UNIT-5

UNDERGROUND CABLES

Types of Cables, Construction, Types of insulating materials, Calculation of insulation resistance, stress in insulation and power factor of cable, Numerical Problems. Capacitance of single and 3-Core belted Cables, Numerical Problems. Grading of Cables – Capacitance grading and Inter sheath grading, Numerical Problems.

INTRODUCTION:

Underground cables are used for power applications where it is impractical, difficult, or dangerous to use the overhead lines. They are widely used in populated urban areas, in factories, and educational institutes.

An underground cable consists of one or more conductors covered with some suitable insulating material and surrounded by a protecting cover. The cable is laid underground to transmit electric power.

The underground system of electrical distribution of power in large cities in increasingly being adopted, although it is costly system of distribution as compared to overhead system. It ensures the continuity of supply apart from the following advantages:

- It ensures non-interrupted continuity of supply
- Its maintenance is less
- It has a long life
- Its appearance is good
- It eliminates hazards of electrocution due to breakage of overhead conductors.

TYPES OF CABLES:

Although several types of cables are available, the type of cable to be used will depend upon the working voltage and service requirements. In general, a cable must fulfil the following necessary requirements:

(i) The conductor used in cables should be tinned (coating the wire with tin provides it with more durability and strength) stranded copper or aluminium of high conductivity. Stranding is done so that conductor may become flexible and carry more current.

(ii) The conductor size should be such that the cable carries the desired load current without overheating and causes voltage drop within permissible limits.

(iii) The cable must have proper thickness of insulation in order to give high degree of safety and reliability at the voltage for which it is designed.

(iv) The cable mutt be provided with suitable mechanical protection so that it may withstand the rough use in laying it.

(v) The materials used in the manufacture of cables should be such that there is complete chemical and physical .ability throughout.

<u>PROPERTIES OF INSULATING MATERIAL:</u>

- High resistivity.
- High dielectric strength.
- Low thermal co-efficient.
- Low water absorption.
- Low permittivity.
- Non – inflammable.
- Chemical stability.
- High mechanical strength.
- High viscosity at impregnation temperature.
- Capability to with stand high rupturing voltage.
- High tensile strength and plasticity.

<u>INSULATING MATERIALS FOR CABLES:</u>

- **Rubber:**
  - ✓ It can be obtained from milky sap of tropical trees or from oil products.
  - ✓ It has the dielectric strength of 30 KV/mm.
  - ✓ Insulation resistivity of 10 exp 17 ohm.cm

- ✓ Relative permittivity varying between 2 and 3.
- ✓ They readily absorbs moisture, soft and liable to damage due to rough handling and ages when exposed to light.
- ✓ Maximum safe temperature is very low about 38 C

- **Vulcanized India Rubber**
  - ✓ It can be obtained from mixing pure rubber with mineral compounds i-e zinc oxide, red lead and sulphur and heated up to 150 C.
  - ✓ It has greater mechanical strength, durability and wear resistant property.
  - ✓ The sulphur reacts quickly with copper so tinned copper conductors are used.
  - ✓ It is suitable for low and moderate voltage cables.
- **Impregnated Paper**
  - ✓ This material has superseded the rubber, consists of chemically pulped paper impregnated with napthenic and paraffinic materials.
  - ✓ It has low cost, low capacitance, high dielectric strength and high insulation resistance.
  - ✓ The only disadvantage is the paper is hygroscopic, for this reason paper insulation is always provided protective covering.
- **Varnished Cambric**
  - ✓ This is simply the cotton cloth impregnated and coated with varnish.
  - ✓ As the varnish cambric is also hygroscopic so need some protection.
  - ✓ Its dielectric strength is about 4KV / mm and permittivity is 2.5 to 3.8.
- **Polyvinyl chloride (PVC)**

- ✓ This material has good dielectric strength, high insulation resistance and high melting temperatures.
- ✓ These have not so good mechanical properties as those of rubber.
- ✓ It is inert to oxygen and almost inert to many alkalis and acids.

• **XLPE Cables (Cross Linked Poly-ethene)**

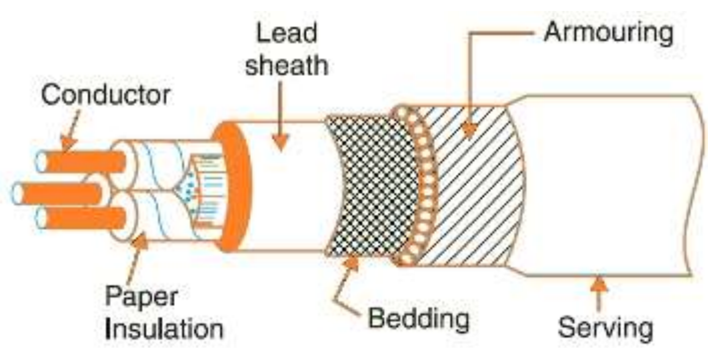
- ✓ This material has temperature range beyond 250 – 300 C
- ✓ This material gives good insulating properties
- ✓ It is light in weight, small overall dimensions, low dielectric constant and high mechanical strength, low water absorption.
- ✓ These cables permit conductor temperature of 90 C and 250 C under normal and short circuit conditions.
- ✓ These cables are suitable up to voltages of 33 KV.

<u>CONSTRUCTION OF A CABLE:</u>

The various parts of cable are:

(i) Cores or Conductors:

A cable may have one or more than one core (conductor) depending upon the type of service for which it is intended.



(ii) Insulation:

Each core or conductor is provided with a suitable thickness of insulation, the thickness of layer depending upon the voltage to be withstood by the cable. The commonly used materials for insulation are impregnated paper, varnished cambric or rubber mineral compound.

(iii) Metallic sheath:

In order to protect the cable from moisture, gases or other damaging liquids (acids or alkalies) in the soil and atmosphere, a metallic sheath of lead or aluminium is provided over the insulation as shown in Fig.

(iv) Bedding:

Over the metallic sheath is applied a layer of bedding which consists of a fibrous material like jute or hessian tape. The purpose of bedding is to protect the metallic sheath against corrosion and from mechanical injury due to armouring.

(v) Armouring:

Over the bedding, armouring is provided which consists of one or two layers of galvanized steel wire or steel tape. Its purpose is to protect the cable from mechanical injury while laying it and during the course of handling.

(vi) Serving:

In order to protect armouring from atmospheric conditions, a layer of fibrous material (like jute) similar to bedding is provided over the armouring. This is known as serving.

*Bedding, armouring and serving are only applied to the cables for the protection of conductor insulation and to protect the metallic sheath from mechanical injury.

<u>ELECTRICAL CHARACTERISTICS OF CABLES:</u>

❖Electrical Stress in Single-Core Cables

❖Capacitance of Single Core Cables

❖Charging Current

❖Insulation resistance of Single Core Cables

❖Dielectric Power Factor & dielectric Losses

❖Heating of Cables: Core loss; Dielectric Loss and Intersheath Loss

CLASSIFICATION OF CABLES:

Cables for underground service may be classified in two ways according to (i) the type of insulating material used in their manufacture (ii) the voltage for which they are manufactured. However, the latter method of classification is generally preferred, according to which cables can be divided into the following groups :

A) Low-tension (LT.) Cables upto 1000V .

B) High-tension (H.T.) Cables upto 11000V.

C) Super-tension (S.T.) Cables from 22kV to 33kV.

D) Extra-high Tension (E.H.T) Cables....... from 33kV to 66 kV.

E) Extra Super Voltage Cables beyond 132 kV.

SINGLE-CORE LOW TENSION CABLE:

A cable may have one or more than one core depending upon the type of service for which it is intended. It may be (i) single-core (ii) two-core (iii) three-core (iv) four-core etc.

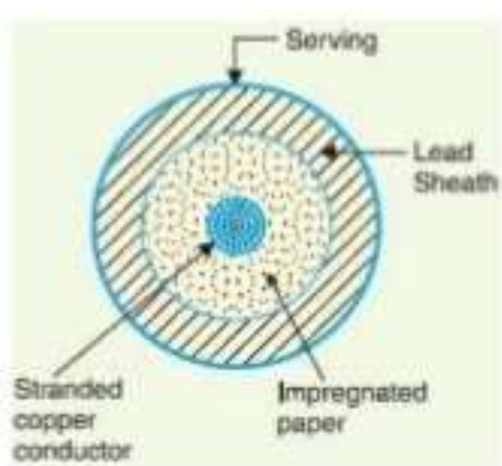


Fig. shows the constructional details of a single-core low tension cable. The cable has ordinary construction because the stresses developed in the cable for low voltages (upto 6600 V) are generally small.

It consists one circular core of tinned standard copper (or aluminium) insulated by a layer of impregnated paper. The insulation is surrounded by a lead sheath which prevents the entry of moisture into the inner parts.

In order to protect the lead sheath from corrosion, an overall serving of compounded fibrous material (jute etc.) is provided.

CABLES FOR 3-PHASE SERVICE:

To deliver 3-phase power either three-core cable or three single core cables may be used. For voltages up to 66 kV, 3-core cable (i.e., multi-core construction) is preferred due to economic reasons. For voltages beyond 66 kV, 3-core-cables become too large and bulky and, therefore, single-core cables are used.

The following types of cables are generally used for 3-phase service:

1. Belted cables — up to 11 kV

2. Screened cables — from 22 kV to 66 kV

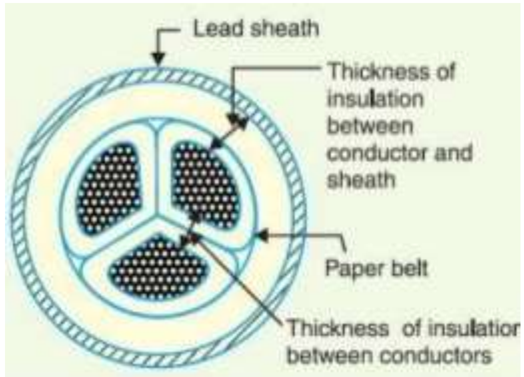
3. Pressure cables — beyond 66 kV.

BELTED CABLES

Fig. shows the constructional details of a 3- core belted cable.

The cores are insulated from each other by layers of impregnated paper. Another layer of impregnated paper tape, called paper belt is wound round the grouped insulated cores. The gap between the insulated cores is filled with fibrous insulating material (jute etc.) so as to give circular cross-section to the cable.

The cores are generally stranded and may be of noncircular shape to make better use of available space. The belt is covered with lead sheath to protect the cable against ingress of moisture and mechanical injury. The lead sheath is covered with one or more layers of armouring with an outer serving (not shown in the figure).



The belted type construction is suitable only for low and medium voltages as the electrostatic stresses developed in the cables for these voltages are more or less radial i.e., across the insulation.

The tangential stresses become important for high voltages (beyond 22 kV). These stresses act along the layers of paper insulation and set up leakage current along the layers of paper insulation. The leakage current causes local heating, resulting in the risk of breakdown of insulation at any moment.

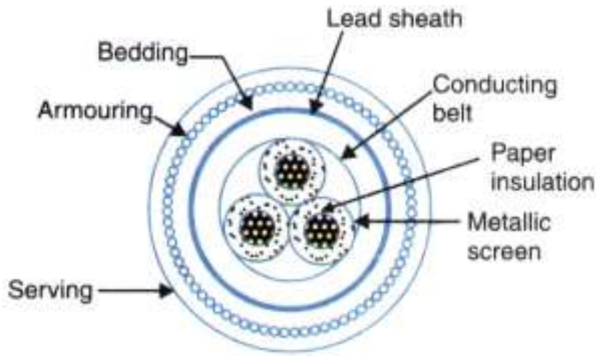
In order to overcome this difficulty, screened cables are used where leakage currents are conducted to earth through metallic screens.

SCREENED CABLES:

These cables are meant for use upto 33 kV, but in particular cases may be extended to operating voltages upto 66 kV. Two principal types of screened cables are H-type cables and S.L. type cables.

(i) H-TYPE CABLES.

This type of cable was first designed by H. Hochstadter and hence the name. Fig. shows the constructional details of a typical 3-core, H-type cable. Each core is insulated by layers of impregnated paper. The insulation on each core is covered with a metallic screen which usually consists of a perforated aluminium foil. The cores are laid in such a way that metallic screens make contact with one another.



An additional conducting belt (copper woven fabric tape) is wrapped round the three cores.

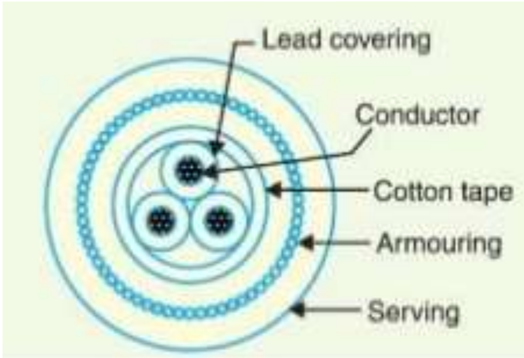
The cable has no insulating belt but lead sheath, bedding, armouring and serving follow as usual. It is easy to see that each core screen is in electrical contact with the conducting belt and the lead sheath. As all the four screens (3 core screens and one conducting belt) and the lead sheath are at earth potential, therefore, the electrical stresses are purely radial and consequently dielectric losses are reduced.

Advantages

❖Perforations in the metallic screens assist in the complete impregnation of the cable with the compound and thus the possibility of air pockets or voids (vacuous spaces) in the dielectric is eliminated. ❖ Metallic screens increase the heat dissipating power of the cable.

(ii) S.L. TYPE CABLES:

It is basically H-type cable but the screen round each core insulation is covered by its own lead sheath. There is no overall lead sheath but only armouring and serving are provided.



Advantages

❖ Separate sheaths minimise the possibility of core-to-core breakdown.

❖ Bending of cables becomes easy due to the elimination of overall lead sheath.

Disadvantage

❖ Three lead sheaths of S.L. cable are much thinner than the single sheath of H-cable and, therefore, call for greater care in manufacture.

LIMITATIONS OF SOLID TYPE CABLES:

Above cables are referred to as solid type cables because solid insulation is used and no gas or oil circulates in the cable sheath. The voltage limit for solid type cables is 66 kV due to the following reasons :

(a) As a solid cable carries the load, its conductor temperature increases and the cable compound (i.e., insulating compound over paper) expands. This action stretches the lead sheath which may be damaged.

(b) When the load on the cable decreases, the conductor cools and a partial vacuum is formed within the cable sheath. If the pinholes are present in the lead sheath, moist air may be drawn into the cable.

(c) In practice, voids are always present in the insulation of a cable. Under operating conditions, the voids are formed as a result of the differential expansion and contraction A the sheath and impregnated compound.

The breakdown strength A voids is considerably less than that A the insulation. If the void is small enough, the electrostatic stress across it may cause its breakdown. The voids nearest to the conductor are the first to break down, the chemical and thermal effects of ionization causing permanent damage to the paper insulation.

PRESSURE CABLES:

When the operating voltages are greater than 66 kV and up to 230 kV, pressure cables are used. In such cables, voids are eliminated by increasing the pressure of compound and for this reason they are called pressure cables. Two types of pressure cables viz oil-filled cables and gas pressure cables are commonly used. (i) Oil-filled cables In such types of cables, channels or ducts are provided in the cable for oil circulation. The oil under pressure (it is the same oil used for impregnation) is kept constantly supplied to the channel by means of external reservoirs placed at suitable distances (say 500 m) along the route of the cable.

Oil under pressure compresses the layers of paper insulation and is forced into any voids that may have formed between the layers.

Oil-filled cables are of three types viz., single-core conductor channel, single-core sheath channel and three-core filler-space channels.

PRESSURE CABLES-OIL FILLED:

The oil channel is formed at the centre by stranding the conductor wire around a hollow cylindrical steel spiral tape. The oil under pressure is supplied to the channel by means of external reservoir.

The disadvantage of this type of cable is that the channel is at the middle of the cable and is at full voltage w.r.t. earth, so that a very complicated system of joints is necessary. Conductors

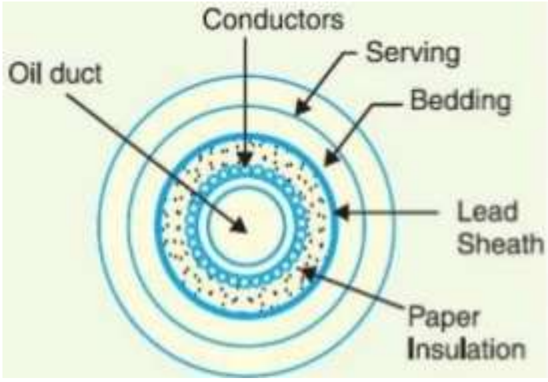
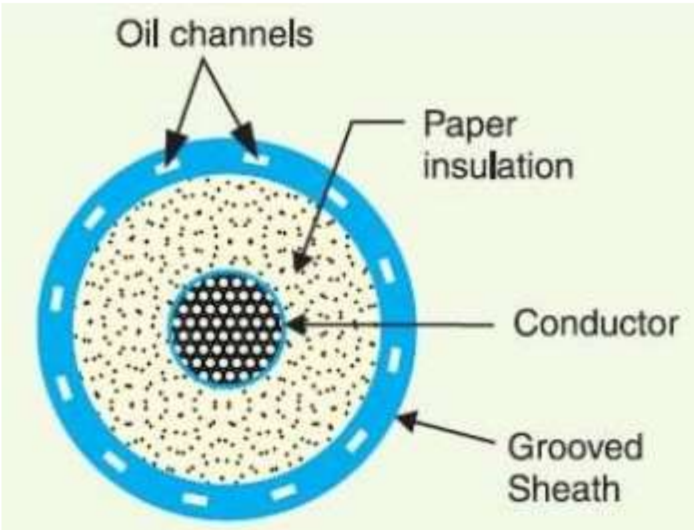


Fig. Single-core conductor channel. oil-filled cable

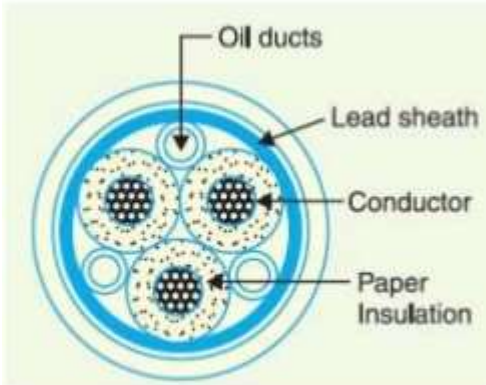
PRESSURE CABLES-OIL FILLED

Fig. shows the constructional details of a single core sheath channel oil-filled cable. In this type of cable, the conductor is solid similar to that of solid cable and is paper insulated. However, oil ducts are provided in the metallic sheath as shown.



PRESSURE CABLES-OIL FILLED:

In the 3-core oil-filler cable shown in Fig. , the oil ducts are located in the filler spaces. These channels are composed of perforated metal-ribbon tubing and are at earth potential.



The oil-filled cables have three principal advantages. Formation of voids and ionisation are avoided. Allowable temperature range and dielectric strength are increased. If there is leakage, the defect in the lead sheath is at once indicated and the possibility of earth faults is decreased. Disadvantages are the high initial cost and complicated system of laying.

GAS PRESSURE CABLES:

The voltage required to set up ionisation inside a void increases as the pressure is increased. Therefore, if ordinary cable is subjected to a sufficiently high pressure, the ionisation can be altogether eliminated. At the same time, the increased pressure produces radial compression which tends to close any voids. This is the underlying principle of gas pressure cables.

Fig. shows the section of external pressure cable designed by Hochstadter, Vogal and Bowden. The construction of the cable is of triangular shape and thickness of lead sheath is 75% that of solid cable. The triangular section reduces the weight and gives Is thermal resistance but the main reason for triangular shape is that the lead sheath acts as a pressure membrane. The sheath is protected by a this metal tape. The cable is laid in a gas-tight steel pipe. The pipe is filled with dry nitrogen gas at 12 to 15 atmospheres. The gas pressure produces radial compression and closes the voids that may have formed between the layers of paper insulation. Advantages +Such cables can carry more load current and operate at higher voltages than a normal cable. Moreover, maintenance cost is small and the nitrogen gas helps in quenching any flame. Disadvantage: the overall cost is very high.

COMPARISON BETWEEN UNDERGROUND & OVERHEAD SYSTEM :

S.No.	PARTICULAR	OVERHEAD SYSTEM	UNDERGROUND SYSTEM
1	Public safety	It is less safe.	It is more safe.
2	Initial cost	It is less expensive.	It is more expensive.
3	Faults	Faults occur frequently.	Very rare chances of faults.
4	Appearance	It gives shabby look.	Its appearance is good as wires arc not visible.
5	Flexibility	It is more flexible, as new conductors can be laid along the existing conductor.	It is not flexible, as new conductors can be laid along the existing conductor.
6	Location of fault	Fault point can be easily located.	Fault point cannot be easily located.
7	Repair	Can be easily repaired.	Cannot be easily repaired.
8	Working voltage	It can work upto 400 kV.	It can work only upto 66 kVdue to insulation difficulty.
	Lightning thunder	More chances of being subjected to lightning.	Very little chances of being subjected to lightning.
10	Supply interruption	More chances of supply interruption.	Very little chances of supply interruption.
11	Frequency of accidents	More chances of accidents.	Little chances of accidents.

12	interferes with communication system	It interferes with communication system.	No interference with communication system
13	Insulation cost	Less. The overhead conductor are bare. Supported on steel rowers, insulated from the towers through insulators.	More insulation cost. Under-ground cables are provided with various wrappings of high grade tape etc. Lead sheath is provided.
14	Erection cost	Much lees comparatively	Erection cost of high voltage cable is quite high.
15	Uses is	This is used for long distance transmission cable is quite high.	The loge charging current on high voltage limits the use of long distance transmission.

INSULATION RESISTANCE OF A CABLE

The Fig 1 shows the section of a single core cable which is insulated with the help of layer of an insulating material.

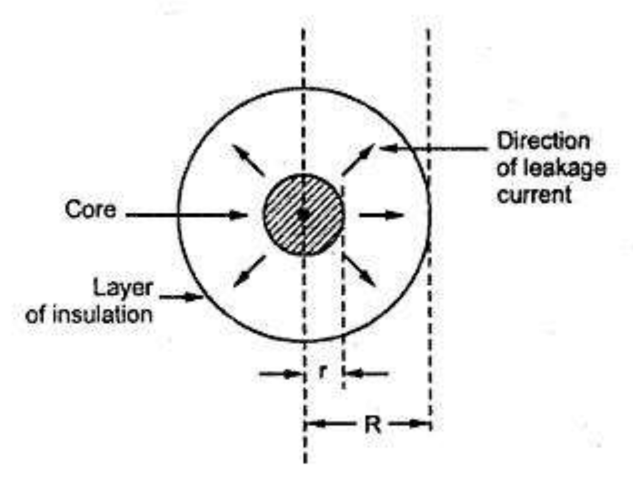


Fig. 1 Single core cable

In such cables, the leakage current flows radially from centre towards the surface as shown in the Fig.1. Hence the cross-section of the path of such current is not constant but changes with its length. The resistance offered by cable to path of the leakage current is called an insulation resistance consider an elementary section of the cylindrical cable of radius x and the thickness dx as shown in the Fig. 2. Let us find the resistance of this elementary ring.

Let d = Diameter of core

r = d/2 = Radius of core

D = Diameter with sheath

R = D/2 = Radius of cable with sheath

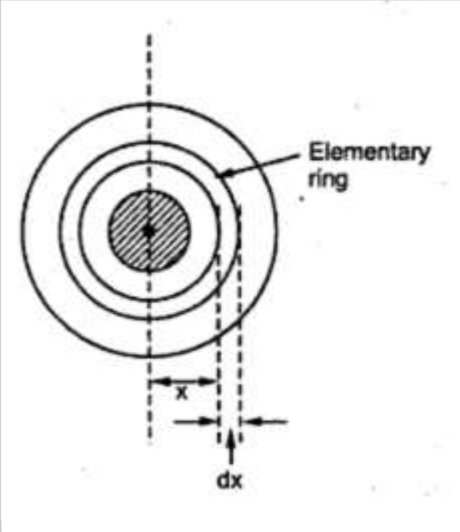


Fig. 2 Elementary ring

As the leakage current flows radially outwards, the length along which the current flows in an elementary ring is dx. While the cross-sectional area perpendicular to the flow of current depends on the length of l of the cable.

Cross-section area = Surface area for length l of cable

= (2 π x) x l

Hence the resistance of this elementary cylindrical shell is,

$$dR_i = \rho \cdot \frac{dx}{2\pi x l} \qquad \dots \text{ As } R = \frac{\rho l}{A}$$

where ρ = Resistivity of the insulating material

The total insulation resistance of the cable can be obtained by integrating the resistance of an elementary ring from inner radius upto the outer radius i.e. r to R.

$$\therefore \quad R_i = \int_r^R dR_i = \int_r^R \rho \frac{dx}{2\pi x l} = \frac{\rho}{2\pi l}\int_r^R \frac{dx}{x} = \frac{\rho}{2\pi l}[ln\,x]_r^R = \frac{\rho}{2\pi l}[ln\,R - ln\,r]$$

$$\therefore \quad \boxed{R_i = \frac{\rho}{2\pi l} ln \frac{R}{r}\ \Omega}$$

This can be expressed in terms of diameters as,

$$\boxed{R_i = \frac{\rho}{2\pi l} ln \frac{D}{d}\ \Omega}$$

The value of R_i is always very high. The expression shows that the insulation resistance is inversely proportional to its length. So as the cable length increases, the insulation resistance decreases.

This shows that if two cables are joined in series then total length increases and hence their conductor resistances are in series giving higher resistance but insulation resistance are in parallel decreasing the effective insulation resistance. Thus if two cables are connected in parallel, conductor resistances get connected in parallel while the insulation resistance get connected in series.

CAPACITANCE OF SINGLE CORE CABLE

A single core cable is equivalent to two long co-axial cylinders. The inner cylinder is the conductor itself while the outer cylinder is the lead sheath. The lead sheath is always at earth potential.

Let d = Conductor diameter

D = Total diameter with sheath

The co-axial cylindrical from of cable and its section are shown in the Fig. 1(a) and (b).

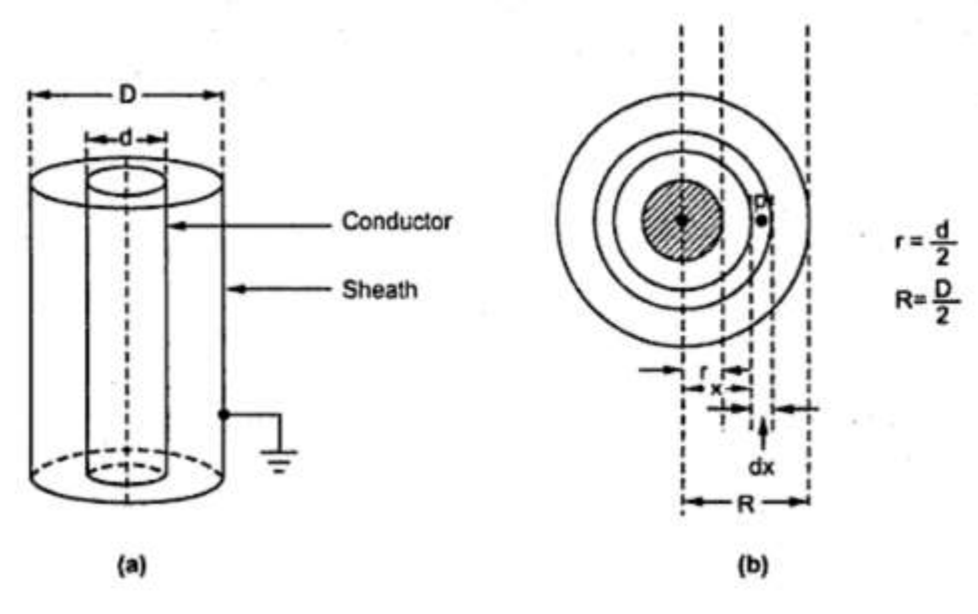


Fig. 1 Capacitance of single core cable

Let Q = Charge per meter length of conductor in coulombs

ε = Permittivity of material between core and sheath

Now $\varepsilon = \varepsilon_o \varepsilon_r$

Where ε_o = permittivity of free space = 8.854×10^{-12} F/m

and ε_r = Relative permittivity of the medium

Consider an elementary cylinder with radius x and axial length of 1 m. The thickness of the cylinder is dx.

According to Gauss's theorem, the lines of flux coming due to charge Q on the conductor are in parallel direction and total flux line are equal to the total charge possessed i.e. Q lines. As lines are in radial direction, the cross-sectional area through which lines pass is surface area. For a cylinder with radius x, the surface area is (2πx x axial length) m^2. As axial length considered is 1 m, the surface area is 2 π x m^2.

$$\therefore \quad \text{Flux density} = \frac{Q}{\text{Surface area}} = \frac{Q}{2\pi x} \ C/m^2$$

The electric field intensity at any point P on the elementary cylinder is given by,

$$\text{Minimum } g_{max} = \frac{2V}{d} \qquad \dots \text{As } \ln\left(\frac{D}{\frac{D}{2.718}}\right) = 1 \qquad \dots (5)$$

$g_x = Dx/\varepsilon$ where Dx = Electric flux density

$$= \frac{Q}{2\pi x \varepsilon} = \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r} \quad \text{V/m}$$

Hence the work done in moving a unit charge through a distance dx in the direction of an electric field is g_x dx.

Therefore the work done in moving a unit charge from the conductor to sheath is the potential difference between the conductor and the sheath given by,

$$V = \int_{d/2}^{D/2} g_x \, dx = \int_{d/2}^{D/2} \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r} dx = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} \int_{d/2}^{D/2} \frac{dx}{x} = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} [ln\ x]_{d/2}^{D/2}$$

$$= \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} \left[ln\frac{D}{2} - ln\frac{d}{2} \right]$$

$$\therefore \quad V = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} ln\left[\frac{D}{d}\right] = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} ln\left[\frac{R}{r}\right]$$

The capacitance of a cable is given by,

$$C = \frac{Q}{V} = \frac{Q}{\left[\frac{Q}{2\pi \varepsilon_0 \varepsilon_r} ln\left(\frac{R}{r}\right)\right]}$$

$$\therefore \quad \boxed{C = \frac{2\pi \varepsilon_0 \varepsilon_r}{ln\left[\frac{R}{r}\right]} \text{ F/m} = \frac{2\pi \varepsilon_0 \varepsilon_r}{ln\left[\frac{D}{d}\right]} \text{ F/m}} \quad \ldots (1)$$

Note that as length considered is 1 m, the capacitance is F/m.

If required for length 'l' multiply c by 'l'.

Substituting value of ε_o,

$$C = \frac{2\pi \times 8.854 \times 10^{-12}\varepsilon_r}{ln\left[\frac{R}{r}\right]} = \frac{5.563 \times 10^{-11}\varepsilon_r}{ln\left[\frac{R}{r}\right]}$$

$$= \frac{55.63 \times 10^{-12}\varepsilon_r}{ln\left[\frac{R}{r}\right]} = \frac{\varepsilon_r \times 10^{-6}}{\left(\frac{1}{55.63}\right) ln\left[\frac{R}{r}\right]} \; \mu F/m = \frac{\varepsilon_r \times 10^{-6}}{0.0179\, ln\left[\frac{R}{r}\right]} \; \mu F/m$$

$$= \frac{\varepsilon_r \times 10^{-6}}{0.0179 \times 10^{-3}\, ln\left[\frac{R}{r}\right]} \; \mu F/km \qquad \text{... Expressed per km}$$

$$= \frac{\varepsilon_r}{17.9\, ln\left[\frac{R}{r}\right]}$$

$$\therefore \quad \boxed{C = \frac{\varepsilon_r}{18\, ln\left[\frac{R}{r}\right]} = \frac{\varepsilon_r}{18\, ln\left[\frac{D}{d}\right]} \; \mu F/km} \qquad \text{... (2)}$$

If the length l of cable is known then the total capacitance of cable is,

$$\boxed{C = \frac{\varepsilon_r\, l}{18\, ln\left[\frac{D}{d}\right]} \; \mu F} \qquad \text{... If } l \text{ is in km}$$

Note : To avoid the confusion of units, students can use the expression given by equation (1), to calculate capacitance while solving the problem.

Charging current : When the capacitance C of a cable is known then its reactance is given by,

$X_c = 1/(\omega C) = 1/(2\pi f C) \quad \Omega$

Then the charging current of the cable is given by,

$$\boxed{I = \frac{V_{ph}}{X_C}}$$

Where V_{ph} = Phase voltage between core and sheath = $V_{line}/\sqrt{3}$

1.1 Stress in Insulation

The electrical stress in insulation is the electric field intensity acting at any point P in insulation.

$$\therefore \quad g_x = \text{Electrical stress at point P at a distance } x = \frac{Q}{2\pi\varepsilon_0\varepsilon_r x} \text{ V/m}$$

$$\text{Now} \quad V = \frac{Q}{2\pi\varepsilon_0\varepsilon_r} \, ln\left[\frac{D}{d}\right]$$

$$\therefore \quad Q = \frac{2\pi\varepsilon_0\varepsilon_r V}{ln\left[\frac{D}{d}\right]}$$

$$\text{Substituting in } g_x, \quad g_x = \frac{2\pi\varepsilon_0\varepsilon_r V}{ln\left[\frac{D}{d}\right] 2\pi\varepsilon_0\varepsilon_r x}$$

$$g_x = \frac{V}{x \, ln\left[\frac{D}{d}\right]} = \text{Stress in insulation V/m}$$

The stress is maximum at the surface of the conductor i.e. when x = r.

$$\therefore \quad g_{max} = \frac{V}{r \, ln\left[\frac{D}{d}\right]} \text{ V/m}$$

$$\text{Now } r = \frac{d}{2}, \quad g_{max} = \frac{2V}{d \, ln\left[\frac{D}{d}\right]} \text{ V/m}$$

Similar the minimum stress will be at the length i.e. x = R hence

$$g_{min} = \frac{V}{R \, ln\left[\frac{D}{d}\right]} \text{ V/m}$$

$$\text{Now } R = \frac{D}{2}, \quad g_{min} = \frac{2V}{D \, ln\left[\frac{D}{d}\right]} \text{ V/m}$$

The variation of stress in dielectric material is shown ion the Fig. 2.

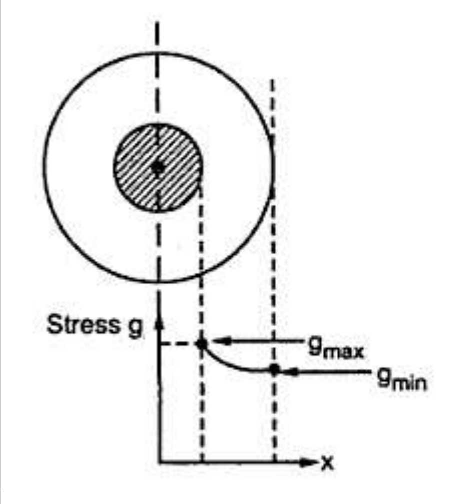


Fig. 2

The ratio of maximum and minimum stress is,

$$\frac{g_{max}}{g_{min}} = \frac{\dfrac{2\,V}{d\,ln\left[\dfrac{D}{d}\right]}}{\dfrac{2\,V}{D\,ln\left[\dfrac{D}{d}\right]}}$$

$$\therefore \qquad \boxed{\frac{g_{max}}{g_{min}} = \frac{D}{d}}$$

Key Point : If value of voltage used is r.m.s. we get r.m.s. values of stresses and if value of voltage used is peak, we get peak values of stresses.

1.2 Economical core Diameter/ size of the conductor:

In practice, the maximum stress value should be as low as possible. When the voltage V and sheath diameter D are fixed, the only parameter to be selected is the core diameter d. So d should be selected for which value is minimum.

The value of will be minimum when $\partial g_{max}/\partial d = 0$

Now $$g_{max} = \frac{2V}{d\, ln\left[\frac{D}{d}\right]}$$

$$\frac{\partial g_{max}}{\partial d} = \frac{d\, ln\left[\frac{D}{d}\right]\frac{\partial}{\partial d}(2V) - 2V\frac{\partial}{\partial d}\left[d\, ln\left(\frac{D}{d}\right)\right]}{\left[d\, ln\left(\frac{D}{d}\right)\right]^2}$$

$$= \frac{0 - 2V\frac{\partial}{\partial d}\left[d\, ln\left(\frac{D}{d}\right)\right]}{\left[d\, ln\left(\frac{D}{d}\right)\right]^2} \quad \text{as} \quad \frac{\partial(2V)}{\partial d} = 0$$

$$= \frac{-2V}{\left[d\, ln\left(\frac{D}{d}\right)\right]^2}\left\{ln\left(\frac{D}{d}\right) + d \cdot \frac{1}{\left(\frac{D}{d}\right)} \cdot \left(\frac{-D}{d^2}\right)\right\}$$

As $$\frac{\partial}{\partial x}\left[ln\left(\frac{c}{x}\right)\right] = \frac{1}{\left(\frac{c}{x}\right)} \cdot \frac{\partial}{\partial x}\left[\frac{c}{x}\right] = \frac{1}{\left(\frac{c}{x}\right)}\left(\frac{-c}{x^2}\right)$$

∴ $$\frac{\partial g_{max}}{\partial d} = \frac{-2V}{\left[d\, ln\left(\frac{D}{d}\right)\right]^2}\left\{ln\left(\frac{D}{d}\right) - 1\right\} \quad \text{... (3)}$$

Now the value of ∂gmax/∂d must be zero to get minimum gmax.

∴ $$ln\left(\frac{D}{d}\right) - 1 = 0$$

∴ $$ln\left(\frac{D}{d}\right) = 1$$

∴ $$\frac{D}{d} = e^1 = 2.718$$

∴ $$\boxed{d = \frac{D}{2.718}} \quad \text{... (4)}$$

Key Point : The core diameter must be 1/2.718 times the sheath diameter D so as to give the minimum value of gmax.

The value of minimum gmax is,

$$\text{Minimum } g_{max} = \frac{2V}{d} \quad \text{... As } ln\left(\frac{D}{\frac{D}{2.718}}\right) = 1 \quad \text{... (5)}$$

... Minimum gmax = V/r ..... As r = d/2

For high voltage cable, for a required if d is determined by the expression (5), it gives very large values of d than required for current carrying capacity. And such extra copper required can increase the cost tremendously. Hence it increase d without the use of an extra copper following methods are used :

1. Aluminium is used instead of copper as the aluminium size is more than copper for the same current carrying capacity.
2. Using stranded copper conductors around a dummy core of tube instead of hemp.
3. Using stranded copper conductors around a lead tube instead of hemp.

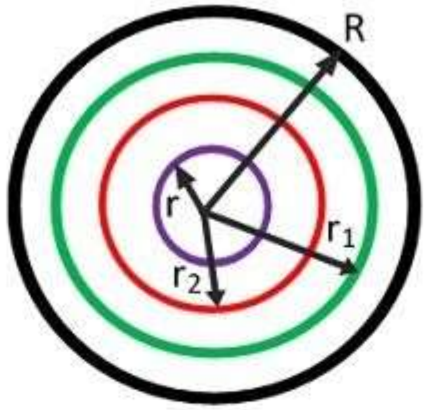
GRADING OF CABLE:

Definition:Grading is defined as the process of equalizing the stress in the dielectric of the cable. Generally, the electrical stress is maximum at the surface of the conductor or the innermost part of conductor while it is minimum at the outermost sheath of the conductor. If the stress is equal to all the dielectric of the conductor, then the thickness of the conductor is reduced. But if the stress is maximum at any of the dielectrics then it increases the thickness of the cable due to which the cost of the cable also increases. There are two methods of grading the cable

- Capacitance Grading
- Intersheath Grading

CAPACITANCE GRADING OR DIELECTRIC GRADING

In this type of grading, the homogeneous dielectric is replaced by layers of dielectric having a different value of relative permittivity. For getting a uniform stress, an infinite number of dielectric will be required. The electrical stress can be uniformly distributed by using two or more dielectric having suitable permittivity.



Dielectric Grading

Circuit Globe

The dielectric stress is given by the equation

$$g_x = \frac{q}{2\pi\varepsilon_0\varepsilon_r x} = \frac{constant}{\varepsilon_r x}$$

Let us considered a cable having three dielectrics of relative permittivity ε_1, ε_2, and ε_3, such that $\varepsilon_1 < \varepsilon_2 < \varepsilon_3$. Let r_1, r_2 and R be the outer radii of the dielectric.

The potential difference across the inner layer is

$$V_1 = \int_r^{r_1} g_x \, dx = \int_r^{r_1} \frac{q}{2\pi\varepsilon_0\varepsilon_1 x} dx$$

$$V_1 = \frac{q}{2\pi\varepsilon_0\varepsilon_1} In\frac{r_1}{r}$$

$$V_1 = \frac{q}{2\pi\varepsilon_0\varepsilon_1 r}.rIn\frac{r_1}{r} = g_{max1} rIn\frac{r_1}{r}$$

Similarly the potential difference between r_1 and r_2 i.e., across the middle layer

$$V_2 = g_{max2} r_1 In\frac{r_2}{r_1}$$

and the potential difference between r_2 and R i.e., across the outer layer

$$V_3 = g_{max3} r_1 In\frac{R}{r_2}$$

The total potential difference between core and earthed sheath

$$V = V_1 + V_2 + V_3 \quad V = g_{max1} r In\frac{r_1}{r} + g_{max2} r In\frac{r_2}{r_1} + g_{max3} r In\frac{R}{r_2}$$

The capacitance of the cable

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

$$C = \frac{2\pi\varepsilon_0}{\frac{1}{\varepsilon_1} In\frac{r_1}{r} + \frac{1}{\varepsilon_2} In\frac{r_2}{r} + \frac{1}{\varepsilon_3} In\frac{R}{r_2}}$$

The maximum stress is given by

$$g_{max1} = \frac{q}{2\pi\varepsilon_0\varepsilon_1 r}$$

$$g_{max2} = \frac{q}{2\pi\varepsilon_0\varepsilon_2 r}$$

$$g_{max3} = \frac{q}{2\pi\varepsilon_0\varepsilon_3 r}$$

In case the maximum stress is the same in the each layer

$$g_{max1} = g_{max2} = g_{max2} = g_{max}$$

$$\varepsilon_1 r = \varepsilon_2 r = \varepsilon_3 r$$

The total voltage applied across the cable

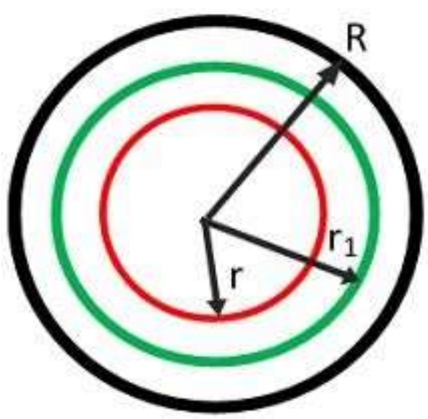
$$V = g_{max}\left(rIn\frac{r_1}{r} + r_1\frac{r_2}{r_1} + r_2In\frac{R}{r_2}\right)$$

g_{max} represent the peak value of electrical stress, and all the voltages are represented in peak values, not in RMS value.

INTERSHEATH GRADING:

Intersheath grading is the method of keeping the gradual voltage across the insulator by using the layers of the insulators. In this method, the uniform voltage is developed across the cable insulators. The total layer of the insulation material is divided into numbers of layers by providing intersheath.

Intersheath are thin metallic cylindrical sheaths concentric with the conductor and placed between the conductor and the outside sheath. Consider a cable with one intersheath only as shown below.



Intersheath Grading

Let r_1= radius of the intersheath

R=radius of the outer sheath

V_1 = voltage between the core and the intersheath

V_2= voltage between the innersheath and outer sheath

V = applied voltage between the core and the sheath

The maximum potential gradient in the second layer

$$g_{max1} = \frac{V_1}{rIn\frac{r_1}{r}}$$

The maximum potential gradient in second equation

$$g_{max1} = \frac{V_2}{r_1In\frac{R}{r}}$$

If the two potential gradients are equal

$$\frac{V_1}{rIn\frac{r_1}{r}} = \frac{V_2}{r_1In\frac{R}{r_1}} = g_{max}$$

Also

$$V = V_1 + V_2 = g_{max}\left(rIn\frac{r_1}{r} + r_1In\frac{R}{r_1}\right)$$

For economical size of the cable

$$\frac{r_1}{r} = e$$

and

$$g_{max} = \frac{V_1}{r} \quad r_1 = er = \frac{eV_1}{g_{max}}$$

Also,

$$g_{max} = \frac{V_2}{r_1 In\frac{R}{r_1}}$$

$$\frac{V_1}{r} = \frac{V_2}{r_1 In\frac{R}{r_1}}$$

$$In\frac{R}{r_1} = \frac{V_2}{V_1} \times \frac{r}{r_1} = \frac{V_2}{eV_1} = \frac{V - V_1}{eV_1} = \frac{V}{eV_1} - \frac{1}{e}$$

$$\frac{R}{r_1} = e^{\frac{V}{eV_1} - \frac{1}{e}}$$

$$\frac{R}{r_1} = e^{\frac{V}{eV_1} - \frac{1}{e}} = \frac{eV_1}{g_{max}} e^{\frac{V}{eV_1} - \frac{1}{e}}$$

$$= \frac{eV_1}{g_{max}} e^{1-\frac{1}{e}} e^{\frac{V}{eV_1}}$$

$$= AV_1 e^{\frac{V}{eV_1}}$$

Where A is a constant equal to 1/gmax $e^{1-1/e}$

For minimum value of R

$$\frac{dR}{dV_1} = 0$$

$$AV_1\left(\frac{-V}{eV_1^2}\right)e^{\frac{V}{eV_1}} + AV_1 e^{\frac{V}{eV_1}} = 0$$

$$AV_1 e^{\frac{V}{eV_1}}\left(1 - \frac{V}{eV_1}\right) = 0$$

$$V_1 = \frac{V}{e}$$

From the above equation, we get,

$$r = \frac{V_1}{g_{max}} = \frac{V}{e g_{max}}$$

$$r_1 = \frac{V_1 e}{g_{max}} = \frac{V}{g_{max}}$$

$$R = \frac{V}{g_{max}} e^{1-\frac{1}{e}}$$

We know that, e = 2.718

$$e^{1-\frac{1}{e}} = 2.718^{\left(1-1/2.718\right)} = 2.718^{1.718}/2.718 = (2.718)^{0.632} = 1.881$$

$$R = 1.881\frac{V}{g_{max}}$$

LIMITATIONS OF GRADING

The main disadvantage of the capacitance grading is that the range of permittivity value of insulating material available for cable insulation is limited. The permittivity of the layers may not remain constant thereby change the stress distribution and cause the insulation break down at normal operating condition.

In Intershaeth grading, the intersheath layers are very thin and are liable to be damaged during transportation or installation. Also, thin intersheath are not able to carry the damage charging current of long cable line and thus the current-carrying capacity of the cable is reduced. For these reasons the present trends is to avoid grading.

CAPACITANCE OF THREE CORE CABLES:

In three core cables, capacitance play an important role because in such cables capacitances exist between the cores as well as each core and the sheath. These capacitances are dominating as the dielectric constant of the dielectric used in cables is much more than the air. The capacitances are shown in the Fig. 1.

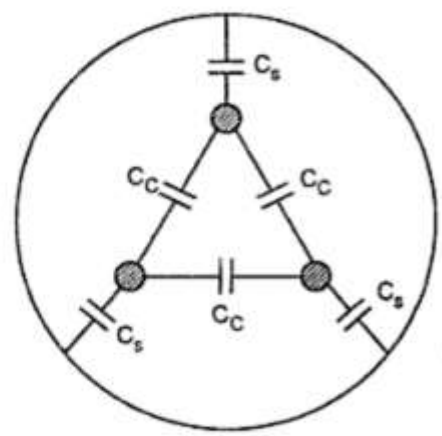


Fig. 1

The core to core capacitances are denoted as Cc while core to sheath capacitance are denoted as Cs.

The core to core capacitances Cc are in delta and can be represented in the equivalent star as shown in the Fig. 2.

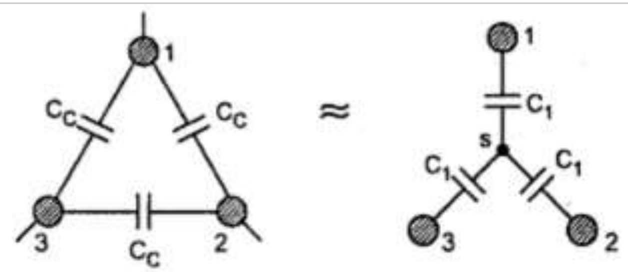


Fig. 2

The impedance between core 1 and the star point, Z_1 can be obtained as,

$$Z_1 = \frac{Z_{12} \times Z_{13}}{Z_{12} + Z_{13} + Z_{23}}$$ ...From delta-star conversion

Now $$Z_{12} = Z_{13} = Z_{23} = \frac{1}{\omega C_C}$$

$\therefore$ $$Z_1 = \frac{\frac{1}{\omega C_C} \times \frac{1}{\omega C_C}}{\frac{3}{\omega C_C}} = \frac{1}{3} \cdot \frac{1}{\omega C_C}$$

And $$Z_1 = \frac{1}{\omega C_1}$$ ... in equivalent star

$\therefore$ $$\frac{1}{\omega C_1} = \frac{1}{3} \cdot \frac{1}{\omega C_C}$$

$\therefore$ $$C_1 = 3\, C_C$$

If star point is assumed to be at earth potential and if sheath is also earthed then the capacitance of each conductor to neutral is,

$$C_N = C_s + C_1 = C_s + 3\, C_C$$

If V_{ph} is the phase voltage then charging current per phase is,

$$I = \frac{V_{ph}}{\text{Capacitive reactance per phase}}$$

$$= \frac{V_{ph}}{X_{CN}} = \frac{V_{ph}}{\frac{1}{\omega C_N}}$$

$\therefore$ $$I = \omega C_N V_{ph} \text{ A}$$

MEASUREMENT OF C_S AND C_C

The total capacitance is not easy to calculate but by actual practical measurement C_s and C_c can be determined.

Practical measurement involves two cases :

Case 1 : The core 2 and 3 are connected to sheath.

Thus the C_c between cores 2 and 3 and C_s between cores 2, 3 and sheath get eliminated as shown in the Fig. 3.

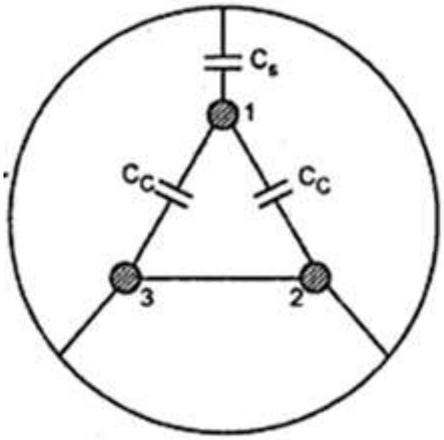


Fig. 3

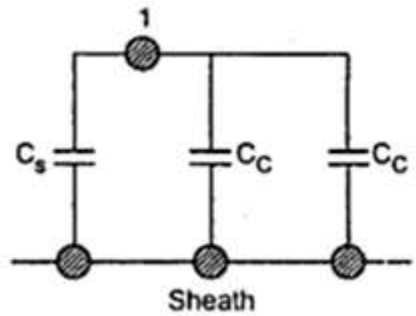


Fig. 4

All the three capacitances are now in parallel across core 1 and the sheath.

The capacitance of core 1 with sheath is measured practically and denoted by C_a.

$$C_a = C_s + 2C_c \qquad \text{...........(1)}$$

Case 2 : All the three cores are bundled together.

This eliminates all the core-core capacitances. This is shown in the Fig. 5.

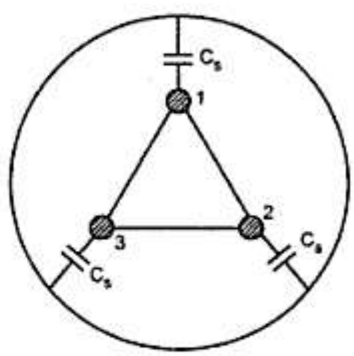


Fig. 5

The capacitances C_s are in parallel between the common core and sheath.

This capacitance is practically measured and denoted as C_b.

$$C_b = 3\,C_s \qquad \text{..........(2)}$$

Solving (1) and (2) simultaneously,

$C_a = (C_b/3) + 2C_c$

$C_c = (C_a/2)-(C_b/2)$ and $C_s = C_b/3$

Thus both the capacitances can be determined.

$C_N = C_s + 3C_c = (C_b/3) + 3((C_a/2) - (C_b/2))$

$$\therefore \quad C_N = \frac{3C_a}{2} - \frac{C_b}{6}$$

CAPACITANCE OF THREE CORE CABLE

There is one empirical formula to calculate the capacitance of a three core belted cable, stated by Simon. It is applicable for the circular conductors. The formula gives the capacitance of a three core cable to neutral per phase per kilometer length of the cable. The formula is given as,

Where ε_r = Relative permittivity of the dielectric

d = Conductor diameter

t = Belt Insulation thickness

T = Conductor insulation thickness

The formula can be used when the test results are not available. This gives approximate value of the capacitance. If ε_r is not given, it can be assumed to be 3.5. It must be remembered that all the values of d, t and T must be used in the same units while using the formula.

Example : A three core cable has core diameter 0f 2 cm and core to core distance of 4 cm. The dielectric material has relative permittivity of 5. Compute the capacitance of this cable per phase per km. Thickness of the conductor insulation is 1 cm and that of belt insulation is 0.5 cm.

Solution : d = 2 cm , $\varepsilon_r = 5$, T = 1 cm, t = 0.5 cm

Use the empirical formula as the test results are not given.

$$C_N = \frac{0.0299\ \varepsilon_r}{ln\left[1+\frac{T+t}{d}\left\{3.84-1.7\frac{t}{T}+0.52\frac{t^2}{T^2}\right\}\right]}\ \mu F/km$$

$$= \frac{0.0299\times 5}{ln\left[1+\frac{1+0.5}{2}\left\{3.84-\frac{1.7\times 0.5}{1}+\frac{0.52\times(0.5)^2}{(1)^2}\right\}\right]}$$

$$= \frac{0.0299\times 5}{ln\ [1+0.75\ \{3.84-0.85+0.13\}]} = \frac{0.0299\times 5}{ln[3.34]} = \mathbf{0.1239\ \mu F/km}$$