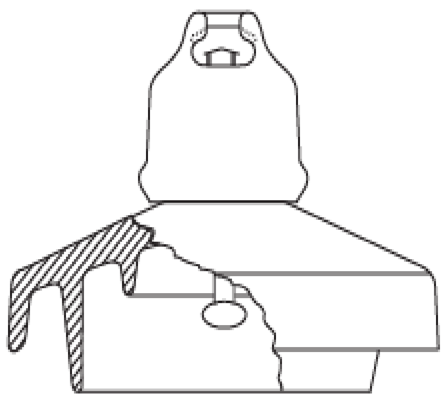
Suspension insulators being free to swing, the clearances required between the power conductor and the supporting structure are more as compared to pin type insulators. This means the length of the cross arm for suspension insulators is more as compared with the pin type.

The suspension insulators, in addition to being economical as compared to pin type for voltages more than 33 kV, have the following further advantages:

1. Each insulator is designed for 11 kV and hence for any operating voltage a string of insulators can be used. For example, for 132 kV transmission, the number of insulators required is 12 (maximum).
2. In case of failure of one of the units in the string, only that particular unit needs replacement rather than the whole string.
3. Since the power conductor and string swing together in case of wind pressure, the mechanical stresses at the point of attachment are reduced as compared with the pin type of insulator where because of the rigid nature of the attachment fatigue and ultimate brittleness of the wire result.
4. The operating voltage of the existing transmission can be increased by adding suitable number of discs in the string instead of replacing all the insulators as is necessary in case of pin type insulators.

The strain insulators are exactly identical in shape with the suspension insulators. These strings are placed in the horizontal plane rather than the vertical plane as is done in case of suspension insulators (discs are in vertical plane in case of string insulators). These are used to take the tension of the conductors at line terminals, at angle towers, at road crossings and at junction of overhead lines with cables. These insulators are, therefore, known as tension or strain insulators. For low voltages of the order of 11 kV, shackle insulators are used. But for higher voltages a string of insulators is used. Whenever the tension in the conductor is very high as at long river crossings etc., sometimes two, even three, strings of insulators in parallel have been used.





MCQ – Post Test

1. Which fault is most likely to occur in cables?
   a. Cross or short-circuit fault
   b. Open circuit fault
   c. Breakdown of cable insulation
   d. all of the above
   Ans: d

2. ___________cables are used for 132 kv lines
   a. High tension
   b. Super tension
   c. Extra high tension
   d. Extra super
   Ans: d

3. What is the dielectric strength of porcelain?
   a. 55 kV/cm.
   b. 60 kV/cm.
   c. 75 kV/cm.
   d. 80 kV/cm.
   Ans: b

4. Which type of insulator is used on 132 kV transmission lines?
   a. Pin type.
   b. Disc type.
   c. Shackle type.
   d. All the above
   Ans: b

5. Where is the strain type of insulators used?
   a.Dead ends
   b.Intermediate
   c. Straight run.
   d. (a) or (b).
   Ans: d

Summary

Insights of various insulators and cables are studied for design of HT.

References

1. C.L.Wadhva, Generation Distribution and Utilization of Electrical Energy, New Age International Publishers ltd.-New Delhi
2. V.K Mehta, Principle of Power Systems, S.Chand Publishers, New Delhi

Audio/video

https://www.youtube.com/watch?v=Od0k9nqtoCM

Assignment

1. Each conductors of 33 kv 3 ph, is suspended by a string of 3 similar insulators, capacitor of each disc is nine time the capacitor to ground. Find voltage at each insulator. Find string efficiency.

2. Find maximum voltage (working) of a sheathed single core cable having a conductor 1 cm diameter and sheath 5 cm dia inside. Two Insulating material with permissibility = 4, 2.5 and max stress 60, 50 kv/cm.

Name of the Course **: Generation Transmission and Distribution**

Name of the unit **: Mechanical Design and HVDC Transmission**

Topic – Title **: Study of mechanical design**

Aim and Objective

Study of mechanical design of transmission line and dc transmission and applications.

Pre-requisites

DC transmission and AC transmission comparison and mechanical strength of transmission line.

Pre – Test MCQ

1. For HV transmission line conduction are suspended from towers so as to
   a. Increase the clearance from ground
   b. Reduce the clearance from ground
   c. Take care of increase length
   d. Reduce wind effect
   Ans: a

2. Wooden pole are used as line support for
   a. 11 kv
   b. 22 kv
   c. 66 lv
   d. 400 kv
   Ans: b

3. Maximum permissible span for pole is
   a. 20 m
   b. 30 m
   c. 50 m
   d. 100 m
   Ans: c

4. Steel poles are for protection against
   A. Birds
   B. Termites
   C. Corrosion
   D. All of the above
   Ans: c

5. RCC poles of span
   a. 250 – 400 m.
   b. 100 – 150 m.
   c. 50 – 105 m.
   d. 10 – 75 m.
   Ans: b

Theory

Sag Tension Calculation

Tension T: To calculate tension *T* at any point *P*(*x*, *y*) on the wire, use is made of equations and (7.2). Squaring and adding equations (7.1) and (7.2), we get

$$T^2\cos^2\psi + T^2\sinh^2\psi = w^2c^2 + w^2s^2$$

$$T^2 = w^2(s^2 + c^2)$$

$$= w^2\left(c^2\sinh^2\frac{x}{c} + c^2\right)$$

$$= w^2c^2(1 + \sinh^2 x/c)$$

$$= w^2c^2\cosh^2 x/c$$

$$T = wc\cosh x/c$$

$$T = wy$$

From equation (7.14) it is clear that the tension in the wire at any point *P*(*x*, *y*) in the wire is the product of the *y*-coordinate of the point and the weight per unit length of the wire. *Sag d*: The sag *d* at point *P*(*x*, *y*) is the vertical distance between the point *P* and the lowest point *H*. To calculate the sag, equation (7.13) is used

$$y = c + \frac{x^2}{2c}$$

$$y - c = \frac{x^2}{2c} = \text{sag } d$$

Now this sag is maximum when $x = l/2$.

$$d = \frac{l^2}{8c}$$

$$d = \frac{l^2}{8c} = \frac{wl^2}{8T} = \frac{wl^2}{8fA} = \frac{l^2\delta}{8f}$$

where *f* = stress corresponding to tension *T*, *A* = area of cross section of the conductor, and

δ = *w/A* constant. δ is the density of the conductor material and is, therefore, constant for a particular material.

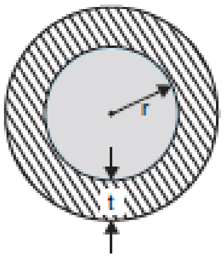
Length L of the Conductor: Substituting x = (l/2) to get the length of the conductor between the point H and the support end *A* or *B*, We have used the relation $T = wc$ instead of $T0 = wc$. This approximation is true for small values of sag and it can be assumed that when d is small, the tension T is approximately uniform throughout the wire.

Having derived the basic equations for a wire strung between two supports we are now ready to design the transmission lines. An overhead line must be designed from the view point of worst probable loads rather than the worst possible loads because the cost of the overhead line will become very large if designed on the basis of worst possible conditions.

The sag to be allowed in a conductor at the time of erection *i.e.*, still air and relatively higher temperature must be such that in bad weather conditions which are a combination of wind and lower temperatures (snow or ice coating), a specified maximum tension for the conductor is not exceeded. The problem can be restated as follows:

Given the maximum tension which must not be exceeded under specified severe conditions of wind, ice or other loading at a specified temperature, to determine the sag and tension at some other conditions of loading and temperature, including the still air and higher temperatures.

Effect of Wind and Ice Loading: As discussed earlier the severe conditions are the wind and ice loadings. Under this condition the per unit length of the wire experiences the following loading: (*i*) the weight of the conductor w acting vertically downwards, (*ii*) the ice loading wi acting vertically downwards, and (*iii*) the wind loading wa acting horizontally.



Still Air and Higher Temperature:
$L2$ = length of the conductor between the supports
$q2$ = loading factor which is unity under these conditions
$f2$ = maximum working stress in the conductor in kg/cm2 corresponding to $f1$ under wind and ice loading condition
$t2$ = ambient temperature
E = modulus of elasticity in kg/cm2
α = coefficient of linear expansion.
The problem now is, given $f1$ calculate $f2$ which is required for stringing the conductor during fair weather (still air) conditions.

$$s = x + \frac{x^3}{6c^2}$$

for $x = l/2$

$$\frac{L_2}{2} = \frac{l}{2} + \frac{l^3}{48c^2} \quad \text{or} \quad L_2 = l + \frac{l^3}{24c^2}$$

Now with loading different from w the value of $c = T/W$, where W is the total loading kg/metre

$$c = \frac{fA}{W} = \frac{f \cdot Aw}{Ww} = \frac{f}{\delta q}$$

Substituting this value of *c* in the expression for *L*2,

$$L_2 = l + \frac{l^3 \delta_2^2 q_2^2}{24 f_2^2}$$

As said earlier under this condition of standstill air and higher temperature, *q*2 = 1.

Similarly,

$$L_1 = l + \frac{l^3 \delta_1^2 q_1^2}{24 f_1^2}$$

In order to relate *f*2 with *f*1, one possibility is to find out some relation between the two lengths *L*1 and *L*2. Now due to higher temperature the length under standstill condition is *l* × *α* (*t*2 – *t*1) metres more than under ice loading conditions but due to increased sag at higher temperatures the stress in the material is reduced from *f*1 to *f*2 and hence there is contraction of length at higher temperature than lower temperature.

Therefore,

$$L_2 = L_1 + l\alpha(t_2 - t_1) - \frac{f_1 - f_2}{E} l$$

It is to be noted here that little error is introduced if *l* is taken instead of *L* for the last term on the right hand side of the above equation.

Now substituting for *L*2 and *L*1,

$$l + \frac{l^3 \delta_2^2 q_2^2}{24 f_2^2} = l + \frac{l^3 \delta_1^2 q_1^2}{24 f_1^2} + l\alpha(t_2 - t_1) - \frac{f_1 - f_2}{E} l$$

$$f_1 - \frac{l^2 \delta^2 q_1^2}{24 f_1^2} E = f_2 - \frac{l^2 \delta^2 q_2^2}{24 f_2^2} E + \alpha(t_2 - t_1)E$$

The quantities on the left hand of the above expression are known so that putting this equal to *K* we have

$$K = f_2 - \frac{l^2 \delta^2 q_2^2}{24 f_2^2} E + \alpha(t_2 - t_1)E$$

or $$K - \alpha(t_2 - t_1)E = f_2 - \frac{l^2 \delta^2 q_2^2}{24 f_2^2} . E$$

Again the quantity on the left hand side is known and let this

$$N = f_2 - \frac{l^2 \delta^2 q_2^2}{24 f_2^2} E$$

or $$f_2^2(f_2 - N) = \frac{l^2 \delta^2 q_2^2}{24} E$$

The quantity on the right hand side of the above expression is known and let this be equal to *M*; we then have *f*2 2(*f*2 – *N*) = *M*

This is a cubic equation in *f*2. This equation can be solved on a slide rule as follows: Set the cursor on scale *A* corresponding to the figure *M*. Make a suitable guess of the solution and set the end of the slide at this guessed value on scale *D*. If the figure on scale *B* under the cursor is equal to (*f*2 – *N*), where *f*2 is the guessed value, the guess is correct, otherwise have a fresh guess and proceed until the requirement is met.

The procedure for evaluating *f*2 is summarized as follows:

1. Evaluate the loading factors *q*1 and *q*2 for the two conditions of load from

$$q = \frac{\sqrt{(\bar{w} + \bar{w}_i)^2 + w_a^2}}{w}$$

2. Calculate K from the expression

$$K = f_1 - \frac{l^2 \delta^2 q_1^2 E}{24 f_1^2}$$

3. Evaluate N and M from the expressions

$$N = K - \alpha t E \text{ and } M = \frac{l^2 \delta^2 q_2^2 E}{24}$$

4. Evaluate f_2 from the cubic equation

$$f_2^2 (f_2 - N) = M$$

5. The sag is then evaluated from the expression

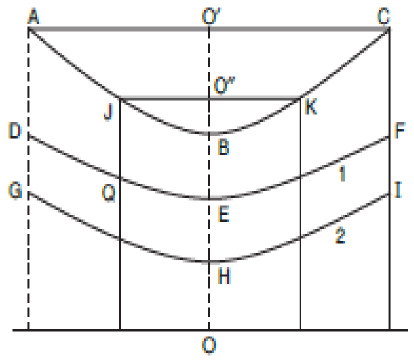
$$d = \frac{l^2 \delta^2 q_2^2}{8 f_2}$$

Sag template

Normally there are two types of supports being used.

(*i*) The standard or straight run or intermediate tower.
(*ii*) The angle or anchor or tension tower.

While the straight run towers are used for straight runs and normal conditions, the angle towers are used at angles, terminals and other points where a considerable amount of unbalanced pull may be thrown on the supports. The angle towers are, therefore, designed to withstand heavy loadings as compared to standard towers.nIn order to locate the position of the towers, the first step is to know a suitable value for the support height and if there are no special guiding factors which dictate this choice, several alternatives may be tried.



The next step is to plot a sag template on a piece of transparent paper which consists of a set of curves as shown in Fig. 7.5. The horizontal and vertical distances represent the span lengths and sags respectively. GHI is the tower footing line (2), *i.e.*, this line gives the location of the footing of the tower. DEF is the ground clearance line (1) *i.e.*, the minimum clearance of the power conductor from the ground. This clearance to ground will depend upon the operating voltage and is given, according to Indian Electricity Rules, in the following table:

Voltage between lines	*Minimum height (metres)*	*Remarks*
Less than 650 d.c.	5.8	Across public roads
or	5.2	Other positions
325 V a.c.	4.6	Inaccessible areas to vehicles
Less than 66 kV	6.0	
Between 66 kV and 110 kV	6.3	
Between 110 kV and 165 kV	6.6	
Exceeding 165 kV	6.9	

Curve *ABC* is such that with a span length of *AC*, the maximum sag of the conductor would be *O′B* and with span *JK*, the maximum sag is *O″B*. The curve *DEF* is obtained from *ABC* by subtracting ordinates from *ABC* equal to the minimum ground clearance required and curve *GHI* is obtained from *ABC* by setting off from *ABC* a distance representing the height of the standard tower from the point of attachment of the lowest conductor to the ground level.

It is then clear that if such a transparent template is placed upon a profile map of the route, as indicated such that the ground clearance line just touches the profile as at *Q* then points *G* and *I*, where the ‘support foot’ line cuts the profile, will indicate the position of the towers represented by *GA* and *IC*. The curve *ABC* will represent the actual shape and position of the lowest conductor, and since *JQ* represents the correct ground clearance, the conductor nowhere approaches the ground by more than the safe amount.

In the particular case shown the points of conductor support are upon the same horizontal level, but the same process applies when the route is a steeply sloping one, and the shape and position of the conductor will always be represented by the curve *ABC* as shown in Fig.

High voltage DC Transmission

The use of d.c. for day to day application is much older than that of a.c. The first Central Electric Station was installed by Edison in New York in 1882 which operated at 110 V d.c. It is of interest to know as to why then a.c. almost replaced all d.c. lines and why direct current again is being used for some high voltage transmission lines.

The use of transformer for transmitting power over longer distances and at higher voltages justified the use of a.c. especially where the electric energy was to be harnessed from water power which usually is available far from the load centres. The polyphase induction motors which serve the majority of industrial and residential purposes are simpler and rugged in construction and cheaper as compared to d.c. motors of the same ratings. The commutators of d.c. machines impose limitation on voltage, speed and size due to the commutation problem (sparking). For operating a machine at high voltage, a relatively large diameter commutator is required which restricts the speed of the machine due to the centrifugal force and a low speed machine is heavier and costlier than a high speed machine of equal rating. The use of steam turbines which have a higher efficiency at high speed made the use of a.c. generator superior as compared to d.c. generators. For all such reasons power was generated, transmitted, distributed and consumed as alternating current. If, however, some applications needed the use of d.c., alternating current was converted to direct current locally by motor-generator sets, rotary convertors or by mercury arc rectifiers.

The supporters of d.c., however, did not forget the advantages of d.c. transmission. They suggested that there are strong technical reasons at least for two cases where the use of direct current transmission be resorted to. However, generation use and even most transmission and distribution may be done by a.c.

(*i*) Because of large charging currents, the use of high voltage a.c. for underground transmission
over longer distances is prohibited. The transmission of power using d.c. has no such limitation.

(*ii*) Parallel operation of a.c. with d.c. which increases the stability limit of the system or interconnection of two large a.c. systems by a d.c. transmission tie line. Here the d.c. line is an asynchronous link between two rigid (frequency constant) systems where otherwise slight difference in frequency of the two large systems would produce serious problems of power transfer control in the small capacity link.

The Historic Thury System named after a French engineer René Thury who designed the system requires for d.c. transmission a large number of series wound generators driven by prime movers, to be connected in series for high voltage at the sending end of the line, and at the receiving end a comparable number of series wound d.c. motors can be again connected in series to drive low voltage d.c. or a.c. generators. The system operated at constant current.

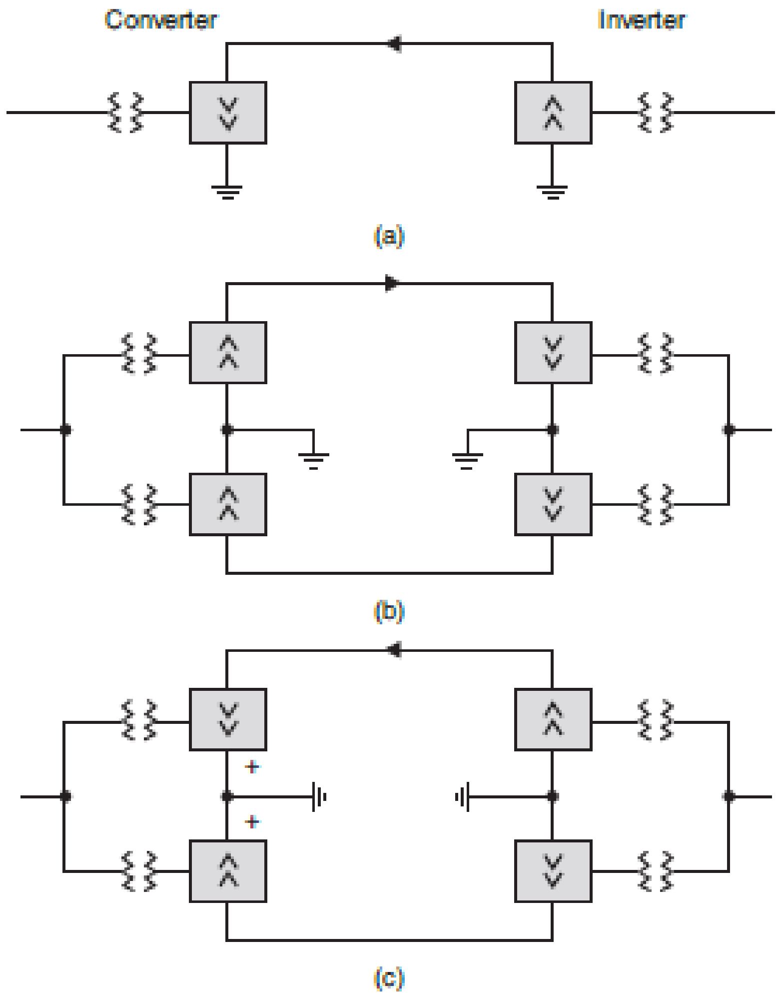
Switching and instrumentation was simple. An ammeter and a voltmeter were the only instruments required. The Thury System worked well for transfer of small powers. For large power, of course, the limitation of d.c. machines came in the way and therefore better convertors than motor generator sets were required.

Extensive research has been carried out especially in Sweden for the development of high voltage convertors. Thyristors of ratings 50 kV and 100 amperes have been developed and now there are many countries in the world where the transmission of power over longer distances and high voltages is being done by d.c. A d.c. transmission line requires convertor at each end. At the sending end a.c. is converted into d.c. and at the receiving end it is converted back to a.c. for use.

Kinds of D.C.Link

D.C. lines are classified as follows: (1) Monopolar lines, (2) Bipolar lines and (3) Homopolar lines. As the name suggests monopolar lines are those in which the line has one conductor only and the earth is used as the return conductor.

The line is normally operating with negative polarity as the corona loss and the radio interference are reduced. The bipolar lines have two conductors—one operating with +ve polarity and the other negative polarity. There are two converters of equal voltage rating and connected in series at each end of the d.c. line. Refer to Fig. The rating of the bipolar line is expressed as ± 650 kV for example and is pronounced as plus and minus 650 kV. The junction of the converters may be grounded at one end or at both the ends. If it is grounded at both the ends each line can be operated independently.



The homopolar lines have two or more conductors having the same polarity usually negative for the reason of corona and radio interference and always operate with ground as the return.
In case of HVDC transmission, the voltage and current levels are so high that a single thyristor cannot meet these requirements. Under such circumstances, it is essential to use more than one thyristors in parallel to obtain increased current requirements and, in series, to achieve higher voltage.

Parallel Connections

When thyristors are connected in parallel, the current sharing between them may not be equal. The thyristor with lower dynamic resistance will take more current resulting in further reduction in resistance and further increasing the flow of current through it. The process is cumulative till the thyristor gives way.

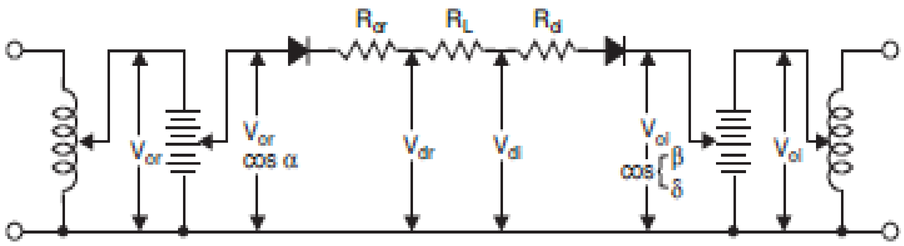
For parallel operation of thyristors, it is desirable that the finger voltage of various devices should be same, the latching current level of all the devices is such that when gate pulse is applied, all of them will turn on and remain on when the gate pulse is removed. Also, the holding current of various devices should not differ much.

In order to nullify the difference in characteristics of the thyristors due to slightly different turn-on time, finger voltage, holding current, latching current etc. which results in unequal current sharing, it is desirable to insert suitable value of inductance in each thyristor circuit.

Series Connection of Thyristors

In order to obtain higher d.c. voltage for HVDC transmission, two or more than two thyristors are to be connected in series. In case, the thyristors have different leakage resistances, the thyristor with higher leakage resistance will have larger voltage drop across it. High resistances of equal values are connected across the thyristors.

The equivalent circuit of a d.c. transmission system under steady state operating condition is shown in Fig.



Equivalent circuit of a d.c. transmission link.

The current I_d in the line is given by

$$I_d = \frac{V_{or}\cos\alpha - V_{oi}\cos(\beta \text{ or } \delta)}{R_{cr} + R_L \pm R_{ci}}$$

where *RL* is the line resistance, *Rcr* and *Rci* are the fictitious rectifier and inverter resistances. If the inverter operates with constant ignition angle in the expression for *Id*, cos β and + *Rci* are used otherwise for constant extinction angle δ, cos δ and – *Rci* are used. Here in our study we consider constant ignition angle β operation of inverter as ignition angle β can be controlled directly whereas δ is controlled indirectly through controlling β to values computed from the

direct current *Id*, the commutating voltage and the desired extinction angle. From the equation, it is clear that the current *Id* is proportional to the difference of the two internal voltages (rectifier and inverter voltages) and is controlled by regulating these voltages as the resistances in the denominator of the expression for *Id* are practically fixed for a given system.

Internal voltages can be controlled by any one or both of the following methods:

(i) Grid Control.

(ii) Tap Change Control.

Small changes in voltages are adjusted using grid control as it is quite fast (about 5 ms) and large changes are brought about by tap changes which are inherently slow (about 5 sec. per step). Both these methods are used cooperatively at each terminal for voltage control and hence control of *Id* and power flow. From equation it is clear that *Id* and hence the difference of internal voltages are always positive as the thyristors can conduct only in one direction. Therefore, if it is desired to reverse the direction of power transmission, the polarity of the direct voltages at both ends of the line must be reversed while maintaining the sign of their algebraic difference. Inverter then acts as a rectifier and the rectifier as an inverter. It is to be noted that the terminal voltage of the rectifier is always greater in absolute value than that of the inverter, although it is lesser algebraically in the event of negative voltage.

Power flow in an HVDC system can be regulated by the following methods:

(*i*) Constant Current, variable voltage.
(*ii*) Constant Voltage, variable current systems.

In case of constant current system, all the loads and power sources are connected in series. A load is taken out of the circuit by short circuiting it by a switch and a source is taken out of the circuit by first reducing its e.m.f. to zero and then short circuiting it. In constant voltage system, various loads and sources are connected in parallel. A load or a source is taken out of the circuit by opening the switch in the corresponding branch. Whereas the constant current system was used in the past for street lighting and on some of the earlier d.c. transmission projects, the constant voltage system is almost universally used these days in a.c. transmission and distribution networks.

Most of the HVDC projects to date are two terminal networks, therefore, the distinction between series and parallel connection of the converter and inverter disappears. The comparison between the constant current and constant voltage system is, therefore, made on the following grounds:

(*i*) The limitation of variation of current due to faults on the d.c. line or converter or due to variation in a.c. voltages.
(*ii*) The energy losses and efficiency. On a constant current system, the short circuit currents are limited to theoretically full load current but practically at the most two times the full load currents. However, in case of constant voltage a.c. systems the fault currents are as high as 20 times the full load current as the current is limited by the effective impedance of the system. On constant voltage d.c. system fault currents would be much greater, as these are limited only by circuit resistance.

As regards losses $I2R$ losses are relatively larger in a constant current system (always full load losses) as compared to the constant voltage system where the losses are proportional to square of the power transmitted. As the system operates for a short time at its rated power, the daily or annual energy loss is much less in constant voltage system. The opposite is true of those losses which are a function of operating voltage such as corona and dielectric losses.

These are more for a constant voltage system as compared to constant current system. In practice, however, the voltage dependent losses are always much less than the current dependent losses. Thus, consideration of fault levels favour the constant current system whereas the energy loss favours the constant voltage systems. In the past it was possible to operate the system either as constant current or constant voltage system. However, with advancement in technology it is now possible with the help of automatic controls to operate the system combining the best features of the two systems.

In case of HVDC transmission it is desirable to have a high power factor of the system for the following reasons:
(*i*) For a given current and voltage of the thyristor and transformers, the power rating of the converters is high.
(*ii*) The stresses on the thyristors and damping circuits are reduced.

(*iii*) For the same power to be transmitted the current rating of the system is reduced and also the copper losses in the a.c. lines are reduced.
(*iv*) In a.c. lines the voltage drop is reduced.
The p.f. on the a.c. side can be improved by using shunt capacitors. However, this involves cost both for the capacitors and the switching devices.

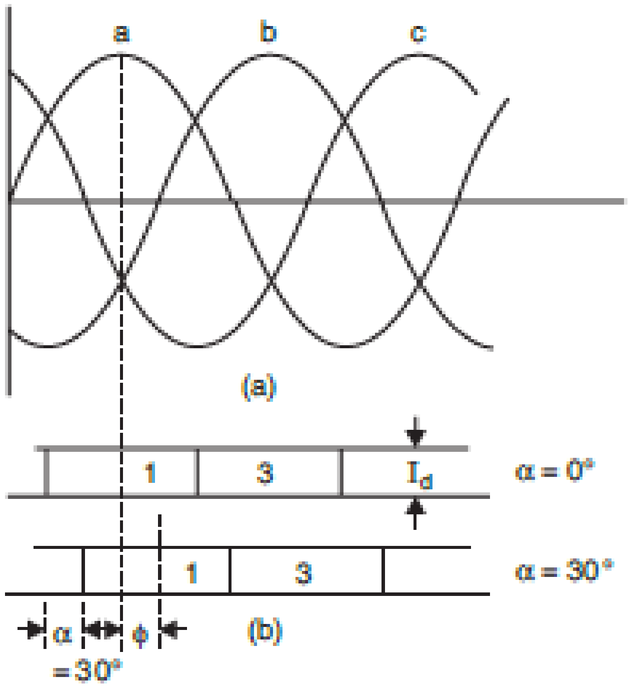
In practice and under normal condition α is kept near 15° for the following reasons:

(i) To ensure that all the thyristors of a bridge will be fired at the same instant in time.

(*ii*) To allow a small margin for an immediate small power increase, if it is dictated by the rectifier grid control regulator.

It is concluded that smaller the firing angle, the smaller will be the *V Ar* requirements of the rectifier as then sin ø is smaller.

Similar to rectifier operation, the p.f. angle ø increases with increase in angle δ in case of inverter. Therefore, for $\delta = 0$, the *V Ar* demand of the inverter will be minimum and for $\beta > 0$ the current leads the voltage and the inverter consumes lagging *Vars*.



Advantages of DC Transmission

There is a fundamental difference between the transmission of power in a d.c. and in an a.c. system. In an a.c. system power is given by $P = E_1 E_2 / X$ *and* sin δ, where $E1$ and $E2$ are line voltages at the two ends, δ the electrical angle between $E1$ and $E2$ and X is the line reactance whereas in d.c. the power is given by $P = (Ed_1 – Ed_2 / R)\ Ed_2$

where $Ed1$ and $Ed2$ are the d.c. voltages at the two ends and R is the line resistance. From this it is clear that the d.c. power is proportional to the difference of the line voltages and thus will vary much more with the voltages than in the case of the a.c. transmission, where the power is proportional to the product of the line end voltages.

Line Circuit: The line construction is simpler as compared to a.c. transmission. A singleconductor line with ground as return can be compared with a 3-phase single circuit line. Hence the line is relatively cheaper and has the same reliability as that of a 3-phase single circuit line because 3-phase lines cannot operate, except for a short time when there is a single line to ground fault or a *L-L* fault as this creates unbalancing in the voltages and hence interfere with the communication lines and other sensitive apparatus on the system. It is claimed that a bipolar d.c. line has the same reliability index as a two-circuit 3-phase line having six line conductors.

Power per Conductor: For transmitting power both on a.c. and d.c. circuits let us assume that the two lines have the same number of conductors and insulators. Assuming that the current is limited by temperature rise, the direct current equals the r.m.s. alternating current.

Since the crest voltage in both cases is same for the insulators the direct voltage is 2 times the r.m.s. alternating voltage. The power per conductor in case of d.c. is

The power per conductor in case of d.c. is

$$P_d = V_d I_d$$

and the power per conductor in a.c. is

$$P_a = V_d I_a \cos\phi$$

where I_a and I_d are the currents per conductor and V_a and V_d the line to ground voltages and $\cos\phi$ the power factor.

Now since $V_d = \sqrt{2}V_a$ and $I_a = I_d$

$$\frac{P_d}{P_a} = \frac{V_d I_d}{\frac{V_d}{\sqrt{2}}.I_d\cos\phi} = \frac{\sqrt{2}}{\cos\phi}$$

since cos ø ≤ 1.0, the power per conductor in case of d.c. is more as compared to a.c.

Power per Circuit: Let us compare the power transmission capabilities of a 3-phase single circuit line and a bipolar line. The power capabilities of the respective circuits are

$$P_d = 2p_d \text{ and } P_a = 3p_a$$

where p_d and p_a are the power transmitted per conductor of d.c. and a.c. lines. The ratio

$$\frac{P_d}{P_a} = \frac{2p_d}{3p_a} = \frac{2V_d I_d}{3V_a I_a\cos\phi} = \frac{2V_d I_d}{\frac{3}{\sqrt{2}}V_d I_d\cos\phi}$$

$$= \frac{2\sqrt{2}}{3\cos\phi} = \frac{2.828}{3\cos\phi}$$

Normally cos ø < 1 and is of the order of 0.9. Therefore, the power transmission capability of the bipolar line is same as that of the 3-phase single circuit line. The d.c. line is cheaper and simpler as it requires two conductors instead of three and hence 2/3 as many insulators, and the towers are cheaper and narrower and hence a narrow right of way could be used.

No Charging Current: In case of a.c. the charging current flows in the cable conductor, a severe decrease in the value of load current transmittable occurs if thermal rating is not to be exceeded; in the higher voltage range lengths of the order of 32 km create a need for drastic derating. A further current loading reduction is caused by the appreciable magnitude of dielectric losses at high voltages. Since in case of d.c. the charging current is totally absent the length of transmission is not limited and the cable need not be derated.

No Skin Effect: The a.c. resistance of a conductor is somewhat higher than its d.c. resistance because in case of a.c. the current is not uniformly distributed over the section of the conductor. The current density is higher on the outer section of the conductor as compared to the inner section. This is known as skin effect. As a result of this the conductor section is not utilized fully. This effect is absent in case of d.c.

No Compensation Required: Long distance a.c. power transmission is feasible only with the use of series and shunt compensation, applied at intervals along the line. For such lines shunt compensation (shunt reactors) is required to absorb the line charging kVAs during light load conditions and series compensation (use of series capacitors) for stability reasons. Since d.c. line operate at unity power factor and charging currents are absent no compensation is required.

Less Corona Loss and Radio Interference: The corona loss is directly proportional to (f + 25), where f is the frequency of supply. f being zero in case of d.c., the corona losses are less as compared to a.c. Corona loss and radio interference are directly related and hence radio interference in case of d.c. is less as compared to a.c. Also corona and radio interference slightly decrease by foul weather conditions (snow, rain or fog) in case of d.c. whereas they increase appreciably in case of a.c. supply.

Higher Operating Voltages Possible: The modern high voltage transmission lines are designed based on the expected switching surges rather than the lightning voltages because the former are more severe as compared to the latter. The level of switching surges due to d.c. is lower as compared to a.c. and hence, the same size of conductors and string insulators can be used for higher voltages in case of d.c. as compared to a.c. In cables, where the limiting factor is usually the normal working voltage the insulation will withstand a direct voltage higher than that of alternating voltage, which is already 1.4 times the r.m.s. value of the alternating voltage.

No Stability Problem: For a two machine system the power transmitted from one machine to another through a lossless system is given by $P = E_1 E_2/X \sin\delta$

where X is the inductive reactance between the machines. The longer the length of the line, the higher is the value of X and hence lower will be the capability of the system to transmit power from one end to the other. With this the steady state stability limit of the system is reduced. The transient state stability limit is normally lower than the steady state; therefore with longer lines used for transmission, the transient stability also becomes very low. A d.c. transmission line does not have any stability problem in itself because d.c. operation is an asynchronous operation of the machines. In fact two separate a.c. systems interconnected only by a d.c. link do not operate in synchronism even if their nominal frequencies are equal and they can operate at different nominal frequencies *e.g.*, one operating at 60 Hz and the other at 50 Hz.

Low Short Circuit Currents: The interconnection of a.c. system through an a.c. system increases the fault level to the extent that sometimes the existing switchgear has to be replaced. However, the interconnection of a.c. system with d.c. links does not increase the level so much and is limited automatically by the grid control to twice its rated current. As a result of this fault d.c. links do not draw large currents from the a.c. system.

Disadvantage of DC Transmission

However, the d.c. transmission has certain disadvantages as well which are listed below:

Expensive Converters: The converters required at both ends of the line have proved to be reliable but they are much more expensive than the conventional a.c. equipments. The converters have very little overload capacity and they absorb reactive power which must be supplied locally. The converters produce lot of harmonics both on d.c and a.c. sides which may cause interference with the audio-frequency communication lines. Filters are required on the a.c. side of each converter for diminishing the magnitude of harmonics in the a.c. networks. These also increase the cost of the converters.

Voltage Transformation: The power transmitted can be used at lower voltage only. Voltage Transformation is not easier in case of d.c. and hence it has to be done on the a.c. side of the system. Circuit breaking for multi-terminal lines is difficult.

MCQ – Post Test

1. Which among HVDC project in India
   a. Rihand – Delhi HVDC
   b. Vindhyachal
   c. Chandrapur
   d. All of these
   Ans: d

2. What type of insulation is preferred for DC smoothing reactor?
   a. Air
   b. Oil
   c. Paper
   d. Varnish
   Ans: b

3. For what voltage, is twin conductor bundle used in India?
   a. 220 kV
   b. 500 kV
   c. 750 kV
   d. 330 kV
   Ans: b

4. Voltage regulation in short transmission is
   a. Positive
   b. Negative
   c. Both a and b
   d. Not defined
   Ans: c

5. Series compensation is primarily for
a. Improve voltage profile

b. improve stability
c. Reduce fault currents
d. None
Ans: b

Summary

HV DC Transmission overview and mechanical design of transmission line characteristics are discussed.

References

1. C.L.Wadhva, Generation Distribution and Utilization of Electrical Energy, New Age International Publishers ltd.-New Delhi
2. V.K Mehta, Principle of Power Systems, S.Chand Publishers, New Delhi

Audio / Video

https://www.youtube.com/watch?v=MtmG7ZIfaDA

Assignment

1. Discuss the difference between AC transmission line and DC transmission line.
2. Discuss the effect of ice and wind on transmission line.