CHAPTER 3

Distribution Systems, Cables & Insulators

3.1 Distribution Systems

Introduction

The conductor system by means of which electrical energy is conveyed from bulk power source or sources (generating stations or major substations supplied over transmission lines) to the consumers is known as ***"distribution system"***. Distribution system is an integral part of any electric power system. Like transmission system, distribution system based on voltage levels can be further classified as

(i) Primary distribution system:
From generating stations, the electrical power is usually transmitted to various substations through extra high tension transmission lines at voltage from 33 kV to 400 kV. At these substations this voltage is stepped down to 11 or 6.6 or 3.3 kV and power at this voltage is conveyed to different substations for distribution and to the bulk supply consumers. Such a system is known as ***"high voltage"*** or ***"primary distribution system"***.

(ii) Secondary distribution system:
At distribution substations, the voltage is stepped down to 400 volts. From these substations various low voltage (400 volts between phases and 230 volts between phase and neutral) distributors radiate out and feed the consumers. This system of distribution is known as ***"low voltage"*** or ***"secondary distribution system"***.

(iii) Tertiary distribution system:
A 400 V, 3-phase system is an example of a tertiary distribution system.

Distribution system has mainly two components which are as follows:

1. **Feeder:** A feeder in a distribution system is a circuit carrying power from a main substation to a secondary substation such that the current loading is the same all along its length. Therefore, the main criterion for the design of a feeder is its current carrying capacity rather than voltage drops.
2. **Distributor:** A distributor has a variable loading along its length due to the service conditions, tapping off at intervals by the individual consumers. The permissible voltage variation at consumer terminals must be within ±5%. Excessing voltage variations at consumer terminals lead to equipment failure. Hence, the main criterion for the design of a distributor is the limit on percentage voltage variations.

Remember: Feeders are not tapped in between the sub-transmission substation and the distribution substations, while distributors are tapped throughout at several points to serve the consumers.

Determination of Size of Conductor for Feeders and Distributors

- Practically, ACSR conductors are universally employed for distribution systems (feeders and distributors). However, in case of distributors all aluminium conductors (AAC) can also be used provided the span are same.
- The conductor size for feeder is mainly governed by the current carrying capacity and overall economy. The current carrying capacity is usually determined for a maximum operating temperature of 75°C. After determining the size of the conductor on the basic of current carrying capacity it should be checked that voltage drop in the feeder is not out of the range of the regulating equipment.
- The main consideration for the determination of size of conductor for a distributor is the permissible voltage drop in the line. If the calculated voltage drop is found more than permissible, the conductor size of the distributor is then increased to the next higher standard value and voltage drop calculation is made again. This process is continued till the voltage drop in the distributor is within limits.

Classification of Distribution Systems

- Distribution systems may be classified in various ways.
- According to current, the distribution systems can be classified as
  (*i*) **AC distribution**
  (*ii*) **DC distribution**
  AC system is universally employed for distribution of electrical power.
- According to the construction, the distribution system may be classified as
  (*i*) **Overhead distribution system** and
  (*ii*) **Underground distribution system**
  Due to low cost, overhead type system is usually employed. Underground distribution system is used where overhead system becomes impractical.
- According to number of wires, the distribution system is classified as
  (*i*) **two-wire**
  (*ii*) **three-wire**
  (*iii*) **four-wire distribution systems**
  In case of dc supply, 3-wire distribution system is usually used due to its advantage over two-wire distribution system. 3-phase, 3-wire system is used for balanced loads such as power loads, 3-phase, 4-wire system is used for unbalanced loads such as light and power loads combined and single-phase two-wire system is employed for lighting and small power applications.
- According to the scheme of connections the distribution system may be classified as
  (*i*) **radial**
  (*ii*) **parallel**
  (*iii*) **ring** and
  (*iv*) **interconnected distribution system** as shown in Figure 3.1.

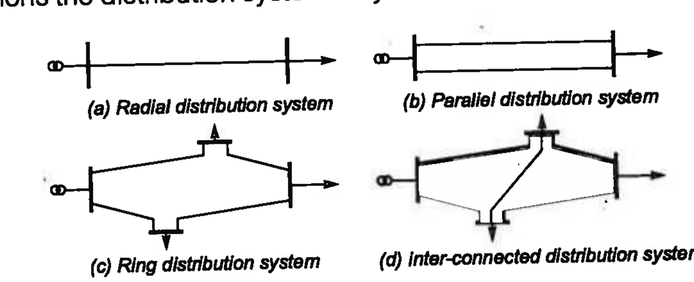


Figure-3.1 : *Various arrangements of feeders and distributors*

NOTE

- A radial system is used in light and medium density load areas. The radial system is the simplest and lowest in first cost but, has poorest service reliability.
- A parallel or loop system is more reliable than the radial system because an alternate path is available for transfer of power.
- The ring system provides alternative supplies to a number of scattered substations.
- The interconnected network is a common development of the simple ring system. It is preferred for large distribution areas for large loads which have to be supplied with greater reliability with all other advantages of grid system. This system gives a better voltage regulation.

Comparison of Various Distribution Systems

Although DC distribution system has been phased out in almost every country, some applications of DC power are still there. But, in transmission both DC and AC exist. The various possible distribution systems are

1. **DC 2-wire system** (Monopolar)
2. **DC 2-wire system with mid-point earthed** (Bipolar)
3. **AC 1-phase, 2-wire system**
4. **AC 3-phase, 3-wire system**
5. **AC 3-phase, 4-wire system**

Following assumption are made for comparison:

(a) In all cases, power transmitted remains same.
(b) In all cases, distance and power loss are same.
(c) The line should have the same insulation level.

Let, V = Maximum potential difference between any conductor and the earth

I = Line current

1. DC 2-wire System

Figure 3.2 shows the 2-wire DC system where mid-point is earthed.

Here, power transmitted, $P = VI$

and Power loss $= 2I^2R = \dfrac{2P^2R}{V^2}$ ...(1)

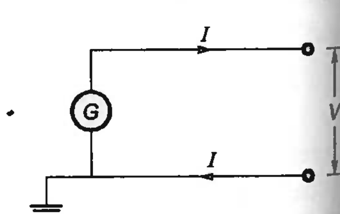


Figure-3.2 : wired system

2. DC 2-wire System with Mid-point Earthed

Figure 3.3 shows the DC 2-wire system with mid-point earthed.

As no load is fed, therefore, $I_1 = I_2$

Also, load voltage = 2 V

Let cross-sectional area of each conductor be a and resistance be R_1 each.

$\therefore$ Power transmitted is, $P = 2\,VI$

and Power loss, $P_1 = 2I_1^2R_1 = \dfrac{P^2R_1}{2V^2}$ ...(2)

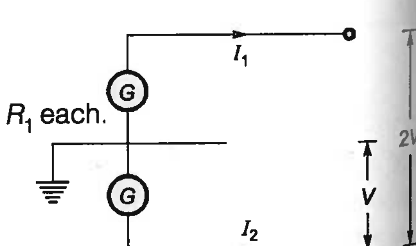


Figure-3.3 : DC 2-wire mid-point earthed system

If power loss is same in case (*i*) and (*ii*) then, power loss given by equations (1) and (2) will be equal.

i.e., $\dfrac{2P^2R}{V^2} = \dfrac{P^2R_1}{2V^2}$ or $R = \dfrac{R_1}{4}$ ...(3)

Since, $R = \dfrac{\rho l}{a}$ therefore, equation (3) can be written as

$$a_1 = \frac{a}{4}$$

As number of conductor remains same in case (i) and (ii) therefore, the ratio of volume of conductors is

$$\frac{v_1}{v} = \frac{a_1 \cdot 2l}{a \cdot 2l} = \frac{1}{4} \quad \text{...(4)}$$

NOTE

- The volume of the conductor used in the case of DC 2-wire mid-point earthed is only 1/4th of that of the DC 2-wire system.
- For monopolar operation, ground is used as return path and only one conductor is used, therefore,

  saving of conductor volume will be $\frac{1}{2}$ since $\frac{v_1}{v} = \frac{a_1 2l}{al} = \frac{1}{2}$.

3. AC single-phase 2-wire System

Figure 3.4 shows a single-phase 2-wire system with V middle point earthed.

Here, maximum voltage between one of the outer wires and the earth is V volts.

$\therefore$ $V_{rms} = \dfrac{V}{\sqrt{2}}$

Voltage between the two outer conductor is $\dfrac{2V}{\sqrt{2}} = \sqrt{2}\,V$.

$\therefore$ Current in outer wire is,

$I = \dfrac{P}{\sqrt{2}\,V\cos\phi}$ (ϕ = load pf angle)

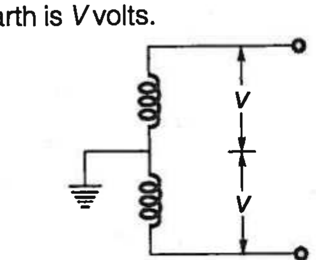


Figure-3.4 : Single-phase, 2-wire ac system

If R_2 be the resistance of each wire, the copper loss $= 2\left[\dfrac{P^2}{2V^2\cos^2\phi}\right]\cdot R_2$

$$= \frac{P^2}{V^2\cos^2\phi}\cdot R_2 \quad \text{...(5)}$$

NOTE: Copper loss in AC single-phase 2-wire system is $1/(V\cos\phi)^2$ ....(Important result)

4. AC three-phase 4-wire System

Figure 3.5 shows a 3-phase 4-wire AC system

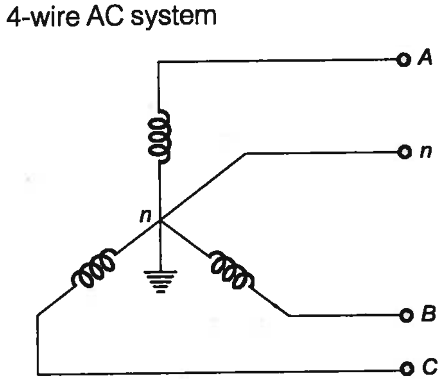


Figure-3.5 : 3-phase 4-wire AC system

Maximum value of voltage between one phase and ground neutral is V volts.

$$V_{rms} = \frac{V}{\sqrt{2}}$$

So, current per phase under balanced condition = $\dfrac{P}{3 \times \dfrac{V}{\sqrt{2}} \cos\phi}$.

(Here, ϕ = load *pf* angle)

Let R_3 be the resistance per conductor then, copper loss is given by

$$\text{Copper loss} = 3 \cdot \frac{2P^2}{9V^2 \cos^2\phi} \cdot R_3 = \frac{2}{3} \cdot \frac{P^2}{V^2 \cos^2\phi} \cdot R_3 \quad \text{...(6)}$$

Equating equations (2) and (6) copper loss due to 3-phase 3-wire as calculated with DC 2-wire system, we have

$$\frac{P^2 R_1}{2V^2} = \frac{2P^2}{3V^2 \cos^2\phi} \cdot R_3$$

or,

$$\frac{R_1}{R_3} = \frac{4}{3} \cdot \frac{1}{\cos^2\phi} \quad \text{...(7)}$$

or,

$$\frac{a_3}{a_1} = \frac{4}{3} \cdot \frac{1}{\cos^2\phi} \quad \text{...(8)}$$

NOTE

DC distribution is no longer used because of inability to change voltage levels. DC would be used for very short distance for some special purpose. Now a days, 3-phase 4-wire AC system is universally used for distribution of power throughout the world.

Types of Distributors

Following are the different types of distributors:

1. Distributors fed at one end
2. Distributors fed at both ends
3. Distributors fed at the center
4. Ring main distributor

1. Distributor Fed at One End

In this type of feeding, the distributor is connected to supply mains at one end and loads are tapered at different points along the length of the distributor as shown in Figure 3.6.

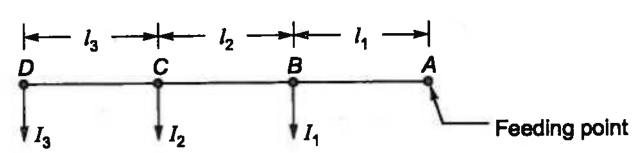


Figure-3.6 : *Distributor fed at one end*

Let I_1, I_2, I_3 be the load currents and resistance per unit length of the distributor be r.

Then, Total voltage drop = (Voltage drop in section *AB*) + (Voltage drop in section *BC*) + (Voltage drop in section *CD*)

$$= (I_1 + I_2 + I_3)\, l_1 r + (I_2 + I_3) l_2 r + I_3 l_3 r$$

$$= I_1 l_1 r + I_2 (l_1 + l_2) r + I_3 (l_1 + l_2 + l_3) r$$

NOTE

Disadvantage of distributor fed at one end:

If fault occurs in any section of distributor, the whole distributor is required to be disconnected from the supply mains and thus supply continuity is disturbed.

2. Distributor Fed at Both Ends

In this type of feeding, the distributor is connected to supply mains at both ends as shown in Figure 3.7. The voltage at both feeding points may be different or equal. If such a distributor is fed at only one end, the voltage drop at the far end may be unacceptable.

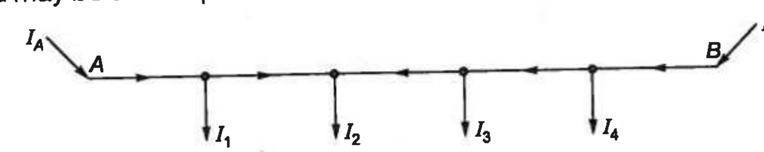


Figure-3.7 : *Distributor fed at both ends*

Here, the total voltage drop across the distributor = $(V_A - V_B)$.

The current Ia and I_B can be calculated using Kirchhoff's laws.

NOTE

Advantages of distributors fed at both ends:

- The continuity of supply is maintained if a fault occurs in any one feeder feeding the distributor by feeding it from other end.
- The continuity of supply is maintained if any section of the distributor is isolated in case of fault.
- It is economical as cross-section of conductor required will be less.

3. Distributors Fed at The Center

In this type of feeding, the center of the distributor is connected to the supply mains as shown in Figure 3.8.

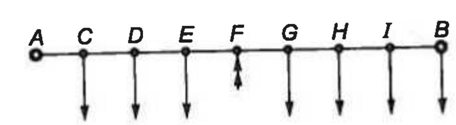


Figure-3.8 : *A distributor fed at the center*

This type of distributor is equivalent to two-singly-fed distributors, each distributors being of one half of its length and having common feeding point.

4. Ring main Distributor

When the two ends of a distributor are fed at equal voltages and are brought together then, such a distributor is called a ***"ring main distributor"***. A ring main distributor is shown in Figure 3.9.

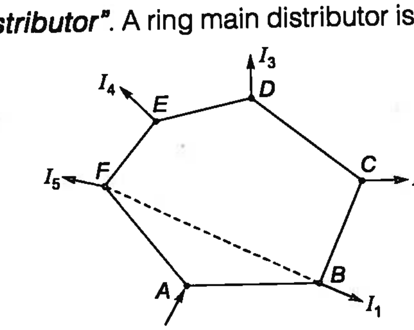


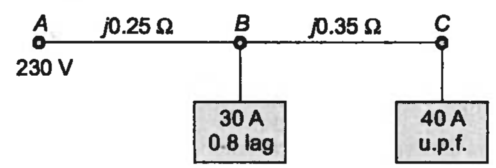
Figure-3.9 : *Ring main distributor fed at one end*

NOTE

Advantages of ring main distributor:

- Greater reliability and flexibility.
- When a fault occurs on any section, it can be isolated from both sides and the continuity of supply is maintained for the remaining sections.

Example - 3.1 A single-phase ac distributor supplies two single-phase loads as shown in the given figure. The voltage drop from *A* to *C* is



(a) 4.5 + j30 v (b) 30 + j4.5 V
(c) 4.5 – j30 V (d) j30 V

Solution: (a)

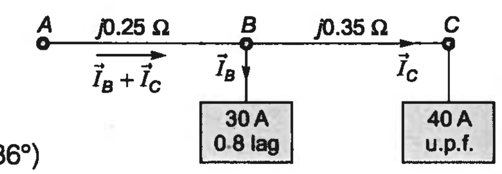
Here, $\vec{I}_B = 30\angle -36.86°$ A and $\vec{I}_C = 40\angle 0°$ A

so, voltage drop from *A* to *C* is

$$\vec{V}_{AC} = (\vec{I}_B + \vec{I}_C)(j0.25) + \vec{I}_C(j0.35)$$

$$= \vec{I}_C(j0.25 + j0.35) + (j0.25)\vec{I}_B$$

$$= (40\angle 0°)(j0.60) + (j0.25)(30\angle -36.86°)$$



or, $\vec{V}_{AC} = (4.5 + j30)$ V

Example - 3.2 Why is a ring main distribution system preferred to a radial system?

1. Voltage drop in the feeder is less.
2. Power factor is higher.
3. Supply is more reliable.

Select the correct answer using the code given below:

(a) 1 and 2 (b) 2 and 3
(c) 1 and 3 (d) 1, 2 and 3

Solution: (c)

Two is wrong because a ring main system is preferred only due to its reliability and less voltage drop in the feeder.

Example - 3.3 For a given power delivered, if the working voltage of a distributor line is increased to *m* times, the cross-sectional area '*a*' of distributor line would be reduced to

(a) $\frac{m}{a}$ (b) $\frac{1}{m}a$

(c) $\frac{1}{2m}a$ (d) $\frac{1}{m^2}a$

Solution: (d)

Let the cross-sectional area and the voltage corresponding to power P_1 of a conductor be A_1 and V_1 respectively. Also, let the cross-sectional area and the voltage corresponding to power P_2 of a conductor be A_2 and V_2 respectively such that $V_2 = mV_1$.

Since power delivered is same therefore, $P_1 = P_2$

or, $V_1 I_1 \cos\phi = V_2 I_2 \cos\phi$ or $V_1 I_1 = mV_1 I_2$

or, $I_2 = \frac{I_1}{m}$ ...(1)

Now, a distributor is designed based on voltage drop. Therefore, % voltage drop for conductors remain same

i.e. $\left(\frac{I_1 R_1}{V_1} \times 100\right) = \left(\frac{I_2 R_2}{V_2} \times 100\right)$

or, $\left(\frac{I_1 R_1}{V_1} \times 100\right) = \left(\frac{\frac{I_1}{m} R_1}{mV_1} \times 100\right)$ [(Using equation (1)]

or, $R_1 = \frac{R_2}{m_2}$

or, $R_2 = m^2 R_1$ ...(2)

Now, we know that resistance $R \propto \frac{1}{A}$

So, $\frac{R_2}{R_1} = \frac{A_1}{A_2}$ or $\frac{A_1}{A_2} = m^2$ [Using equation (2)]

or, $A_2 = \frac{1}{m^2} \cdot A_1$

If, $A_1 = a$

then, $A_2 = \frac{1}{m^2} a$

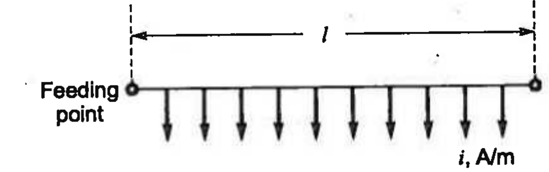
Example - 3.4 In the ring main distribution system, the distributor is fed

(a) by two feeders (b) by one feeder
(c) by four feeders (d) at different points

Solution: (b)

In ring main distribution system, the distributor is fed by two feeders both at equal voltages and are brought together.

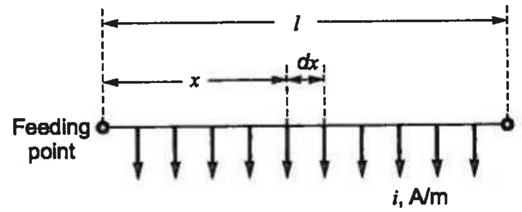
Example - 3.5 Figure given below shows a uniformly loaded distributor fed at one end. The total length of the distributor is taken *l* and *i* is the current tapped off per unit length. The voltage drop upto a distance *x* from the feeding point is (*r* = resistance per unit length of both wires of the distributor (i.e. go and return):



(a) $\frac{1}{4} Irl$ (b) Irl

(c) $\frac{1}{2} Irl$ (d) $\frac{1}{3} Irl$

Solution: (c)



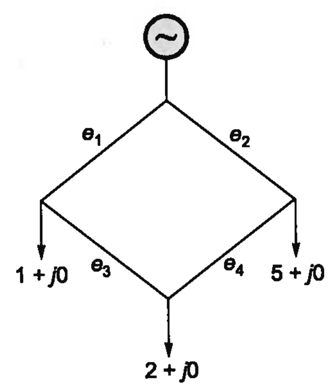
Voltage drop upto distance x from the feeding point = $\int_0^x r \cdot x i dx + i(l-x)dx = irlx - \frac{1}{2} i r x^2$

$\therefore$ Total voltage drop over the length is

$$V = \frac{1}{2} i r l^2 = \frac{1}{2} I r l \quad \text{(Putting } x = l \text{ in above equation)}$$

(Here, $I = il$ = total current supplied by the distributor)

Example - 3.6 **Single line diagram of a 4-bus single source distribution system is shown below. Branches e_1, e_2, e_3 and e_4 have equal impedance. The load current values indicated in the figure are in pu.edances. The load current values indicated in the figure are in pu.**



Distribution company's policy requires radial system operating with minimum losses. This can be achieved by opening of the branch.

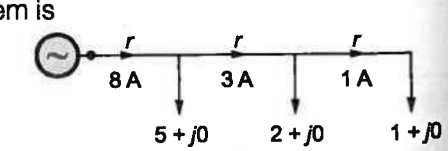
(a) e_1 **(b) e_2**
(c) e_3 **(d) e_4**

Solution: (d)

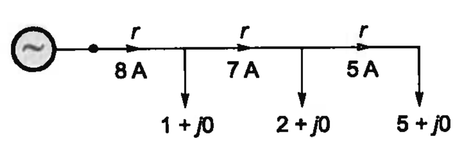
Let the resistance of each branch be r.

When branch e_1 is opened as shown below, losses in the system is

$$P_1 = 8^2r + 3^2r + 1^2r$$
$$= 64r + 9r + r = 74r \text{ Watt}$$

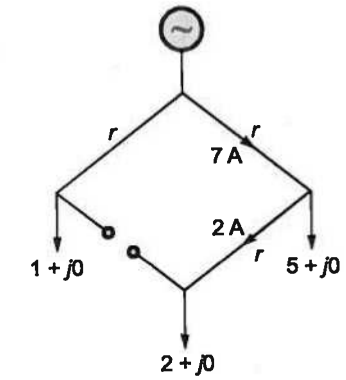


When branch e_2 is opened, total losses in the system is



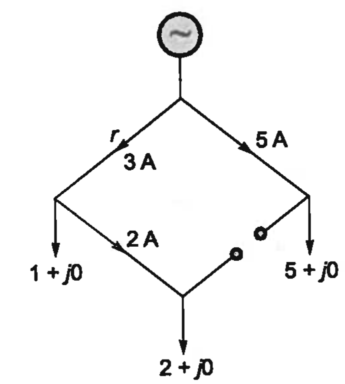
$$P_2 = 8^2r + 7^2r + 5^2r = 138r \text{ Watt}$$

When branch e_3 is opened, total losses in the system is



$$P_3 = 1^2r + 7^2r + 2^2r = 54r \text{ Watt}$$

When branch e_4 is opened, total losses in the system is

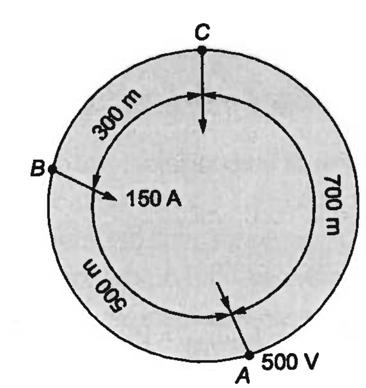


$$P_4 = 3^2r + 2^2r + 5^2r = 38r \text{ Watt}$$

Thus, when e_4 is opened losses will be minimum.

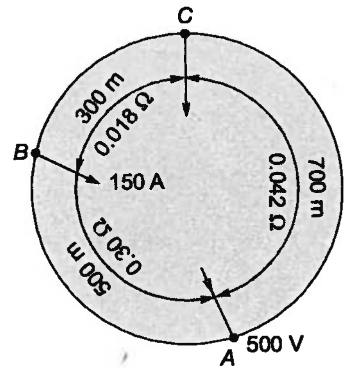
Hence, option (d) is correct.

Example - 3.7 **In a dc ring main shown in figure, a voltage of 500 volts is maintained at *A*. At *B* a load of 150 A is taken and at *C* a load of 200 A is taken. Find the voltages at *B* and *C*. The resistance of each conductor of the main is 0.03 Ω per kilometer.**



Solution:

Resistance of both conductors of section *AB* of the ring main is



$$R_{AB} = \frac{2 \times 0.03}{1000} \times 500 = 0.03\ \Omega$$

Similarly, $$R_{BC} = \frac{2 \times 0.03 \times 300}{1000} = 0.018\ \Omega$$

and $$R_{AC} = \frac{2 \times 0.03 \times 700}{1000} = 0.042\ \Omega$$

Let I_1 be the current flowing in section *AB* then, current in section *BC* will be $(I_1 - 150)$ *A* and in section *CA* will be $(I_1 - 350)$ *A*.

Using Kirchhoff's voltage law, we have

$$I_{AB}R_{AB} + I_{BC}R_{BC} + I_{CA}R_{CA} = 0$$

or, $0.03I_1 + 0.018(I_1 - 150) + 0.042(I_1 - 350) = 0$

or, $$I_1 = \frac{17.40}{0.09} = 193.3\ \text{A}$$

Current in section *AB* is,

$I_1 = 193.3$ A (flowing from *A* to *B*)

Current in section *BC* is,

$I_2 = 193.3 - 150 = 43.3$ A (flowing from *B* to *C*)

∴ Voltage at *B* is, $V_B = V_A - I_1R_{AB} = 500 - 193.3 \times 0.03 = 494.2$ V

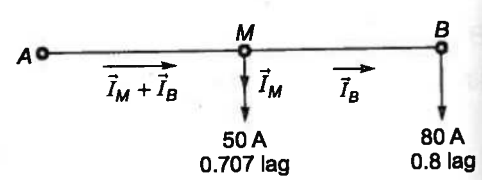
and voltage at *C* is, $V_C = V_B - I_{BC}R_{BC}$

$= 494.2 - 43.3 \times 0.018 = 493.42$ V

Example - 3.8 **A single-phase distributor has loop resistance of 0.3 Ω and a reactance of 0.4 Ω. The far end of the distributor has a load current of 80 A and power factor of 0.8 lagging at 220 V. The mid-point *M* of the distributor has a load current of 50 A at power factor of 0.707 lagging with reference to voltage *M*. Calculate the sending end voltage and power factor.**

Solution:

The situation is shown in figure.



Impedance of section *AB* is, $\vec{Z}_{AB} = (0.3 + j0.4)\ \Omega$

Since *M* is the mid-point of the distributor therefore,

$$\vec{Z}_{AM} = \vec{Z}_{MB} = \frac{\vec{Z}_{AB}}{2} = (0.15 + j0.2)\ \Omega$$

Let voltage at the far end be the reference voltage.

i.e. $\vec{V}_B = 220\angle 0°$ volt

Then, $\vec{I}_B = 80\angle{-36.86°}$ A

So, $\vec{V}_M = \vec{V}_B + \vec{I}_B\vec{Z}_{MB} = 220\angle 0° + (80\angle{-36.86°})(0.15 + j0.2)$

or, $\vec{V}_M = 239.26\angle 1.34°$ volts or $2.39.203\angle 1.334$ volts

Now, at *M*, Current $= 50$ A at 0.707 lag w.r.t $\vec{V}_M$

or, $\phi = \cos^{-1}(0.707) = 45°$

so, $\vec{I}_M = 50\angle{-43.66°}$ A

Now, $\vec{V}_A = (\vec{I}_B + \vec{I}_M)\vec{Z}_{AM} + \vec{V}_M$

$= (80\angle{-36.86°} + 50\angle{-43.66°})(0.15 + j0.2) + (239.26\angle 1.34°)$

or, $\vec{V}_A = 271\angle 2.8°$ volts

Also, sending end current will be $\vec{I}_A = \vec{I}_B + \vec{I}_M$

or, $\vec{I}_A = (80\angle{-36.86°} + 50\angle{-43.66°})$ A

or, $\vec{I}_A = 129.78\angle{-39.47°}$ A

Hence, sending end power factor $= \cos[2.8° - (-39.47°)] = 0.7399 \approx 0.74$ lag

Hence, sending end voltage, $V_A = 271$ volt and

sending end power factor $= 0.74$ lagging

Boosters

A booster is a series wound dc generator which is inserted into a circuit to add or inject a certain voltage for compensating the excessive voltage drop in the feeder. The series wound generator is coupled to a dc shunt motor. The shunt wound motor draws current from the supply mains and drives the generator coupled to it at constant speed.

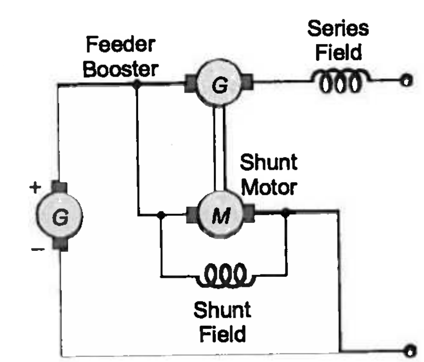


***Figure-3.10 :** Booster*

The booster must be a low voltage and high current generator working on the straight line portion of its voltage current characteristic.

3.2 Underground Cables

Underground cables are used for the transmission and distribution of power where it is impracticable to make use of overhead construction. Such location may be congested urban area where right of way cost would be excessive or local ordinances prohibit overhead lines for reason of safety, or around plants and substations.

The initial heavy cost is the only factor which has discouraged the use of underground cable for the purpose of transmission and distribution of power inspite of it's numerous advantages. Cable installations are useful for submarines, crossings, railway yard, inside power station and in density populated areas.

An electric cable may be defined as a single conductor insulated through its full length; or two or more conductors each provided with it's own insulation and laid up together under one outer protective covering.

Comparison between Overhead and Underground System

Comparison between transmission and distribution of electric power through an overhead transmission line and through an underground cable can be done as follow:

S.No.	Parameter of Comparison	Underground Cable	Overhead Line
1.	Public safety	More safter	Less safer
2.	Initial cost	Very high	Relatively less
3.	Working voltage	Upto 66 kV	Upto 400 kV or higher
4.	Maintenance cost	Very low	High
5.	Frequency if faults/failures	Very less	High
6.	Frequency of accidents	Very low	Very high
7.	Voltage drop	Low (due to less spacing)	High
8.	Fault location & repairs	Difficult	Easy
9.	Charging current	High	Less
10.	Jointing	Difficult	Easy
11.	Damage due to lightning	Negligible	High
12.	Surge effect	Absorbed by sheath	More affected (surge arrester is used)
13.	Interference to communication circuit	No. interference	Interference present

Classification of Cables

The type of cable to be used at a particular location is determined by the mechanical consideration and the voltage at which it is required to operate. According to voltage, the cables are classified as shown by the below table.

S.No.	Types of cable	Voltage level
1.	Low voltage cable (LT cable)	Upto 1 kV
2.	High voltage cable (HT cable)	Upto 11 kV
3.	Super tension cable (ST cables)	Upto 33 kV
4.	Extra high tension cables (EHT cables)	Upto 66 kV
5.	Extra super voltage cables	Upto 132 kV

NOTE: A multi-core cable may be two-core, three-core or four-core. For a 3-phase, 3-wire system either three single core cables or three core cables can be used depending upon the operating voltage and load demand.

3.3 General Construction of a Cable

An underground cable shown in Figure 3.11 consists of following components.

1. Aluminium conductor
2. Insulation or dielectric
3. Sheath
4. Bedding
5. Armouring
6. Serving

Figure-3.11 : An underground cable and it's components

The above components are explained as follows:

1. Aluminium Conductor

An underground cable consists of one central core or a number of cores (two, three or four) of tinned stranded copper or aluminium conductors which provides path for power transmission.

2. Insulation or Dielectric

Insulation or dielectric in an underground cable withstands the operating voltage. The aluminium conductor is insulated from each other by paper or varnished cambric or vulcanized bitumen or impregnated paper. For upto 11 kV HV system, paper insulation is used. When oil is used as an insulating material then, it is called ***oil-filled cables*** which is used to avoid the formation of voids. Oil -filled cables require small amount of insulation and are used for voltages from 66-400 kV. Sometimes SF_6 gas is used as a dielectric medium in a ***"gas-filled cable"***. One advantage of the gas-filled cable is its better heat dissipation by natural convection in the gas. Oil filled and gas filled cables are used in the range of 132 kV to 500 kV.

3. Sheath

A metallic ***"sheath"*** of lead or alloy or of aluminium is provided around the insulation to protect it against ingress of moisture, gases or other damaging liquids (acid or alkalies) in the soil and atmosphere. The main advantages of lead sheaths are the comparative ease with which they are made in lead presses, their flexibility and high corrosion resistance while they have got drawbacks of large specific gravity, low mechanical strength, fluidity and small resistance to vibrations.

4. Bedding

A layer of ***"bedding"*** which consists of paper tape compounded with a fibrous material (i.e. jute, cotton etc.) is provided over the metallic sheath for the protection of metallic sheath against corrosion and from mechanical injury.

5. Armouring

Over the layer of bedding "armouring" consisting of one or two layers of galvanized steel wire or steel tape is provided to save the cable from mechanical injury.

6. Serving

Over the armouring, a layer of fibrous material similar to that of bedding called ***"serving"*** is provided in order to protect the armouring.

NOTE

Single core cables for ac systems are not provided with armouring because eddy currents induced in the steel armour causes additional power losses. In such cables mechanical protection is provided by plastic wrap.

Capacitance of Single-core Cable

In a single-core cable, the conductor is surrounded by the dielectric material with an outer metallic sheath. A single core cable is shown in Figure 3.12. In this type of construction, the electric field is confined to the space between the conductor and the sheath, and has circular symmetry.

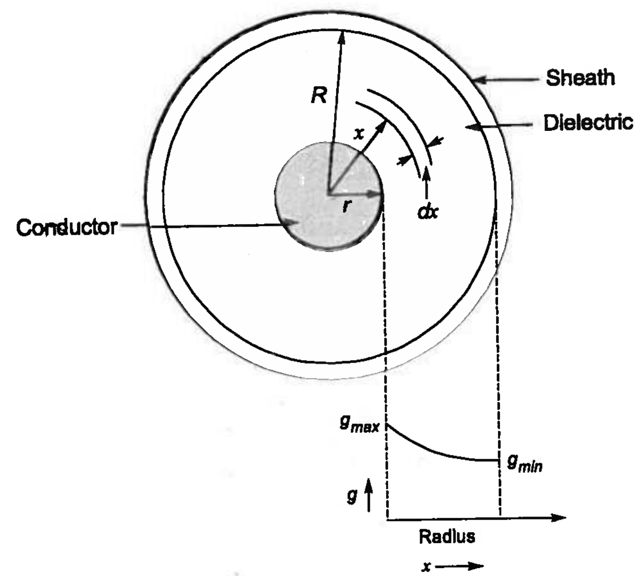


***Figure-3.12 :** Electric stress in a single core cable*

Let,
r = radius of the conductor
R = inner radius of the sheath
ε = permittivity of the dielectric
q = charge in C/m
V = potential of the conductor w.r.t. sheath
g = electric field intensity at a distance x from the center of the conductor with the dielectric material

Then,
$$g = \frac{q}{2\pi\varepsilon x} \text{ V/m} \quad \text{...(1)}$$

Now,
$$V = \int_r^R g \cdot dx = \int_r^R \frac{q}{2\pi\varepsilon x} dx = \frac{q}{2\pi\varepsilon} \ln\left(\frac{R}{r}\right) \quad \text{..(2)}$$

Hence, the capacitance between the core and the sheath is

$$C = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln\left(\frac{R}{r}\right)} \text{ F/m} \quad \text{...(3)}$$

From equations (1) and (2), we have

$$g = \frac{V}{x \ln\left(\frac{R}{r}\right)} = \text{potential gradient at a distance } x$$

Maximum dielectric stress:

It will occur at the surface of the conductor

i.e., $x_{min} = r$

so,
$$g_{max} = \frac{V}{r\ln\left(\frac{R}{r}\right)} \quad \text{...(4)}$$

Minimum dielectric stress:

It will occur at the surface of sheath i.e. at $x_{max} = R$

so,
$$g_{min} = \frac{V}{R\ln\left(\frac{R}{r}\right)} \quad \text{...(5)}$$

Dividing equation (4) by equation (5), we have

$$\frac{g_{max}}{g_{min}} = \frac{R}{r} \quad \text{...(Important result)}$$

Condition for Minimizing Maximum Dielectric Stress (Minimizing g_{max})

For $g_{max} = \dfrac{V}{r\ln\left(\frac{R}{r}\right)}$ to be minimum, denominator should be maximum.

i.e. $r\ln\left(\frac{R}{r}\right)$ should be maximum.

so, $\dfrac{d}{dr}\left[r\ln\left(\frac{R}{r}\right)\right] = 0$ for minimum g_{max}.

or, $\dfrac{R}{r} = e$ or $\dfrac{R}{r} = 2.71882$

NOTE

Dielectric stress at the surface of conductor is minimum if $\frac{R}{r} = e = 2.71882$.

Grading of Cables

Since the dielectric stress in a single core cable has a maximum value g_{max} at the conductor surface and decreases towards as we move towards sheath or away from the conductor, it is advantageous to try to have more uniform stress distribution across the dielectric. This will minimize the quantity of insulation (dielectric) needed for a given r and operating cable voltage. This technique of making the uniform dielectric stress is called ***"grading of cables"***.

It must be noted that there is little application of methods of grading because of constructional reasons.

There are two methods for grading of cables:

1. **Capacitive grading**
2. **Inter sheath grading**

1. Capacitive Grading

In capacitive grading, two or more insulating materials are used and one having larger primitivities is nearer to the conductor.

We know that gradient at a distance x from the center of the conductor is $g_x = \frac{q}{2\pi\varepsilon_0\varepsilon_r x}$. So, $g_x \propto \frac{1}{\varepsilon_0\varepsilon_r x}$

Dielectric stress can be made uniform if the product of ε_r and the distance from the center of the conductor to the inner surface of the dielectric is same.

Let there be three layers of dielectric of outer radii r_1, r_2 and R and of dielectric strength ε_1, ε_2 and ε_3 as shown in Figure 3.13.

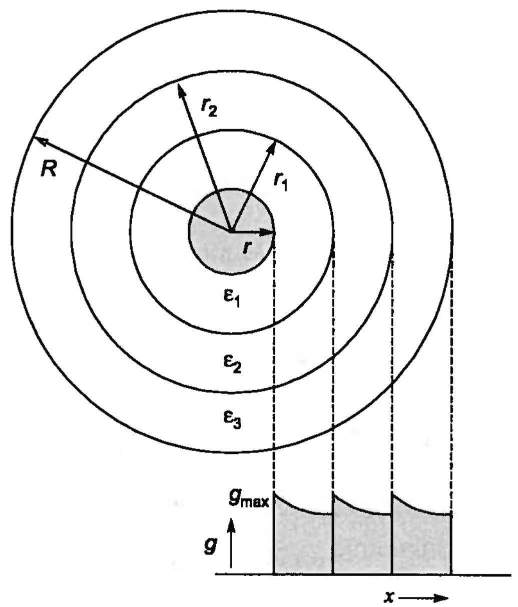


Figure-3.13 : *Capacitance grading of cables*

Now for dielectric stress to be uniform, ε_x should be equal

i.e., $\varepsilon_1 r = \varepsilon_2 r_1 = \varepsilon_3 r_2$

As $r < r_1 < r_2$ therefore, $\boxed{\varepsilon_1 > \varepsilon_2 > \varepsilon_3}$

This clearly shows that the material with the highest dielectric strength should be placed near to the conductor and other layers should be in the descending order of the dielectric strength.

Using Figure 3.12, the total operating voltage of the cable for the working stress of g_{max} is given by

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

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

Also, capacitance of cable is

$$C = \frac{q}{V} = \frac{q}{\frac{q}{2\pi\varepsilon_0}\left[\frac{1}{\varepsilon_1} ln\left(\frac{r_1}{r}\right) + \frac{1}{\varepsilon_2} ln\left(\frac{r_2}{r_1}\right) + \frac{1}{\varepsilon_3} ln\left(\frac{R}{r_2}\right)\right]}$$

or,
$$C = \frac{2\pi\varepsilon_0}{\frac{1}{\varepsilon_1} ln\left(\frac{r_1}{r}\right) + \frac{1}{\varepsilon_2} ln\left(\frac{r_2}{r_1}\right) + \frac{1}{\varepsilon_3} ln\left(\frac{R}{r_2}\right)}$$

Disadvantage of Capacitance Grading

The disadvantage of capacitance grading is that when a dielectric is damaged it must be replaced by a similar dielectric thereby increasing the initial investment.

2. Intersheath Grading

In this method of cable grading a homogenous dielectric is used, which is divided into various layers, by suitably placing the metallic intersheaths. These metallic intersheaths are maintained at the appropriate potential by being connected to tappings on the winding of an auxiliary transformer supplying the cable as shown in Figure 3.14.

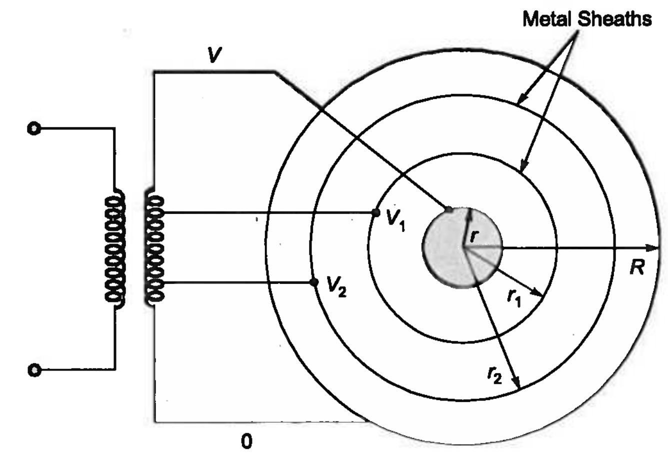


Figure-3.14 : *Intersheath grading of cable*

Due to a definite potential difference between the inner and outer radii of each sheath, it can be considered as a homogenous single core cable.

From Figure 3.14, we can write

$$g_{max_1} = \frac{V_1}{r\, ln\left(\frac{r_1}{r}\right)}, \quad g_{max_2} = \frac{V_2}{r_1\, ln\left(\frac{r_2}{r_1}\right)}$$

with a single intersheath in the dielectric as shown in Figure 3.15,

$$g_{max_1} = \frac{V_1}{r\, ln\left(\frac{r_1}{r}\right)} \quad \text{and} \quad g_{max_2} = \frac{V_2}{r_1\, ln\left(\frac{R}{r_1}\right)}$$

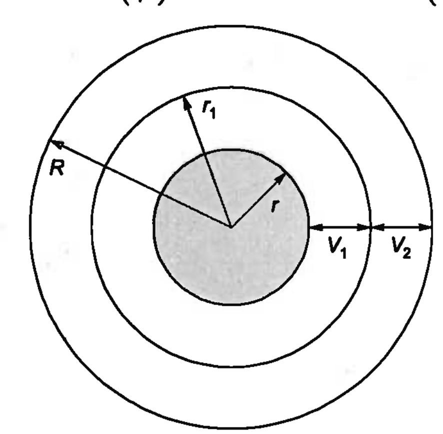


Figure-3.15 : *Single intersheath cable*

Now, for uniform dielectric stress, we have

$$g_{max_1} = g_{max_2} = g_{max} \quad \text{or} \quad \frac{V_1}{r\,ln\left(\frac{r_1}{r}\right)} = \frac{V_2}{r\,ln\left(\frac{R}{r}\right)}$$

Potential difference between the conductor and sheath is

$$V = V_1 + V_2 = r\,g_{max_1}\left(\frac{r_1}{r}\right) + r_1 g_{max_2}\left(\frac{R}{r_1}\right)$$

or

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

Now, for most economical size of the cable, we have

$$ln\left(\frac{r_1}{r}\right) = 1 \quad \text{or} \quad \frac{r_1}{r} = e \quad \text{or} \quad \boxed{r_1 = er} \qquad \text{...(1)}$$

For uniform dielectric stress,

$$g_{max_1} = \frac{V_1}{r\,ln\left(\frac{r_1}{r}\right)} \quad \text{or} \quad g_{max_1} = \frac{V_1}{r.1} \qquad \text{[Using equation (1)]}$$

or,

$$r = \frac{V_1}{g_{max_1}} \quad \text{or} \quad r = \frac{V_1}{g_{max}} \qquad (\text{Since } g_{max_1} = g_{max_2} = g_{max}) \qquad \text{...(2)}$$

Equating equation (1) and (2), we get

$$r_1 = er = \frac{eV_1}{g_{max}} \qquad \text{...(3)}$$

Also, $g_{max_1} = g_{max_2} = g_{max}$

or,

$$\frac{V_2}{r_1 ln\left(\frac{R}{r_1}\right)} = \frac{V_1}{r} \quad \text{or} \quad ln\left(\frac{R}{r_1}\right) = \frac{r}{r_1}\cdot\frac{V_2}{V_1} = \frac{1}{e}\left(\frac{V-V_1}{V_1}\right) = \frac{1}{e}\left(\frac{V}{V_1}-1\right) \qquad (\text{Since } V = V_1 + V_2)$$

or,

$$\frac{R}{r_1} = e^{\frac{1}{e}(V/V_1 - 1)} \quad \text{or} \quad R = r_1 e^{\frac{1}{e}\left(\frac{V}{V_1}-1\right)} \qquad \text{...(4)}$$

Putting the value of r_1 from equation (3) into equation (4), we get

$$R = \frac{eV_1}{g_{max}} e^{\frac{1}{e}\left(\frac{V}{V_1}-1\right)} = \frac{V_1}{g_{max}} e^{\frac{1}{e}\frac{V}{V_1}} \cdot e^{-\frac{1}{e}} \cdot e^1$$

$$= \frac{V_1}{g_{max}} \cdot e^{\frac{V}{eV_1}} \cdot e^{\left(1-\frac{1}{e}\right)} = \left(\frac{e^{(1-1/e)}}{g_{max}}\right) \cdot V_1 \cdot e^{\frac{V}{eV_1}}$$

or,

$$R = AV_1 e^{\frac{V}{eV_1}} \qquad \left(\text{where, } A = \frac{e^{(1-1/e)}}{g_{max}}\right) \qquad \text{...(5)}$$

Remember

For minimum size of cable, the radius of sheath must be minimum.

So,

$$\frac{dR}{dV_1} = 0 \quad \text{or} \quad \frac{d}{dV_1}\left(AV_1 \cdot e^{\frac{V}{eV_1}}\right) = 0$$

or,

$$AV_1 \cdot e^{\frac{V}{eV_1}} \cdot \left(\frac{-V}{eV_1^2}\right) + Ae^{\frac{V}{eV_1}} = 0 \quad \text{or} \quad AV_1 \cdot e^{\frac{V}{eV_1}} \cdot \left(\frac{V}{eV_1^2}\right) = Ae^{\frac{1}{eV_1}}$$

or,

$$\frac{V}{eV_1} = 1 \quad \text{or} \quad V = eV_1$$

or,

$$V_1 = \frac{1}{e}V \qquad \text{...(Important result)}$$

To find radius of conductor or core:

$$r = \frac{V_1}{g_{max}} = \frac{V}{eg_{max}} \qquad \text{...(6)}$$

Now,

$$r_1 = er = \frac{eV}{eg_{max}} = \frac{V}{g_{max}} \qquad \text{...(7)}$$

$$R = AV_1 e^{V/eV_1} = A\cdot\frac{V}{e}\cdot e^{\frac{V}{eV/e}} = A\cdot\frac{V}{e}\cdot e = AV$$

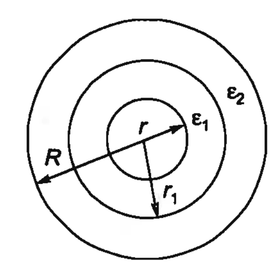
or,

$$R = \left(\frac{e^{(1-1/e)}}{g_{max}}\right)V \qquad \text{...(8)}$$

or,

$$R = 1.881\cdot\frac{V}{g_{max}} \qquad \text{...(9)}$$

Example - 3.9 **For the cable with one intersheath shown in figure below, obtain the condition under which the maximum values of the electric fields in the two regions are equal.**



Solution:

The electric field at a distance x is given by

$$E = \frac{Q}{2\pi\varepsilon x}$$

In region 1, electric field is maximum at $x = r$ i.e. at the surface of the conductor.

In region 2, E is maximum at the surface of intersheath.

For field to be equal in both regions,

$$\frac{Q}{2\pi\varepsilon_1 r} = \frac{Q}{2\pi\varepsilon_2 r_1} \quad \text{or} \quad \varepsilon_1 r = \varepsilon_2 r_1$$

Since $r < r_1$ therefore, for same value of electric fields in the two regions, $\varepsilon_1 > \varepsilon_2$ i.e. the dielectric constant of insulation closer to the conductor should be higher than the dielectric constant of the outer insulation.

Example - 3.10 **Three insulating materials with breakdown strengths of 250 kV/cm, 200 kV/cm, 150 kV/cm and primitivities of 2.5, 3.0 and 3.5 are used in a single core cable. If the factor of safety for the material is 5, the location of the materials w.r.t the core of the cable will be**

(a) 2.5, 3.0, 3.5 **(b) 3.0, 2.5, 3.5**
(c) 3.5, 3.0, 2.5 **(d) 3.5, 2.5, 3.0**

Solution: (a)

Since dielectric stress it always maximum at the surface of the conductor therefore, the material having breakdown strength of 250 kV/cm should be nearest to the core of the cable and that having 150 kV/cm should be fartest from the cable.

Example - 3.11 **A single core cable, consisting of 1 cm diameter cable inside a 2.8 cm diameter sheath, is 20 km long and operates at 13 kV and 50 Hz. The relative permittivity of the dielectric is 5, and the open circuit power factor of the cable is 0.08. The capacitance of the cable and its charging current are respectively**

(a) 5.4 μF, 9 A **(b) 3.8 μF, 10.5 A**
(c) 5.4 μF, 22.05 A **(d) 3.8 μF, 7.68 A**

Solution: (c)

Capacitance per kilometer of the cable is given by

$$C = \frac{2\pi\varepsilon_0\varepsilon_r}{ln\left(\frac{R}{r}\right)} = \frac{2\pi\times 8.854\times10^{-12}\times5}{ln\left(\frac{2.8}{1}\right)} = 0.27\ \mu\text{F/km}$$

Since length of the cable = 20 km therefore, total capacitance of the cable = 0.27 × 20 = 5.4 μF

Also, charging current, $I_C = \frac{V}{X_C} = V\cdot\omega C$

$= 2\pi \times 50 \times 5.4 \times 10^{-6} \times 13 \times 10^3$

$= 22.05$ A

Example - 3.12 **The electrostatic stress in a single core belted cable is**

(a) same throughout the insulation layer
(b) minimum at conductor surface and maximum at sheath
(c) maximum at conductor surface and minimum at sheath
(d) none of the above

Solution: (c)

Example - 3.13 **A 66 kV, single core metal sheathed cable is to be graded by means of a metallic intersheath. Calculated the diameter of the intersheath and the voltage at which it must be maintained in order to obtain minimum overall cable diameter. The maximum voltage gradient at which the insulating material can be worked is 60 kV/cm.**

Solution:

Rms value of the cable voltage is V_{rms} = 66 kV

and maximum value is $V_{max} = 66\sqrt{2}$ kV

Given, g_{max} = 60 kV/m

Let, r be the conductor diameter, r_1 be the outer diameter of the inner insulating layer and R be the outer diameter of the outer insulating layer.

Also, let V_1 = p.d between core and sheath

V_2 = p.d. between intersheath and the outersheath

then,
$$g_{max} = \frac{V_1}{\frac{r}{2}ln\left(\frac{r_1}{r}\right)} = \frac{V_2}{\frac{r_1}{2}ln\left(\frac{R}{r_1}\right)}$$

For minimum overall diameter of the cable,

Conductor diameter,
$$r = \frac{2V_{max}}{e\times g_{max}} = \frac{2\times66\sqrt{2}}{2.71828\times60} = 1.144\ \text{cm}$$

and diameter of intersheath,

$$r_1 = er = 2.71828 \times 1.144 = 3.1\ \text{cm}$$

Voltage between conductor and intersheath is

$$V_1 = \frac{V}{e} = \frac{66}{2.71828} = 24.28\ \text{V}$$

Voltage between the intersheath and sheath overall = $V - V_1$ = 66 − 24.28 = 41.72 kV

Capacitance of Three-core Belted Type Cables

The capacitance of a cable is much greater than that of an overhead line of the same length due to the narrow spacing between the conductors themselves as well as between the conductors and earthed sheath. Moreover, the permittivity of the dielectric medium used in cable has a higher dielectric strength compared to that of air due to which capacitance of a cable becomes very large compared to overhead line.

Due to the potential difference between pairs of conductors and between each conductor and sheath there is a system of electrostatic fields in the cross-section of the cable as shown in Figure 3.16.

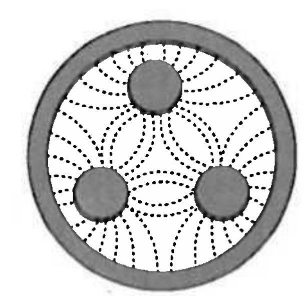


***Figure-3.16 :** A 3-core belted cable with an electrostatic field*

Let, C_c = Capacitance between cores
and C_s = Capacitance between core and sheath

Then, the delta-connected capacitance of the cable shown in Figure 3.17 can be converted into equivalent star-connected capacitances as shown in Figure 3.18.

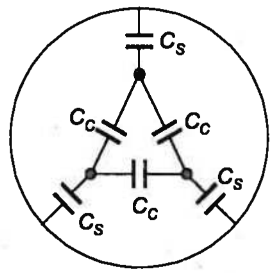


Figure-3.17
A delta-connected 3-core belted cable

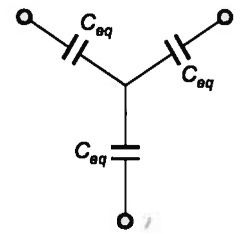


Figure-3.18
Equivalent star-connected capacitances

Then, $C_{eq} = 3\,C_c$ ...(1)

If the star point and the sheath are at zero potential, then the capacitance per phase or capacitance of each core to neutral will be

$$C_N = C_0 = C_{eq} + C_s = (3\,C_c + C_s) \qquad ...(2)$$

Let, V_{ph} be the phase voltage then, charging current is given by

$$I_C = 2\pi f V_{ph} C_N \qquad ...(3)$$

The values of C_c and C_s can be determined by various measurements which are explained by different cases as follows:

Case-I

Capacitance between the three core bunched together and the earthed sheath.

The situation is shown by Figure 3.19 where three capacitances C_c are eliminated leaving the three capacitances C_s in parallel.

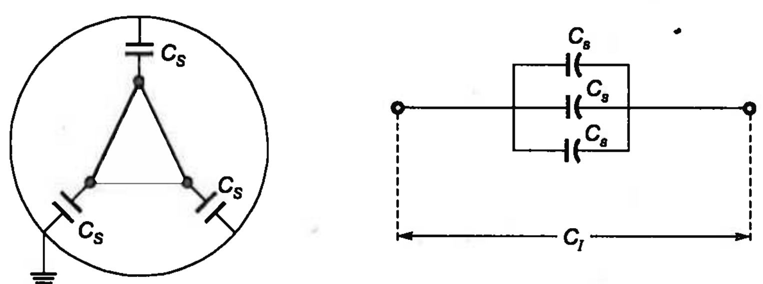


Figure-3.19

Let, the equivalent capacitance be C_I, then

$$C_I = 3\,C_s \quad \text{or} \quad C_s = \frac{C_I}{3} \qquad \text{...(Important result)} \qquad ...(4)$$

Case-II

Capacitance between the two cores or lines with the third core either insulated or connected to sheath.

The situation is shown in Figure 3.20 which eliminates one of the capacitances C_s. Let the equivalent capacitance be C_{II}.

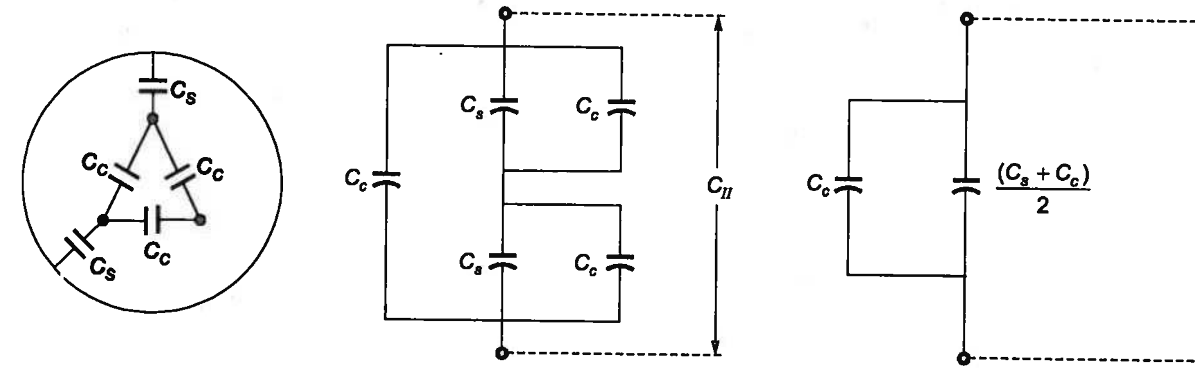


Figure-3.20

Hence, $$C_{II} = C_c + \left(\frac{C_s + C_c}{2}\right) = \frac{1}{2}(3C_c + C_s) = \frac{1}{2}C_N \qquad \text{[Using equation (2)]}$$

or, $$C_{II} = \frac{C_N}{2} \qquad \text{....(Important result)} \qquad ...(5)$$

Case-III

Capacitance between the two cores shorted with the sheath and the third core.

The situation is shown in Figure 3.21. Let the equivalent capacitance be C_{III}.

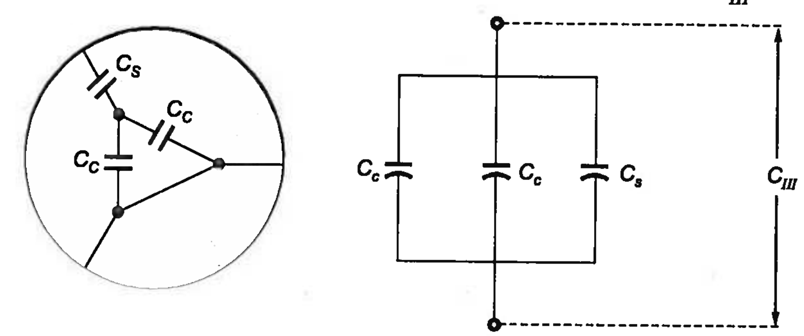


Figure-3.21

The equivalent capacitance becomes,

$$C_{III} = (2\,C_c + C_s) = C_0 - C_c \quad (\text{Since, } C_0 = 3\,C_C + C_s) \quad \text{...(Important result)} \qquad ...(6)$$

Case-IV

Capacitance between two joined cores and the third core.

The situation is shown in Figure 3.22 where the capacitance C_c between the two conductors which are joined together is eliminated.

Let the equivalent capacitance be C_{IV}.

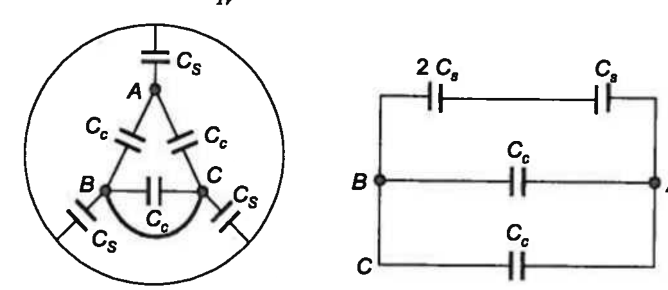


Figure-3.22

Now, $C_{IV} = 2C_c + \frac{2}{3}C_s = \frac{2(C_s + 3C_c)}{3} = \frac{2}{3}C_0$

So, $C_{IV} = \frac{2}{3}(C_s + 3C_c) = \frac{2}{3}C_0$ ...(Important result) ...(7)

Insulation Resistance of a Single-core Cable

The cable conductor is provided with an insulation of suitable thickness so as to avoid leakage current and the opposition offered by the insulation to this leakage current is called the **"insulation resistance"** of the cable.

Leakage current flows through the dielectric from the surface of the conductor to the surface of the sheath.

Let us consider a single core cable of conductor radius r_1, internal sheath radius r_2, length l and insulation material resistivity ρ as shown in Figure 3.23.

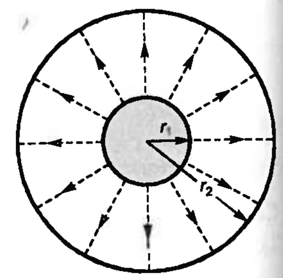


Figure-3.23

The resistance of the element in the radial direction is

$$dR_i = \frac{\rho dr}{2\pi r l}$$

$$\therefore \quad R_i = \int_{r_1}^{r_2} \frac{\rho dr}{2\pi r l} = \frac{\rho}{2\pi l}[\ln r]_{r_1}^{r_2} = \frac{\rho}{2\pi l} \ln\left(\frac{r_2}{r_1}\right) \quad ...(8)$$

Hence, insulation resistance of cable, $\boxed{R_i \,\alpha\, \frac{1}{l}}$ ...(Important result) ...(9)

Dielectric Loss in a Cable

The power loss occuring in the cable due to the insulation resistance is known as ***"dielectric power loss"***. Dielectric loss is caused by dielectric absorption or polarization.

The charging current of a cable I has two components:

One being true capacitance current which is equal to ωCV and leads the applied voltage by 90° and the other being the energy component which is in phase with the applied voltage represents the dielectric loss component of current.

Hence, the equivalent circuit consists of parallel combination of leakage resistance R_i (represents dielectric power loss) and capacitance C as shown in Figure 3.24 (a) with it's phasor diagram shown in Figure 3.24 (b).

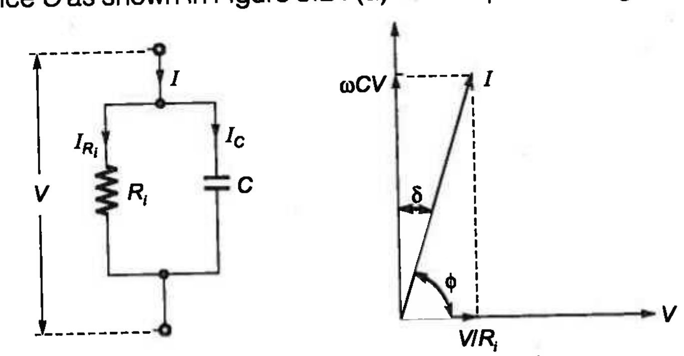


***Figure-3.24**: (a) Equivalent circuit of a cable (b) Phasor diagram of figure (a)*

Let, V = applied voltage
C = capacitance of cable
ϕ = phase angle between V and I (p.f. angle of cable)
δ = loss angle of the dielectric

Now, charging current, $I_C = \frac{V}{X_C} = \frac{V}{\left(\frac{1}{\omega C}\right)} = \omega CV$

∴ Dielectric loss/phase, $P_d = VI\cos\phi = VI\sin\delta$ [∵ ϕ = (90° − δ)]

or, $P_d = V \cdot \frac{I_C}{\cos\delta} \cdot \sin\delta = V\,\omega CV\tan\delta$

or, $P_d = \omega CV^2 \tan\delta$ ...(Important result) ...(10)

Since δ is very small, therefore tanδ ≈ δ (radian) and hence, dielectric power loss per phase becomes,

$P_d = (V^2 \omega C\delta)$ Watts ...(Important result) ...(11)

NOTE

- Dielectric power loss in cable is, $P_d \,\alpha\, V^2 \,\alpha\, \omega \,\alpha\, C$
- P_d is small upto a voltage of 33 kV, but increases as the voltage is increased.
- The dielectric loss leads to the heating of cable.
- The dielectric loss in cable is due to the loss in the equivalent resistance R_i.
- For a 3-core cable, dielectric loss = 3 $V^2 \omega C \delta$ Watts.

Example-3.14 **The insulation resistance of a single core cable is 160 MΩ/km. The insulation resistance for 4 km length is**

(a) 80 MΩ **(b) 40 MΩ**
(c) 120 MΩ **(d) 320 MΩ**

Solution: (b)

We know that insulation resistance of a cable is inversely proportional to the length of the line.

i.e., $R_i \,\alpha\, \frac{1}{l}$

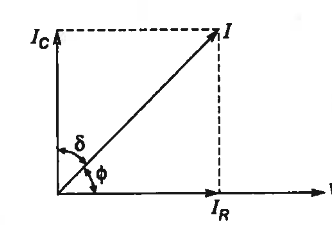
so, $\frac{R_{i_2}}{R_{i_1}} = \frac{1}{4}$ or $R_{i_2} = \frac{1}{4}R_{i_1} = \frac{1}{4} \times 160 = 40$ MΩ

Example-3.15 **The loss angle of a cable is δ. The power factor is**

(a) cos δ **(b) tan δ**
(c) δ **(d) sin δ**

Solution: (d)

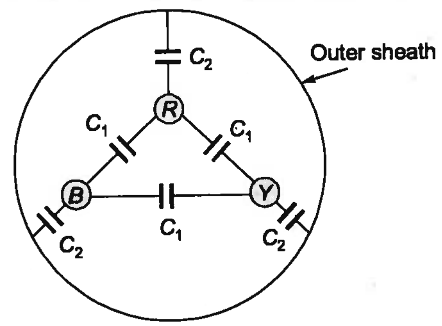
The phasor diagram for the equivalent circuit of a cable is shown below.



Here, ϕ = power factor angle = (90 − δ)

∴ Power factor = cosϕ = cos(90 − δ) = sin δ

Example - 3.16 Consider a three-core, three-phase, 50 Hz, 11 kV cable whose conductors are denoted as R, Y, B in the figure. The inter-phase capacitance (C_1) between pair of conductors is 0.2 μF and the capacitance between each line conductor and the sheath is 0.4 μF. The per phase charging current is



(a) 2.0 A (b) 2.4 A
(c) 2.7 A (d) 3.5 A

Solution: (a)

Given, $C_1 = C_c = 0.2$ μF and $C_s = C_2 = 0.4$ μF

$$V_{ph} = \frac{11}{\sqrt{3}} \text{ kV}$$

Per phase capacitance,

$$C_0 = C_s + 3\,C_c = 0.4 + 3 \times 0.2 = 1 \text{ μF}$$

∴ Per phase charging current is

$$(I_C)_{ph} = \frac{V_{ph}}{X_c} = \frac{V_{ph}}{\left(\frac{1}{\omega C_0}\right)} = V_{ph}\,\omega C_0$$

$$= \frac{11 \times 10^3}{\sqrt{3}} \times 2\pi \times 50 \times 1 \times 10^{-6} \approx 2 \text{ A}$$

Example - 3.17 The capacitance of the 3-core cable belted are measured and found to be as follows:

(*i*) between 3-cores bunched together and the sheath 10 μF.
(*ii*) between conductor and other two connected together to the sheath 6 μF.
Calculate the capacitance to neutral and the total charging KVA when the cable is connected to a 11 kV, 50 Hz 3-phase supply.

Solution:

Given, $C_I = 3C_s = 10$ μF (Case-I of previous article of cable)

$C_{III} = 2C_c + C_s = 6$ μF (Case-II of previous article)

Now, $C_s = \frac{C_I}{3} = \frac{10}{3}$ μF

and $C_{III} = 2C_c + C_s = 6$ μF or $C_c = \frac{6 - C_s}{2} = \left(\frac{6 - 10/3}{2}\right)$

or, $C_c = \frac{8}{6} = \frac{4}{3}$ μF

∴ Capacitance to neutral is, $C_0 = C_s + 3C_c = \frac{10}{3} + 3 \times \frac{4}{3} = \frac{10}{3} + 4 = \frac{22}{3}$ μF or $C_0 = 7.33$ μF

The total charging KVA $= \omega C_0 V^2$

$= 2\pi \times 50 \times 7.33 \times 10^{-6} \times (11 \times 10^3)^2$

$= 278.637$ KVA

Example - 3.18 A 3-core, 3-phase metal sheated cable had (*i*) capacitance of 1 μF between shorted conductors and sheath and (*ii*) capacitance between two conductors shorted with the sheath and the third conductor 0.6 μF. Find the capacitance

(*i*) between any two conductors and
(*ii*) between any two shorted conductors and the third conductor.

Solution:

Capacitance between shorted conductor and sheath is

$C_I = 3C_s = 1$ μF (Refer to Figure 1.39 of previous article)

or, $C_s = \frac{1}{3} = 0.333$ μF

Now, capacitance between two conductors shorted with sheath and the third conductor (refer to Figure 3.21 of previous article) is

$$C_{III} = 2C_c + C_s = 0.6 \text{ μF}$$

or, $C_c = \frac{0.6 - C_s}{2} = \frac{0.6 - 0.333}{2} = 0.1333$ μF

(*i*) Capacitance between any two cores

$$= \frac{1}{2}(3C_c + C_s) = \frac{C_0}{2} = \frac{1}{2}[3 \times 0.1333 + 0.333] = 0.36645 \text{ μF}$$

(*ii*) Capacitance between any two shorted conductors and the third conductor (refer to Figure 3.22 of previous article) is

$$C_{IV} = \left(2C_c + \frac{2}{3}C_s\right) = 2 \times 0.1333 + \frac{2}{3} \times 0.333 = 0.488 \text{ μF}$$

Example - 3.19 A single core cable 1.0 km long has a core diameter of 0.5 cm and diameter under sheath 2.0 cm. The relative permittivity of the insulating material is 3.5. The power factor on open circuit is 0.05 and the supply voltage is 11 kV, 50 Hz. Determine

(*i*) the capacitance of the cable.
(*ii*) the charging current per conductor.
(*iii*) the dielectric loss and
(*iv*) the equivalent insulation resistance.

Solution:

(*i*) Capacitance of the cable is

$$C = \frac{0.024\,\varepsilon_r}{\log\left(\frac{R}{r}\right)}$$

Here, $R = 2$ cm $= 0.02$ m,

$r = 0.05$ cm $= 0.005$ m,

$\varepsilon_r = 3.5$

So, $$C = \frac{0.024 \times 3.5}{\log\left(\frac{0.02}{0.005}\right)} \times 10^{-6} = 0.1395 \text{ μF}$$

(ii) Charging current, $I_C = \omega CV = 2\pi \times 50 \times 0.1395 \times 10^{-6} \times \frac{11 \times 10^3}{\sqrt{3}} = 0.278$ A

(iii) Power factor on open circuit is: $\cos\phi = 0.05$

$\therefore$ $\phi = \cos^{-1}(0.05) = 87.134°$

$\therefore$ Dielectric loss angle, $\delta = (90° - 87.134°) = 2.866°$

so, Dielectric loss $= \omega CV^2 \tan\delta$

$$= 2\pi \times 50 \times 0.1395 \times 10^{-6} \times \left(\frac{11 \times 10^3}{\sqrt{3}}\right)^2 \tan 2.866° = 88.5 \text{ Watts}$$

(iv) The equivalent insulation resistance of the cable is

$$R_i = \frac{V^2}{\text{Dielectric loss}} = \frac{(11 \times 10^3 / \sqrt{3})^2}{88.5} = 0.456 \text{ M}\Omega$$

3.4 Insulator for Overhead Lines

Overhead lines are suspended, which in turn are supported by towers or poles. The line conductors are secured to the supported structures by means of insulating fixtures, called the ***"insulators"*** so that there is no current leakage to the earth through the supports.

Insulators are mounted on the cross arms and the line conductors are attached to the insulators so as to provide the conductors proper insulation and also provide necessary clearances between conductors and metal work. Insulators are the most important and vulnerable links in transmission and distribution practice. Insulators are designed and manufactured for a certain voltage range. The maximum voltage per insulator is about 33 kV.

Properties of an Overhead Line Insulators

The import properties which an overhead line insulator must posses are as follows:

1. **High relative permittivity:** A high value of relative permittivity provide high dielectric strength.
2. **High mechanical strength:** Mechanical strength should be high so that the insulator bears the load due to the weight of line conductors, wind force and ice loading.
3. **High insulation resistance:** It prevents leakage of current to earth.
4. **High ratio of flash-over voltage.**
5. **Ability to withstand large temperature variations:** Insulators should not crack due to high temperature during summer and low temperature during winter.

Insulating Materials

The various materials used for overhead line insulators are:

1. **Porcelain:** It is produced by firing at a controlled temperature a mixture of Kaolin, quartz and feldspar. Porcelain in mechanically stronger than glass. It is less susceptible to temperature variation, leakage current effect on it is very less and is not affected by dirt deposits. The dielectric strength of a sound porcelain insulator is above 6.5 kV/mm of its's thickness.
2. **Glass:** Glass insulators can be used only upto 25 kV under ordinary atmospheric conditions and well upto 50 kV in dry atmosphere. It can withstand higher compressive stresses as compared to porcelain. It has lower coefficient of thermal expansion which minimizes the strain. It has a dielectric strength of 14 kV/mm of the material.
3. **Steatite:** It is a naturally occuring magnesium silicate combined with oxides in various proportions. It has higher tensile and bending stress than porcelain and are used at tension towers or when transmission line takes a sharp turn.

Types of Insulators

Various types of insulators used for overhead transmission and distribution lines are described as follows:

1. **Pin-type insulator:** These are used upto 50 kV only because they become uneconomical for higher voltages. The main advantage of a pin-type insulator is that it is cheaper. The modern practice is not to use it beyond 33 kV.
2. **Suspension-type insulator:** Suspension insulators are made in the form of discs, and a number of them are used together in a flexible string for the voltage range desired, the conductor being attached to the lower end. The entire unit of suspension insulator is called ***string***. Each unit of suspension type insulator is designed for low voltage (about 11 kV) and can be used for connecting them in series, the number depending on the working voltage. The suspension insulators are held in horizontal plane.
3. **Strain-type insulators:** When there is a dead end of the line, or there is a corner or a sharp curve, or the line crosses river etc., a strain-type insulator is used. For low-voltage line (upto 11 kV), ***"shackle insulators"*** can be used, but for higher voltage transmission lines ***"strain insulators"*** consisting of an assembly of ***"suspension type insulators"*** are used. The strain-type insulators are employed in vertical plane.

Figure 3.25 (a), (b) and (c) shows the arrangement of different insulators used in transmission and distribution system.

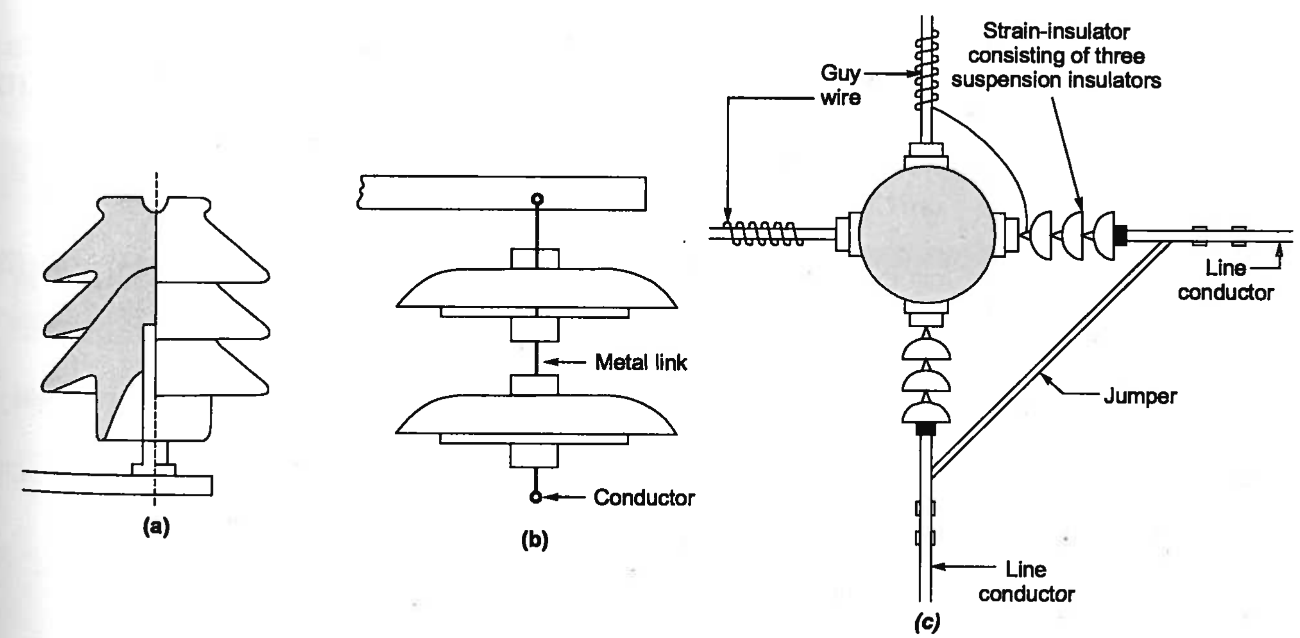


***Figure-3.25:** (a) A pin-type insulator (b) A suspension-type insulator and (c) A strain type insulator*

Potential Distribution Over A String of Suspension Insulators

Due to the capacitance between the metal parts of the insulators and the lower structure, the voltage across the various units of string insulator does not divide equally.

Figure 3.26 shows an equivalent circuit of a string of four identical insulator units.

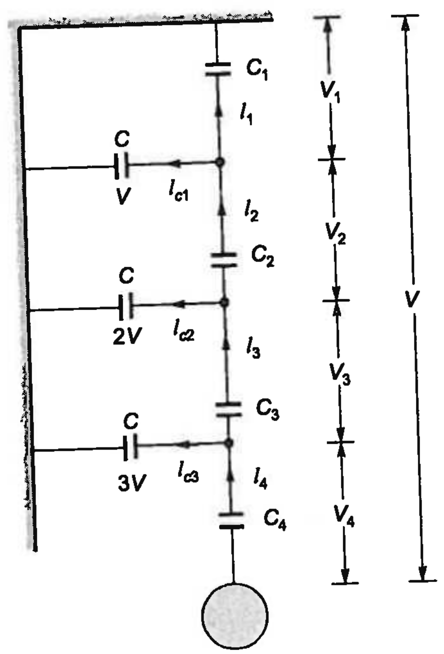


Figure-3.26 : Potential distribution over a string of four insulators

Let the capacitance between the metal part of two insulator disc and transmission tower be C.

Also,
$$m = \frac{\text{Capacitance per insulator}}{\text{Capacitance to ground}} = \frac{mC}{C}$$

where,
$$C_1 = C_2 = C_3 = C_4 = mC$$

Let V be the operating line-to-ground voltage and V_1, V_2, V_3 and V_4 be the voltage drops across the units.

where,
$$V = V_1 + V_2 + V_3 + V_4 \quad ...(1)$$

Using Figure 3.26, we have
$$I_2 = I_1 + I_{C1}$$

or,
$$\omega m\, CV_2 = \omega m\, CV_1 + \omega\, CV_1 \quad \text{(where } \omega = \text{angular frequency)}$$

or,
$$V_2 = V_1\left(1 + \frac{1}{m}\right) \quad ...(2)$$

Also,
$$I_3 = I_2 + I_{C2}$$

or,
$$\omega m\, CV_3 = \omega m\, CV_2 + \omega C(V_1 + V_2)$$

Substituting V_2 for equation (2) in above equation and simplifying, we get
$$V_3 = V_1\left(\frac{m^3 + 3m + 1}{m^2}\right) = V_1\left(1 + \frac{3}{m} + \frac{1}{m^2}\right) \quad ...(3)$$

similarly,
$$I_4 = I_3 + I_{C3}$$

or,
$$\omega m CV_4 = \omega_m CV_3 + \omega C(V_1 + V_2 + V_3)$$

Substituting V_3 from equation (3) in above equation, we get
$$V_4 = V_1\left(\frac{m^2 + 3m + 1}{m^2} + \frac{3m^2 + 4m + 1}{m^3}\right)$$

or,
$$V_4 = V_1\left(1 + \frac{6}{m} + \frac{5}{m^2} + \frac{1}{m^3}\right) \quad ...(4)$$

Let, $m = 5$ (for string of 5 insulators) then,
$$V_2 = 1.2\, V_1,\ V_3 = 1.64\, V_1,\ V_4 = 2.408\, V_1$$

Hence, $V_1 < V_2 < V_3 < V_4$ and $I_4 > I_3 > I_2 > I_1$

NOTE: Potential distribution is maximum near the power conductor and goes on decreasing as one moves near the cross-arm. Hence, as 'm' increases, the division of voltage becomes more equalized.

String Efficiency

String efficiency is a measure of the utilization of material in the string. There is a capacitance between metal fitting of each insulator unit and the earthed pole or tower. The capacitance so formed is called ***"shunt capacitance"*** or ***"stray capacitance"***. Due to this shunt capacitance, charging current is not the same through all the discs of the string. So, voltage across individual units, being directly proportional to the current flowing through them, will be different. This unequal potential distribution is undesirable and is usually expressed in terms of string efficiency.

Percentage string efficiency is defined as
$$\%\eta = \left(\frac{\text{Voltage across the string}}{n \times \text{voltage across the unit adjacent to line}}\right) \times 100 \quad \text{...(Important result)}$$

where, n = total number of insulators in a string.

String efficiency is also defined as,
$$\%\eta = \left(\frac{\text{Flash-over voltage of the string}}{n \times \text{flash-over voltage of one unit}}\right) \times 100 \quad \text{...(Important result)}$$

Example:

If
$$V = 60 \text{ kV},\ m = 5, \text{ then}$$
$$V = V_1(1 + 1.2 + 1.64 + 2.408) = 6.248\, V_1$$

and
$$V_1 = 9.6 \text{ kV},\ V_2 = 11.5 \text{ kV}$$
$$V_3 = 15.8 \text{ kV},\ V_4 = 23.1 \text{ kV}$$
$$\%\eta = \frac{60}{4 \times 23.1} = 63.8\%$$

Remember: The string efficiency indicates the extent of wastage. Although the string efficiency can't be made 100% but it's value should be as high as possible.

Methods of Improving String Efficiency

Some of the methods which can be used to improve the string efficiency are as follows:

1. **Selection of m:** As m is increased by increasing the length of cross arm, C is reduced and hence, the division of voltage becomes more equalized as a result of which string efficiency improves. The value of m lies between 0 to 10.
2. **By capacitance grading:** The non-uniform distribution of voltage across an insulator string is due to leakage current from the insulator pin to the supporting structure and since the voltage for a given current is inversely proportional to the capacitance the unit nearest to the cross arm should have the maximum capacitance in order to reduce the voltage across it. Also, as we move towards the power conductor the unit capacitance should decrease. By correct grading of the capacitances, complete equality of voltage can be achieved. This is called ***"capacitance grading"*** shown in Figure 3.27.

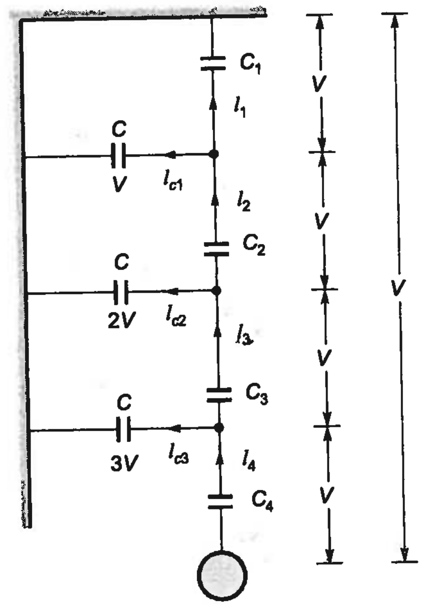


***Figure-3.27 :** Capacitance grading over a string of four insulators*

Let the capacitance between the metal work and the power conductor be negligible.
Let the mutual capacitance be C_1 to C_4 and the ground capacitance be C.
Using Figure 3.27 and applying KCL, we get

$$I_2 = I_1 + I_{C1} = \omega v(C + C_1) = \omega vC_2$$

or, $\omega v(C_1 + C_2) = \omega vC_2$ or $C_1 + C = C_2$ ...(5)

Voltage producing I_{C2} is $2v$

∴ $I_{C2} = 2\omega Cv$

Now, $I_3 = I_2 + I_{C2}$

or, $\omega C_3 v = 2\omega Cv + \omega(C + C_1)\, v$

or, $C_3 = 3C + C_1 = C_1 + (1 + 2)\, C$ ...(6)

Hence, the capacity for the n^{th} unit is

$$C_n = C_1 + (1 + 2 + 3 + ... + \overline{n-1})C \quad ...(7)$$

If $C_1 = 5\,C$ then, we have $C_2 = 6\,C$, $C_3 = 8\,C$, $C_4 = 11\,C$ and so on.

NOTE

The disadvantage of capacitance grading is that it require a large number of different-sized insulator units which is uneconomical and impractical. In order to avoid these limitations, static shielding is used which employ identical insulator discs.

3. **Static shielding:** In this method, the voltage distribution is equalized by providing ***grading***, or ***guard ring***, in the form of a large metal ring surrounding the bottom unit and connected to the metal work at the bottom of this unit, and therefore to the line. This helps to cancel exactly the pin to tower charging currents so that the same current flows through the units of identical capacities to produce equal voltage drops across each unit as shown in Figure 3.28.

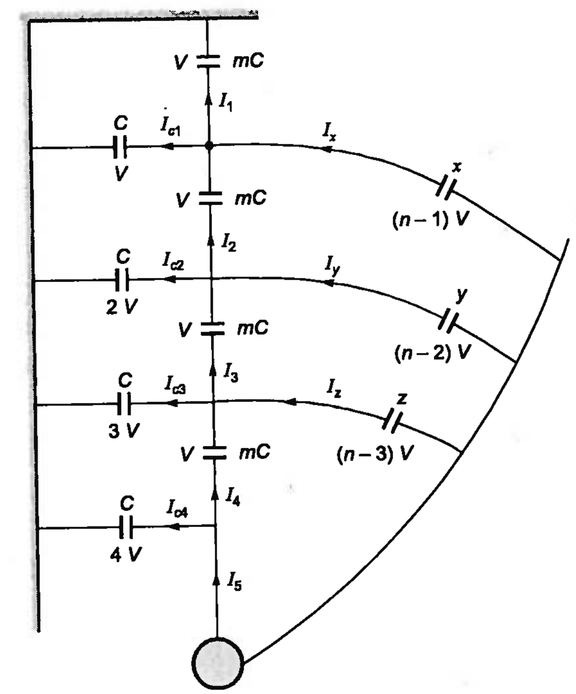


***Figure-3.28 :** Static shielding*

From Figure 3.28 using KCL, we can write,

$$I_2 = I_1 + I_{C1} - I_x$$

$$I_3 = I_2 + I_{C2} - I_y \text{ and so on}$$

For a voltage of v across each identical units, the currents $I_1 = I_2 = I_3$.

Hence, $I_x = I_{C1}$, $I_y = I_{C2}$, $I_z = I_{C3}$ and so on

∴ $vC\omega = (n - 1)\, v x\omega$

and $2\, vC\omega = (n - 2)\, v y\omega$ and $3\, vC\omega = (n - 3)\, v z\omega$

From above equations, we obtain $x = \dfrac{C}{(n-1)}$, $y = \dfrac{2C}{n-2}$ and $z = \dfrac{3C}{n-3}$

In general, the capacitance from the shield to the K^{th} link from the top is

$$C_K = \left(\frac{KC}{n-K}\right) \quad \text{...(Important result)} \quad ...(8)$$

Example - 3.20 **A string insulator has 5 units. The voltage across the bottom most unit is 25% of the total voltage. The string efficiency is**

(a) 25% **(b) 50%**

(c) 80% **(d) 75%**

Solution : (c)

String efficiency is given by $\%\eta = \left(\dfrac{\text{Voltage across the string}}{\eta \times \text{voltage across the unit adjacent to line}}\right) \times 100$

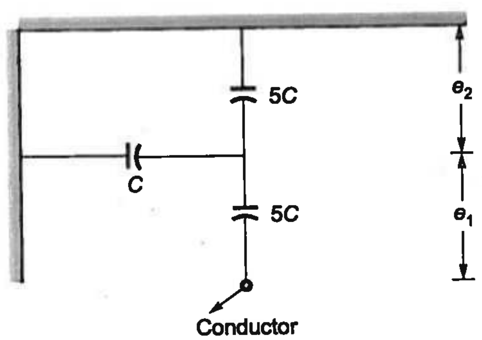
$$= \left(\frac{V}{5 \times \frac{V}{4}}\right) \times 100 = \frac{4}{5} \times 100 = 80\%$$

Example-3.21 Grading ring is used to neutralize the potential distribution across the units of the suspension insulator because it

(a) forms capacitances which help to cancel the charging current from link pins.
(b) form capacitances with link pins to cancel the charging current from link pins.
(c) increases the capacitances of lower insulator units.
(d) decrease the capacitances of upper insulator units.

Solution: **(a)**

Example-3.22 Consider a three-phase, 50 Hz, 11 kV distribution system. Each of the conductor is suspended by an insulator string having two identical porcelain insulators. The self capacitance of the insulator is 5 times the shunt capacitance between the link and the ground, as shown in the Figure. The voltage across the two insulators are



(a) $e_1 = 3.74$ kV, $e_2 = 2.61$ kV
(b) $e_1 = 3.46$ kV, $e_2 = 2.89$ kV
(c) $e_1 = 6.0$ kV, $e_2 = 4.23$ kV
(d) $e_1 = 5.5$ kV, $e_2 = 5.5$ kV

Solution:

Given, $m = \dfrac{5C}{C} = 5$ and $n = 2$

From given figure
(Here, in figure e_1 and e_2 have opposite positions as original)

$$v_1 = v_2 + \frac{v_2}{5} = v_2 + \frac{v_2}{5} = 1.2\, v_2$$

Here, $v_2 = e_2$ and $v_1 = e_1$

so, $e_1 = v_1 = 1.2\, e_2$ ...(1)

Also, $e_1 + e_2 = \dfrac{11}{\sqrt{3}}$ kV (Given)

or, $e_1 + e_2 = 6.351$ kV ...(2)

solving equations (1) and (2), we get

$e_1 = 3.46$ kV and $e_2 = 2.89$ kV

Example-3.23 In a string of three identical insulator units supporting a transmission line conductor, if the self capacitance of each unit is denoted by C farads, the capacitance of each connector pin to ground can be taken as $0.1C$ farads. Determine the voltage distribution across the string if the maximum permissible voltage per unit is given as 20 kV. Also determine the string efficiency.

Solution:

Given: $n = 3$

Here, self capacitance = $mC = C$ farad

pin to ground capacitance = 0.1 C farad

so, $m = \dfrac{C}{0.1C} = 10$

Now, voltage across the bottom most unit is

V_3 = safe working voltage of the unit = 20 kV

Also, $V_3 = V_1\left(1 + \dfrac{3}{m} + \dfrac{1}{m^2}\right)$

or, $$V_1 = \left(\frac{V_3}{1 + \frac{3}{m} + \frac{1}{m^2}}\right) = \left(\frac{20}{1 + \frac{3}{10} + \frac{1}{100}}\right) = 15.267 \text{ kV}$$

Voltage across the middle unit is

$$V_2 = V_1\left(1 + \frac{1}{m}\right) = 15.267\left(1 + \frac{1}{10}\right) = 16.794 \text{ kV}$$

and maximum safe working voltage of the string is

$V = V_1 + V_2 + V_3$

$= 15.267 + 16.794 + 20 = 52$ kV

Also, string efficiency is, $\%\eta = \dfrac{V}{nV_3} \times 100 = \dfrac{52}{3 \times 20} \times 100 = 86.667\%$

Example-3.24 A string of five suspension insulators is to be fitted with a grading ring. If the pin to earth capacitances are equal to C, find the values of line to pin capacitances that would give a uniform voltage distribution along the string.

Solution:

Given, $n = 5$

pin-to-earth capacitance = C

Using equation (8) of the previous article, the capacitance of the K^{th} metal link to the line is given by

$$C_K = \frac{K \times \text{pin-to-earth capacitance}}{(n-K)} = \frac{KC}{n-p}$$

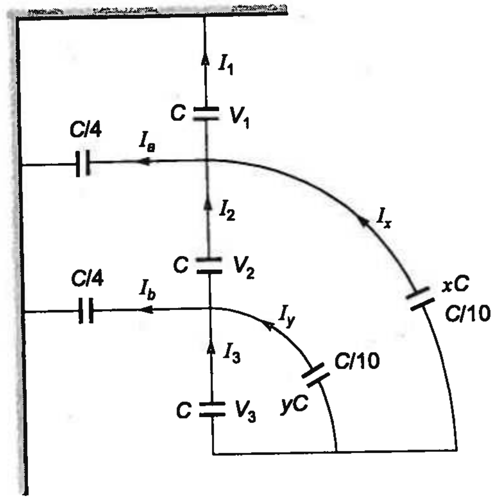
Hence, $C_1 = \dfrac{1 \times C}{5-1} = \dfrac{C}{4} = 0.25C$

$C_2 = \dfrac{2 \times C}{5-1} = \dfrac{2}{3}C = 0.667C$

$C_3 = \dfrac{3 \times C}{5-3} = 1.5C$

and $C_4 = \dfrac{4 \times C}{5-4} = 4C$

Example - 3.25 Calculate the string efficiency of a 3-unit suspension insulator of given figure if the capacitance of the link pins to earth and the line are respectively 25% and 10% of self capacitance *C* of each unit. What should be the values of link pins to the line capacitance for 100% string efficiency?



Solution:

Applying KCL at the node of the given figure, we have

$$I_2 = I_1 + I_a - I_x$$

or, $$\omega C V_2 = \omega C V_1 + \frac{1}{4}\omega C V_1 - \frac{1}{10}\omega C(V_2 + V_3)$$

or, $$25V_1 - 22V_2 - 2V_3 = 0 \qquad ...(1)$$

Again, $$I_3 = I_2 + I_b - I_y$$

or, $$\omega C V_3 = \omega C V_2 + \frac{1}{4}\omega C(V_1 + V_2) - \frac{1}{10}\omega C V_3$$

or, $$5V_1 + 25V_2 - 22V_3 = 0 \qquad ...(2)$$

Therefore, $$V = V_1 + V_2 + V_3 \qquad ...(3)$$

Solving equations (1), (2) and (3), we get

$$V_1 = \frac{466}{1809}V,\quad V_2 = \frac{520}{1809}V,\quad V_3 = \frac{735}{1809}V$$

Hence, string efficiency is given by

$$\%\eta = \frac{V}{3\times\left(\frac{735}{1809}\right)V} = 82.1\% \text{ or } 82.04\%$$

For 100% string efficiency, $V_1 = V_2 = V_3$

and $I_1 = I_2 = I_3$

Therefore, $$I_a = I_x \text{ or } \frac{1}{4}\omega C V_1 = \omega x C\cdot 2V_1 \text{ or } x = \frac{1}{8}$$

Also, $$I_b = I_y \text{ or } \frac{1}{4}\omega C\cdot 2V_1 = \omega y C V_1 \text{ or } y = \frac{1}{2}$$

Hence, for 100% string efficiency, link-pin-to line capacitance will be xC and yC i.e. $\frac{1}{8}C$ and $\frac{1}{2}C$.

Important Expressions

1. Power loss in AC single-phase 2-wire system is $\alpha \frac{1}{(V\cos\phi)^2}$.

2. The maximum dielectric stress occurs at the surface of conductor and is given by $\left[g_{max} = \frac{V}{r\ln\left(\frac{R}{r}\right)}\right]$

3. The minimum dielectric stress ocurrs at the surface of sheath and is given by $\left[g_{min} = \frac{V}{R\ln\left(\frac{R}{r}\right)}\right]$

4. $\left[\frac{g_{max}}{g_{min}} = \frac{R}{r}\right]$

5. For minimum dielectric stress at the surface of conductor, the condition is $\left[\frac{R}{r} = 2.7188\right]$

6. Using capacitance grading, the cable capacitance is given by

$$C = \left(\frac{2\pi\varepsilon_0}{\frac{1}{\varepsilon_1}\ln\left(\frac{r_1}{r}\right) + \frac{1}{\varepsilon_2}\ln\left(\frac{r_2}{r_1}\right) + \frac{1}{\varepsilon_3}\ln\left(\frac{R}{r_2}\right)}\right)$$

7. The cable capacitance of each core to neutral is, $C_N = (3C_C + C_S) = C_0$

   The charging current is, $I_C = 2\pi f V_{ph} C_N$

8. Capacitance between the three cores bunched together and the earthed sheath is given by

   $\boxed{C_I = 3C_S}$

9. Capacitance between the two cores or lines with the third core either insulated or connected to sheath is given by $\boxed{C_{II} = \frac{1}{2}C_N = \frac{1}{2}(3C_C + C_S)}$

10. Capacitance between the two cores shorted with the sheath and the third core is given by $[C_{III} = (2C_C + C_S) = (C_0 - C_C)]$

11. Capacitance between two jointed cores and the third core is given by $\left[C_{IV} = \frac{2}{3}(C_S + 3C_C) = \frac{2}{3}C_0\right]$

12. Insulation resistance of a cable, $R_i \;\alpha \frac{1}{l}$ [where, l = length of cable]

13. Dielectric power loss in a cable is given by

$$P_d = (\omega C V^2 \tan\delta) \text{ watts}$$
$$= (V^2 \omega C \delta) \text{ watts} \qquad \text{(for small value of } \delta)$$

14. Percentage string efficiency is given by

$$\%\eta = \left(\frac{\text{Voltage across the string}}{n \times \text{voltage across the unit adjacent to line}}\right) \times 100$$

$$= \left(\frac{\text{Flash-over voltage of the string}}{n \times \text{flash over voltage of one unit}}\right) \times 100$$

15. For static shielding, the capacitance from the shield to the k_{th} link from the top is given by

$$\left[C_k = \left(\frac{kC}{n-k}\right)\right]$$

Student's Assignments 1

Q.1 In a dc ring main a voltage of 400 V is maintained at *A*. At *B* 500 meters away from *A*, a load of 150 *A* is taken; at *C* 300 meters from *B*, a load of 200 *A* is taken. The distance between *A* and *C* is 700 meters. The resistance of each conductor of the mains is 0.03 Ω per 1000 meters. Find the voltage at *B* and *C* and also find the current in section *BC*.

Q.2 A single-phase ring distributor *ABC* is fed at *A*. The loads at *B* and *C* are 20 *A* 0.8 pf lagging and 15 *A* at 0.6 pf lagging respectively, both expressed with reference to voltage at *A*. The impedance of the sections *AB*, *BC* and *CA* are (1 + *j*1), (1 + *j*2) and (1 + *j*3) ohms respectively. Find the total current fed at A and the current in each section.

Q.3 A kilometer of a 3-core, metal-sheathed cable gave the following results on a test for capacitance.

(*i*) Capacitance between bunched conductors and sheath is 1.0 μF.

(*ii*) Capacitance between two conductors bunched with the sheath and third conductor 0.6 μF.

With the sheath insulated find the capacitance

(a) between any two cores.

(b) between any two bunched conductors and the third conductor.

Q.4 A 110 kV single core metal sheathed cable is to be graded by means of a metallic inter-sheath. Find the diameter of the inter-sheath and the voltage at which it must be maintained in order to obtain the minimum overall diameter *D*. The insulating material can be worked upto 55 kV/cm.

Q.5 Each of the three insulating forming a string has a self capacitance of '*C*' Farads. The shunting capacitance of the connecting metal work of each insulator is 0.2 C to earth and 0.1 C to the line. A guard ring increases the capacitance to the line of the metal work of the lowest insulator to 0.3 C. Calculate the string efficiency of this arrangement with the guard ring.

Student's Assignments 1 Explanations

1. $V_B = 394.2$ V; $V_C = 393.42$ V; $I_{BC} = 13.3$ *A* flowing from *B* and *C*.

2. 23.1∠–32° A, 3.01∠30.1° A, 13.1∠–60.8° A, 34.6∠–34.8° A

3. (a) 0.367 μF (b) 0.489 μF

4. 5.66 cm; 69.5 kV

5. 95.24%

Student's Assignments 2

Q.1 100 per cent string efficiency means
(a) one of the insulator discs shorted
(b) zero potential across each disc
(c) equal potential across each insulator disc
(d) none of these

Q.2 Which of the following materials is not a constituent of material used in making porcelain insulators?
(a) Kaolin (b) Quartz
(c) Silica (d) Feldspar

Q.3 Pin type insulators are generally not used for voltage exceeding
(a) 66 kV (b) 33 kV
(c) 25 kV (d) 11 kV

Q.4 If the frequency of a transmission system is changed from 50 Hz to 100 Hz, the string efficiency
(a) will increase
(b) will decrease
(c) remains unchanged
(d) may increase or decrease depending on the line parameters

Q.5 The purpose of guard ring in transmission lines is to
(a) reduce the earth capacitance of the lowest unit
(b) increase the earth capacitance of the lowest unit
(c) reduce the transmission line losses
(d) none of the above

Q.6 The material commonly used for sheaths of underground cable is
(a) copper (b) lead
(c) steel (d) rubber

Q.7 The insulation resistance of the cable decreases with the
(a) increase in length of cable
(b) decrease in length of cable
(c) electric stresses
(d) none of these

Q.8 The charging current drawn by the cable
(a) lags behind the voltage by 90°
(b) leads the voltage by 90°
(c) leads the voltage by 180°
(d) none of these

Q.9 To obtain the minimum value of stress in cables, the ratio (*R*/*r*) should be
(a) 2.13 (b) 2.718
(c) 1.96 (d) 1.5

Q.10 In a cable of conductor diameter '*d*' and overall diameter with dielectric material '*D*', the maximum dielectric stress
(a) occurs at the conductor surface and is proportional to *d*.
(b) occurs at the conductor surface and is proportional to 1/*d*.
(c) occurs at the middle of the dielectric and is proportional to 1/*D*.
(a) occurs at the outer surface of the dielectric and is proportional to *D*.

Q.11 The surge impedance of a 50 miles long underground cable is 50 Ω. For a 25 miles length it will be
(a) 25 Ω (b) 50 Ω
(c) 100 Ω (d) none of these

Q.12 In a 3-core cable, the capacitance between two conductors (with sheath earthed) is 3 μF. The capacitance per phase will be

(a) 1.5 μF (b) 3 μF
(c) 6 μF (d) 12 μF

Q.13 Consider the following statements:
1. The insulation resistance of cable will increase if the length of cable is increased.
2. For the same overall diameter of cable, the grading of cable will increase the safe working voltage.
3. The normal operating temperature of PVC cable is 70°C.
4. The thermal resistance of soil increases as the moisture content of soil increases.

Of these statements:
(a) 1 and 2 are correct
(b) 2 and 3 are correct
(c) 3 and 4 are correct
(d) 1 and 4 are correct

Q.14 The booster
(a) is a series wound dc generator driven by dc shunt motor.
(b) is a low voltage and high current generator operating on straight or linear portion of its voltage current characteristic.
(c) is a high voltage and low circuit machine.
(d) both (a) and (b)

Q.15 The distributors in residential areas are
(a) single-phase, two-wire
(b) three-phase, three-wire
(c) three-phase, four-wire
(d) two-phase, four-wire

Q.16 The distribution system which is most reliable is
(a) minimize the stress
(b) provide protective against moisture and voltage surges
(c) use inferior insulation
(d) provide property stress distribution

Q.17 Capacitance grading of cable means
(a) use of dielectrics in different concentrations.
(b) introduction of capacitances at various lengths of cable to counter the effect of inductance.
(c) use of dielectrics of different primitivities.
(d) grading according to capacitance per km length of the cable.

Q.18 Which of the following distribution system is not normally used?
(a) 3-phase, 3-wire
(b) 3-phase, 4-wire
(c) single-phase, 3-wire
(d) single-phase, 2-wire

Q.19 The main drawback (s) of overhead system over underground system is/are
(a) underground system is more flexible than overhead system
(b) higher charging current
(c) surge problem
(d) high initial cost

Q.20 Standard domestic ac supply voltage in India is
(a) 220 V (b) 250 V
(c) 240 V (d) 230 V

Q.21 In a transmission system the feeder supplies power to
(a) transformer substations (step-up)
(b) service mains
(c) distributors
(d) all of these

Q.22 For the same voltage drop, increasing the voltage of a distributor n-times
(a) reduces the X-section of the conductor by $1/n$ times
(b) increase the X-section of the conductor by $1/n$ times
(c) reduces the X-section of the conductor by $1/n^2$ times
(d) increase the X-section of the conductor by $1/n^2$ times

Q.23 The conductor connecting consumer's terminals to the distributor is called
(a) feeder (b) distributor
(c) service main (d) none of these

Q.24 HV transmission line uses
(a) pin type insulators
(b) suspension insulators
(c) both (a) and (b)
(d) none of these

Q.25 Dielectric hysteresic loss in a cable varies as
(a) impressed voltage
(b) (impressed voltage)^2
(c) (impressed voltage)$^{1/2}$
(d) (impressed voltage)$^{3/2}$

Direction of Questions (26 to 29):
Each of the following question consists of two statements, one labelled the **'Assertion (A)'** and the other labelled the **'Reason (R)'**. Examine the two statements carefully and decide if the Assertion (A) and Reason (R) are individually true and if so whether the Reason (R) is correct explanation of the Assertion (A). Select your answers to these questions using the codes given below:

Codes:
(a) Both A and R are true and R is the correct explanation of A.
(b) Both A and R are true but R is not a correct explanation of A.
(c) A is true but R is false.
(d) A is false but R is true.

Q.26 **Assertion (A):** Feeders are designed mainly from the point of view of the voltage drop in them.
Reason (R): Current loading of the feeder remains the same along its length.

Q.27 **Assertion (A):** The modern trend is to avoid grading of cables as for as possible and use gas pressure or oil-filled cables.
Reason (R): With intersheath grading, the main objection is the possibility of damage of the intersheath during transportation and installation and with capacitance grading the chief handicap is non-availability of high grade insulating materials whose permittivities can be made to vary over the required range.

Q.28 **Assertion (A):** The string efficiency can be improved by using long X-arms.
Reason (R): Use of long X-arms reduces the ratio of capacity of earth to capacity per insulator thereby increasing the string efficiency.

Q.29 **Assertion (A):** Solid system of cable laying is most suitable for short length cable routes such as in work shops, railway bridge crossings where frequent digging is costlier or impossible.
Reason (R): In solid system of cable laying the cables remain protected mechanically and from chemical reaction due to impurities present in the soil.

Q.30 Match **List-I (Type of insulators)** with **List-II (Use)** and select the correct answer using the code given below the lists:

List-I
A. Pin
B. Shackle
C. Disc
D. Egg

List-II
1. Lines of voltage upto 33 kV
2. Lines of voltage exceeding 33 kV and at dead ends, corners, sharp turns etc.
3. Low voltage lines
4. Guy cables

Codes:

	A	B	C	D
(a)	1	2	3	4
(b)	2	3	4	1
(c)	3	4	1	2
(d)	1	3	2	4

Answer Key:

1. (c)	**2.** (c)	**3.** (b)	**4.** (c)	**5.** (a)
6. (b)	**7.** (a)	**8.** (b)	**9.** (b)	**10.** (b)
11. (b)	**12.** (c)	**13.** (b)	**14.** (d)	**15.** (c)
16. (a)	**17.** (c)	**18.** (c)	**19.** (c)	**20.** (b)
21. (c)	**22.** (c)	**23.** (c)	**24.** (c)	**25.** (b)
26. (d)	**27.** (a)	**28.** (a)	**29.** (d)	**30.** (d)

Student's Assignments 2 Explanations

1. (c)
Due to the formation of stray capacitance, voltage across individual units is different (undesirable). This unequal potential distribution is usually expressed in terms of string efficiency. Hence, if the string efficiency is 100% then, it means that equal potential difference occurs across each insulator disc.

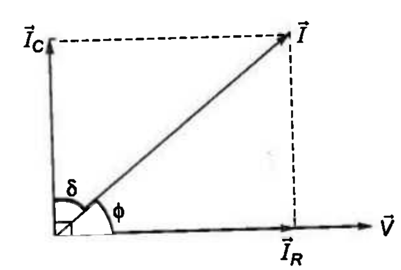
2. (c)
Porcelain is a mixture of kaolin, quartz and feldspar.

4. (c)
String efficiency remains same with the change in frequency of operation of transmission line.

7. (a)
Insulation resistance of a cable is inversely proportional to the length of the cable.

i.e. $$\boxed{R_i \propto \frac{1}{l}}$$

8. (b)



Here, $\vec{I}_C$ and $\vec{V}$ by 90°

9. (b)
Dielectric stress at the surface of conductor is minimum if $\frac{R}{r} = e = 2.718$.

10. (b)
Maximum dielectric stress always occurs at the surface of the conductor.

And, $$g_{max} = \frac{V}{r\,ln\left(\frac{R}{r}\right)}$$

Here, $r = \frac{d}{2}$ and $R = \frac{D}{2}$

Hence, $$\boxed{g_{max} \propto \frac{1}{d}}$$

11. (b)
Surge impedance of a cable or a transmission line is always independent of the length of the cable or line.

12. (c)
Capacitance between two conductors with sheath earthed is given by

$$C_{II} = \frac{C_N}{2} = \frac{1}{2}(3C_C + C_S)$$

Given, $C_{II} = 3\,\mu F$
so, $C_N = 6\,\mu F$ = capacitance per phase

15. (c)
For residential areas, a neutral is required for mixed loading. Hence, three-phase, four wire distributors are used for distribution of power.

19. (c)
Compared to overhead system, underground system are least prone to surge because they lie underground.

21. (c)
Transmission lines are feeders which suppl[y] power to distributors.

26. (d)
Feeders are designed mainly from the point o[f] view of the current carrying capacity. Hence, [A] is false.