SUBJECT:- POWER SYSTEMS-I

Code:- EEC 401

Departmental Core Subject

Academic Session:- 2024-25

Semester:- B.Tech 4^{th} , EE

Chapter- Insulated Cables

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Reference

1. S. Y. King, N. A. Halfter, “**Underground Power Cables**”, Hongkong University Press, 1977.

Insulated Cables

Syllabus:-Types of L. V. Cables for distribution systems: conductor materials, important types of insulating materials, high voltage cables, Stresses developed, economical stress and grading of dielectric materials, screened and pressure cables, mechanism of cable break down charging Current, power factor and losses in cables, determination of current Rating of cables.

After reading this chapter, the students should be able to:

- Understand the need for underground cables.
- Provide constructional features and grading of cables.
- Calculate the dielectric stress, capacitance for single and three-core cables.
- Provide the thermal characteristics and testing of cables.

Introduction:-

- *An* **Insulated cable** *essentially consists of one or more conductors covered with suitable insulation and surrounded by a protecting cover.*
- The underground cables have several advantages such as:
  - less liable to damage through storms or lightning,
  - low maintenance cost,
  - less chances of faults,
  - smaller voltage drop and better general appearance.

- However, their major drawback is that they have greater installation cost and introduce insulation problems at high voltages compared with the equivalent overhead system.
- Underground cables are employed where it is impracticable to use overhead lines. Such locations may be thickly populated areas where municipal authorities prohibit overhead lines for reasons of safety, or around plants and substations or where maintenance conditions do not permit the use of overhead construction.
- The chief use of underground cables for many years has been for distribution of electric power in congested urban areas at comparatively low or moderate voltages.
- However, recent improvements in the design and manufacture have led to the development of cables suitable for use at high voltages.
- This has made it possible to employ underground cables for transmission of electric power for short or moderate distances.

Basic Properties:-

- 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:

- **The conductor used in cables should be tinned stranded copper or aluminium of high conductivity.**

- **Stranding is done so that conductor may become flexible and carry more current.**

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

- **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.**

- **The cable must be provided with suitable mechanical protection so that it may withstand the rough use in laying it.**

- **The materials used in the manufacture of cables should be such that there is complete chemical and physical stability throughout.**

Construction:-

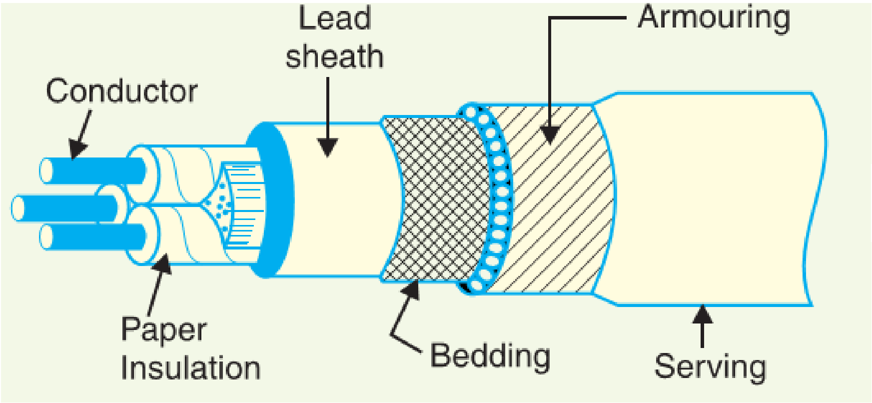


Figure 1

- Figure 1 shows the general construction of a 3-conductor cable. The various parts are :
- *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. For instance, the 3-conductor cable shown in Figure 1 is used for 3-phase service. The conductors are made of tinned copper or aluminium and are usually stranded in order to provide flexibility to the cable.
- *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.
- *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 aluminum is provided over the insulation as shown in Figure 1.
- *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.
- *Armouring.* Over the bedding, armouring is provided which consists of one or two layers of galvanised steel wire or steel tape. Its purpose is to protect the cable from mechanical injury while laying it and during the course of handling. Armouring may not be done in the case of some cables.
- *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.* It may not be out of place to mention here that 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.

Basic Properties of Insulating Materials for Cables:-

- In general, the insulating materials used in cables should have the following properties:
    - **High insulation resistance to avoid leakage current.**
    - **High dielectric strength to avoid electrical breakdown of the cable.**
    - **High mechanical strength to withstand the mechanical handling of cables.**
    - **Non-hygroscopic *i.e.,* it should not absorb moisture from air or soil.**
    - **Non-inflammable.**
    - **Low cost so as to make the underground system a viable proposition.**
    - **Unaffected by acids and alkalies to avoid any chemical action.**
- None of the insulating material possesses all the above mentioned properties.
- Therefore, the type of insulating material to be used depends upon the purpose for which the cable is required and the quality of insulation to be aimed at.
- The principal insulating materials used in cables are:
- **Rubber.**
    - Rubber may be obtained from milky sap of tropical trees or it may be produced from oil products.
    - It has relative permittivity varying between **2 and 3**, dielectric strength is about **30 kV/mm** and resistivity of insulation is $\mathbf{10^{17}}\,\Omega$ cm.
    - It suffers from some major drawbacks *viz.,* readily absorbs moisture, maximum safe temperature is low (about **38ºC**), soft and liable to damage due to rough handling and ages when exposed to light.

Basic Properties of Insulating Materials for Cables:-

- **Vulcanised India Rubber (*V.I.R.*).**
  - It is prepared by mixing pure rubber with mineral matter such as **zinc oxide, red lead etc., and 3 to 5% of sulphur**. The compound so formed is rolled into thin sheets and cut into strips.
  - The rubber compound is then applied to the conductor and is heated to a temperature of about **150ºC**. The whole process is called *vulcanisation*.
  - Vulcanised India rubber has greater mechanical strength, durability and wear resistant property than pure rubber.
  - Its main drawback is that sulphur reacts very quickly with copper and for this reason, cables using *VIR* insulation have tinned copper conductor.
- **Impregnated paper.**
  - It consists of chemically pulped paper made from wood chippings and impregnated with some compound such as paraffinic or napthenic material.
  - It has the advantages of low cost, low capacitance, high dielectric strength and high insulation resistance.
  - The only **disadvantage is that paper is hygroscopic** and even if it is impregnated with suitable compound, it absorbs moisture and thus lowers the insulation resistance of the cable.
  - The paper insulated cables are always provided with some protective covering and are never left unsealed.
  - If it is required to be left unused , its ends are temporarily covered with wax or tar.
  - They are used where the cable route has a few joints.

Basic Properties of Insulating Materials for Cables:-

- **Varnished cambric.**
  - It is a cotton cloth impregnated and coated with varnish.
  - The cambric is lapped on to the conductor in the form of a tape and its surfaces are coated with petroleum jelly compound to allow for the sliding of one turn over another as the cable is bent.
  - As the varnished cambric is hygroscopic, therefore, such cables are always provided with metallic sheath. Its dielectric strength is about 4 kV/mm and permittivity is 2.5 to 3.8.
- **Polyvinyl chloride (*PVC*).**
  - This insulating material is a synthetic compound. It is obtained from the polymerisation of acetylene and is in the form of white powder.
  - For obtaining this material as a cable insulation, it is compounded with certain materials known as plasticizers which are liquids with high boiling point.
  - Polyvinyl chloride has high insulation resistance, good dielectric strength and mechanical toughness over a wide range of temperatures.
  - It is inert to oxygen and almost inert to many alkalies and acids.
  - Therefore, this type of insulation is preferred over *VIR* in extreme environmental conditions such as in cement factory or chemical factory.
  - The mechanical properties (*i.e.,* elasticity etc.) of *PVC* are not so good.
- XLPE cable
  - It stands for cross linked polyethylene cable. It is a hydronic tubing manufactured from polyethylene plastic. XLPE features a 3D molecular bond structure and shape memory characteristics.
  - XLPE insulation performs at both high and low temperatures. Due to its structure, XLPE is extremely resistant to abrasion and other wear and tear. It also boasts resistance to high voltage electricity, chemicals, and other hazardous materials. Cross-linked polyethylene insulation is also a more affordable option.

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:

  (*i*) Low-tension (L.T.) cables — upto 1000 V

  (*ii*) High-tension (H.T.) cables — upto 11 kV

  (*iii*) Super-tension (S.T.) cables —from 22 kV to 33 kV

  (*iv*) Extra high-tension (E.H.T.) cables — from 33 kV to 66 kV

  (*v*) Extra super voltage cables — beyond 132 kV

- **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. For a 3-phase service, either 3-single-core cables or three-core cable can be used depending upon the operating voltage and load demand.**

- Figure 2 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 are generally small.
- It consists of one circular core of tinned stranded copper (or aluminium) insulated by layers 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.
- Single-core cables are not usually armoured in order to avoid excessive sheath losses.

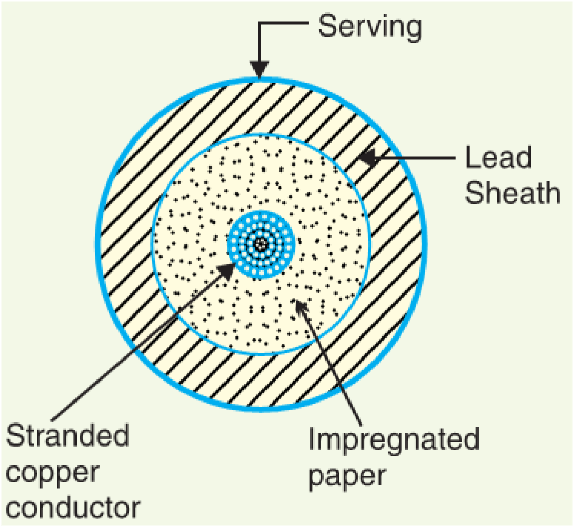


Figure 2

Classification of 3-Phase Cables:-

- For the purpose, of sending 3 phase power either three-core cable or three single core cables may be used.
- For voltages upto 66 kV, 3-core cable (*i.e.,* multi-core construction) is preferred due to economic reasons.
- However, for voltages beyond 66 kV, 3-core-cables become too large and, therefore, single-core cables are used.
- The following types of cables are generally used for 3-phase service:
  - Belted cables — upto 11 kV
  - Screened cables — from 22 kV to 66 kV
  - Pressure cables — beyond 66 kV.

- **Belted cables.** These cables are used for voltages upto 11kV but in extraordinary cases, their use may be extended upto 22kV. Figure 3 shows the constructional details of a 3-core belted cable. The cores are insulated from each other by layers of impregnated paper.

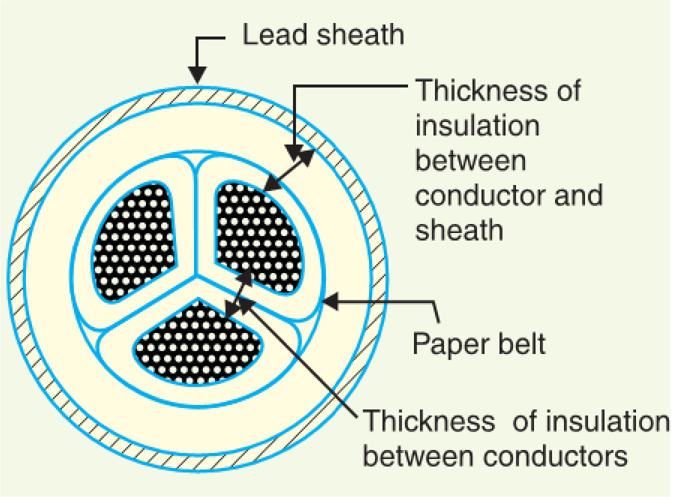


Figure 3

- 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 may be covered with one or more layers of armouring with an outer serving (not shown in the figure).

Classification of 3-Phase Cables:-

- 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.
- However, for high voltages (beyond 22 kV), the tangential stresses also become important. These stresses act along the layers of paper insulation.
- As the insulation resistance of paper is quite small along the layers, therefore, tangential stresses 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 their use 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. Figure 4 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.

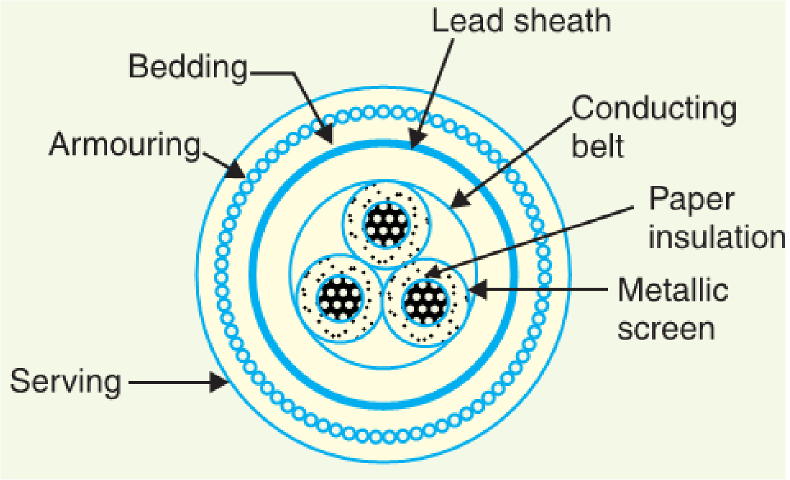


Figure 4

Classification of 3-Phase Cables:-

- 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.
- Two principal advantages are claimed for *H*-type cables.
- Firstly, the 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. The voids if present tend to reduce the breakdown strength of the cable and may cause considerable damage to the paper insulation.
- Secondly, the metallic screens increase the heat dissipating power of the cable.
- **(*ii*) *S.L. type cables:*** Figure 5 shows the constructional details of a 3-core S.L. (separate lead) type cable. 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. The S.L. type cables have two main advantages over *H*-type cables.

- Firstly, the separate sheaths minimise the possibility of core-to-core breakdown.
- Secondly, bending of cables becomes easy due to the elimination of overall lead sheath.
- However, the disadvantage is that the 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.

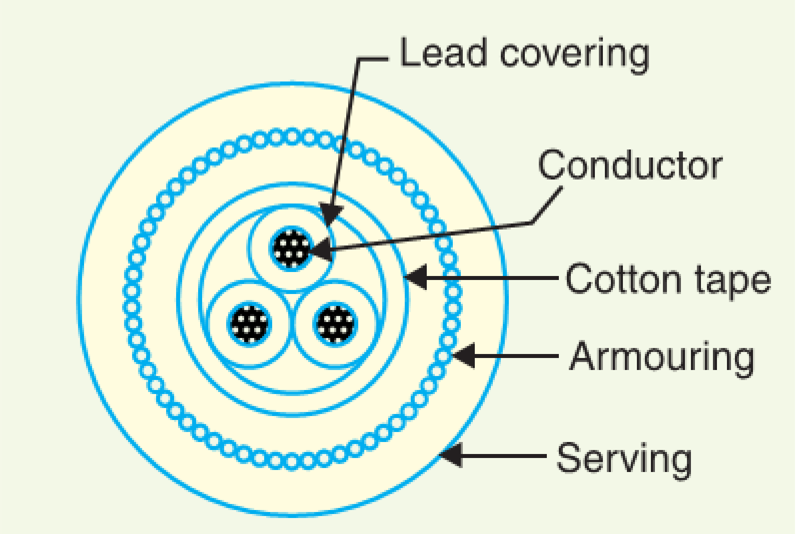


Figure 5

Limitations of solid type cables:-

All the cables mentioned earlier, 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:

- 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 and may damage it.
- 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. The moisture reduces the dielectric strength of insulation and may eventually cause the breakdown of the cable.
- In practice, voids are always present in the insulation of a cable. Modern techniques of manufacturing have resulted in void free cables. However, under operating conditions, the voids are formed as a result of the differential expansion and contraction of the sheath and impregnated compound. The breakdown strength of voids is considerably less than that of 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 ionisation causing permanent damage to the paper insulation.

Classification of 3-Phase Cables:-

- **Pressure cables:** When the operating voltages are greater than 66 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.
- ***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.
  - Due to the elimination of voids, oil-filled cables can be used for higher voltages, the range being from 66 kV upto 230 kV.
  - Oil-filled cables are of three types *viz.,* single-core conductor channel, single-core sheath channel and three-core filler-space channels.
  - Figure 6 shows the constructional details of a single-core conductor channel, oil filled cable. 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. As the channel is made of spiral steel tape, it allows the oil to percolate between copper strands to the wrapped insulation. The oil pressure compresses the layers of paper insulation and prevents the possibility of void formation.

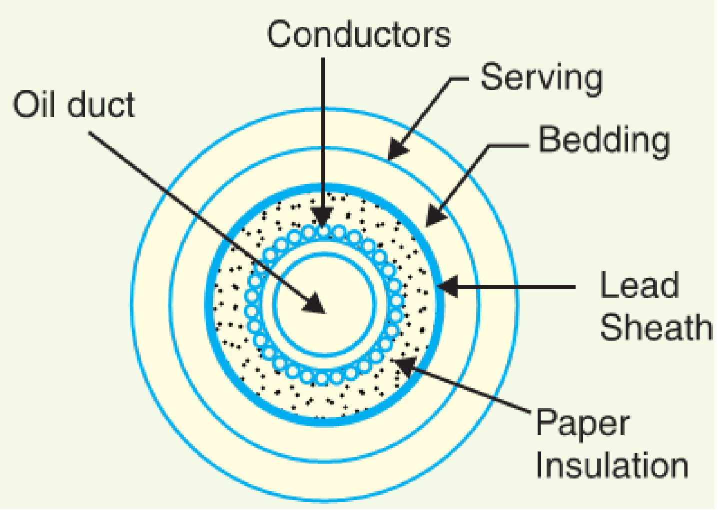


Figure 6

Classification of 3-Phase Cables:-

- The system is so designed that when the oil gets expanded due to increase in cable temperature, the extra oil collects in the reservoir. However, when the cable temperature falls during light load conditions, the oil from the reservoir flows to the channel.

- 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.

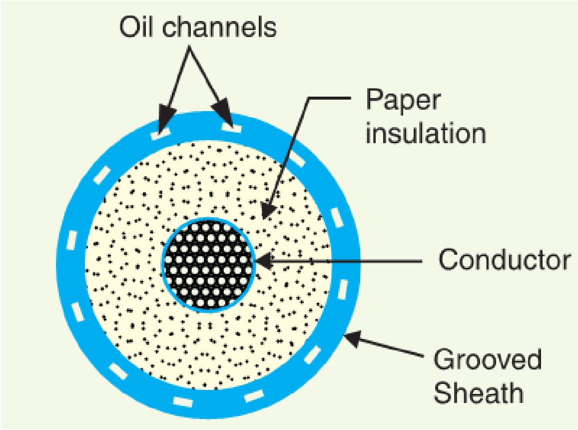


Figure 7

- Figure 7 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.
- In the 3-core oil-filler cable shown in Figure 8, 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.
  - ✓ Firstly, formation of voids and ionization are avoided.
  - ✓ Secondly, allowable temperature range and dielectric strength are increased.
  - ✓ Thirdly, if there is leakage, the defect in the lead sheath is at once indicated and the possibility of earth faults is decreased.
- However, their major disadvantages are the high initial cost and complicated system of laying.

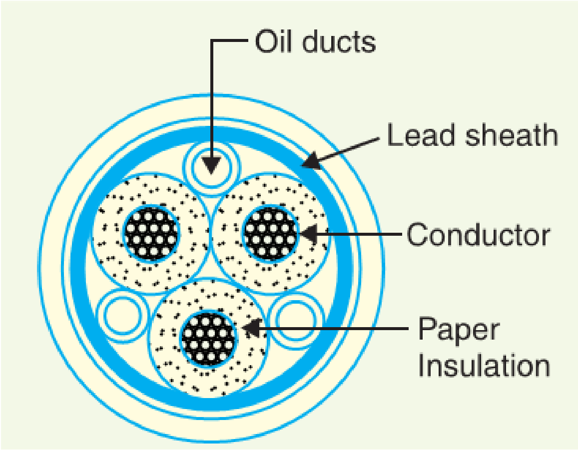


Figure 8

Classification of 3-Phase Cables:-

- ***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.
- Figure 9 shows the section of external pressure cable. The construction of the cable is similar to that of an ordinary solid type except that it is of triangular shape and thickness of lead sheath is 75% that of solid cable.
- The triangular section reduces the weight and gives low 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 thin 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.
- 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.
- However, it has the disadvantage that the overall cost is very high.

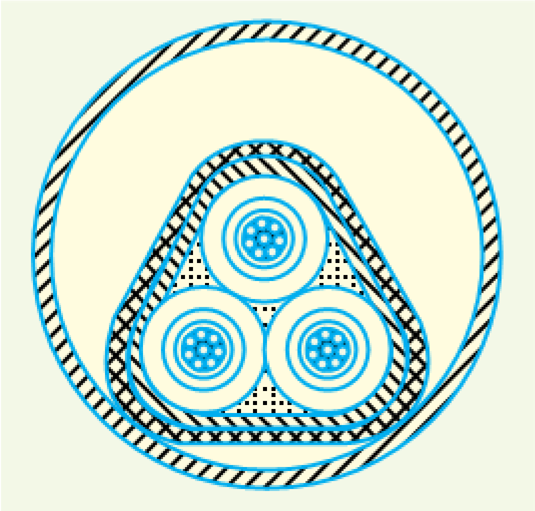


Figure 9

Underground Cable Laying:-

- There are three main methods of laying underground cables *viz.,* direct laying, draw-in system and the solid system.
- **Direct laying:-** This method of laying underground cables is simple and cheap and is much favoured in modern practice. In this method, a trench is dug. The trench is covered with a layer of fine sand and the cable is laid over this sand bed. The sand prevents the entry of moisture from the ground and thus protects the cable from decay. After the cable has been laid in the trench, it is covered with another layer of sand. The trench is then covered with bricks and other materials in order to protect the cable from mechanical injury.
- **Draw-in system:-** In this method, conduit or duct of glazed stone or cast iron or concrete are laid in the ground with manholes at suitable positions along the cable route. The cables are then pulled into position from manholes. The cables to be laid in this way need not be armoured but must be provided with serving of hessian and jute in order to protect them when being pulled into the ducts.
- **Solid system:-** In this method of laying, the cable is laid in open pipes or troughs dug out in earth along the cable route. The troughing is of cast iron, stoneware, asphalt or treated wood. After the cable is laid in position, the troughing is filled with a bituminous or asphaltic compound and covered over. Cables laid in this manner are usually plain lead covered because troughing affords good mechanical protection.

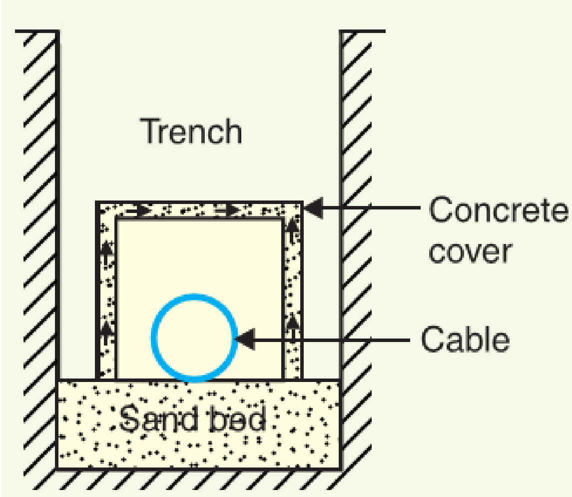


Figure 10

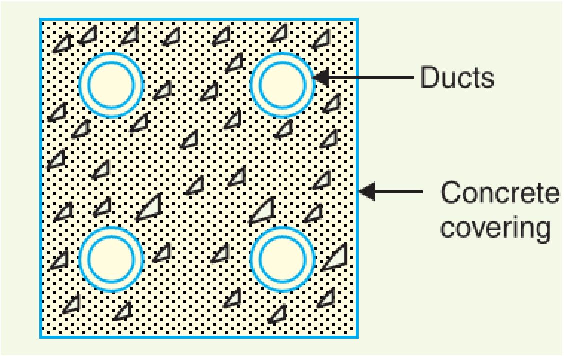
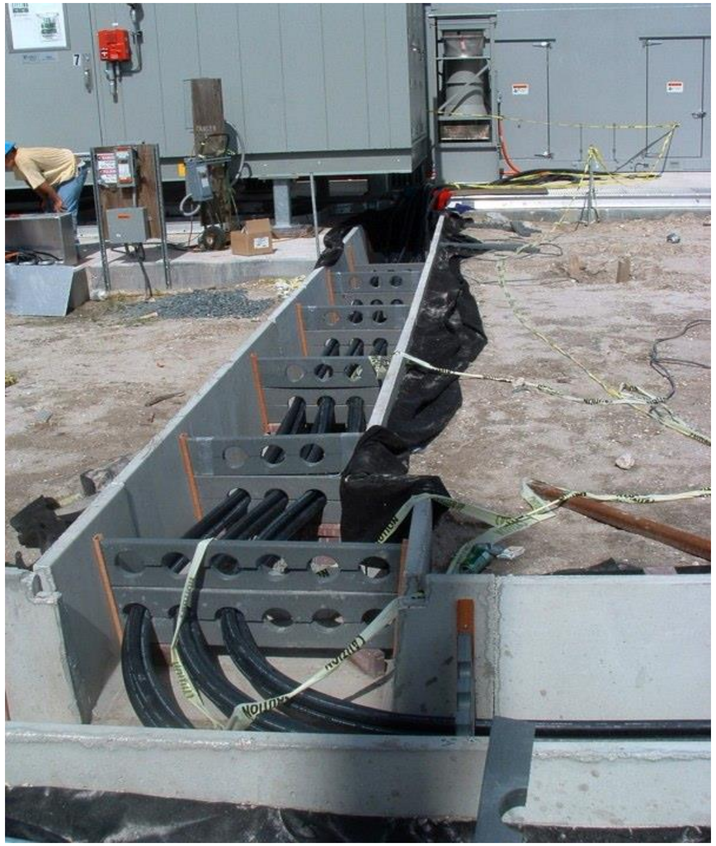


Figure 11



Insulation Resistance of a Single-Core Cable:-

- The cable conductor is provided with a suitable thickness of insulating material in order to prevent leakage current. The path for leakage current is radial through the insulation.
- The opposition offered by insulation to leakage current is known as insulation resistance of the cable. For satisfactory operation, the insulation resistance of the cable should be very high.
- Consider a single-core cable of conductor radius r_1 and internal sheath radius r_2 as shown in Figure 12.
- Let l be the length of the cable and ρ be the resistivity of the insulation.
- Consider a very small layer of insulation of thickness dx at a radius x. The length through which leakage current tends to flow is dx and the area of X-section offered to this flow is $2\pi xl$.
- So, Insulation resistance of considered layer= $\rho\frac{dx}{2\pi xl}$
- Insulation resistance of the whole cable is

$$R = \int_{r1}^{r2} \rho\frac{dx}{2\pi xl} = \frac{\rho}{2\pi l}\int_{r1}^{r2}\frac{dx}{x}$$

$$R = \frac{\rho}{2\pi l} ln\left(\frac{r_2}{r_1}\right)$$

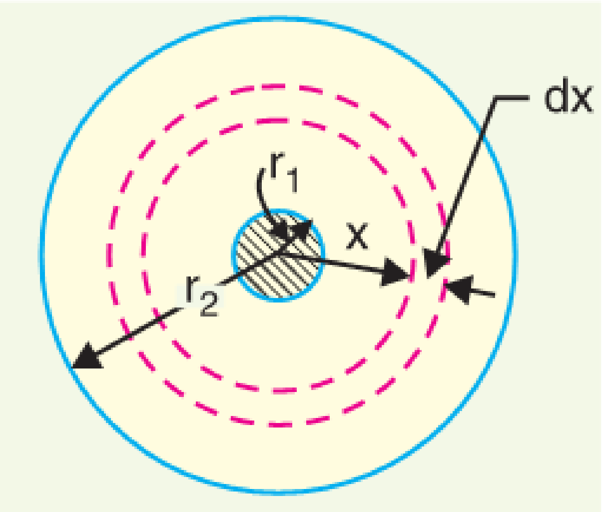


Figure 12

- This shows that insulation resistance of a cable is inversely proportional to its length. In other words, if the cable length increases, its insulation resistance decreases and *vice-versa.*

Capacitance of a Single-Core Cable:-

- A single-core cable can be considered to be equivalent to two long co-axial cylinders.
- The conductor (or core) of the cable is the inner cylinder while the outer cylinder is represented by lead sheath which is at earth potential.
- Consider a single core cable with conductor diameter *d* and inner sheath diameter *D* (Figure in 13). Let the charge per metre axial length of the cable be *Q* coulombs and ε be the permittivity of the insulation material between core and lead sheath. Obviously $\varepsilon = \varepsilon_0\varepsilon_r$ where, ε_r is the relative permittivity of the insulation.
- Consider a cylinder of radius x metres and axial length 1 metre. The surface area of this cylinder is $= 2\pi x \times 1 = 2\pi x$ m². Electric flux density at any point *P* on the considered cylinder is $D_x = \frac{Q}{2\pi x}\ C/m^2$
- Electric intensity at point *P*, $E_x = \frac{D_x}{\varepsilon} = \frac{Q}{2\pi x\varepsilon_0\varepsilon_r}$ *volts/m*
- The work done in moving a unit positive charge from point *P* through a distance dx in the direction of electric field is $E_x dx$.
- Hence, the work done in moving a unit positive charge from conductor to sheath, which is the potential difference *V* between conductor and sheath, is given by:
- $V = \int_{d/2}^{D/2} E_x dx = \int_{d/2}^{D/2} \frac{Q}{2\pi x\varepsilon_0\varepsilon_r} dx = \frac{Q}{2\pi\varepsilon_0\varepsilon_r} ln\left(\frac{D}{d}\right)$
- Capacitance of the cable is

$$C = \frac{Q}{V} = \frac{Q}{\frac{Q}{2\pi\varepsilon_0\varepsilon_r} ln\left(\frac{D}{d}\right)} \quad F/m$$

$$= \frac{2\pi\varepsilon_0\varepsilon_r}{ln\left(\frac{D}{d}\right)} = \frac{2\pi \times 8.854 \times 10^{-12}\varepsilon_r}{ln\left(\frac{D}{d}\right)}\ F/m$$

- If the cable has a length of l meters, the capacitance of the cable is

$$C = \frac{2\pi l \times 8.854 \times 10^{-12}\varepsilon_r}{ln\left(\frac{D}{d}\right)}\ F/m$$

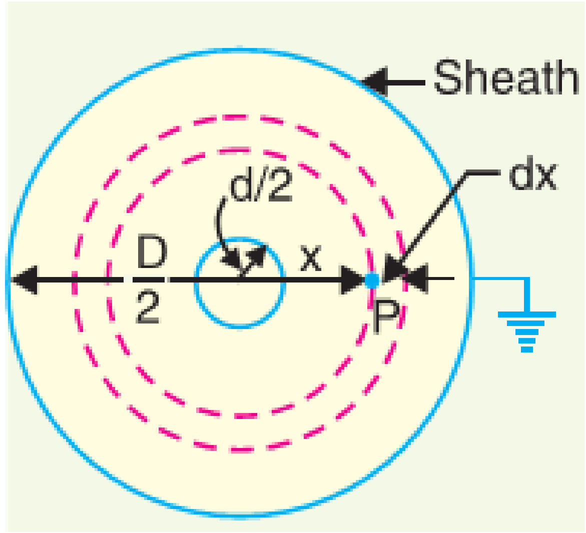


Figure 13

Dielectric Stress in a Single-Core Cable:-

- Under operating conditions, the insulation of a cable is subjected to electrostatic forces. This is known as dielectric stress. The dielectric stress at any point in a cable is in fact the potential gradient (or electric intensity) at that point.
- Consider a single core cable with core diameter d and internal sheath diameter D. The electric intensity at a point x metres from the centre of the cable is $E_x = \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r} Volts/m$
- By definition, electric intensity is equal to potential gradient. Therefore, potential gradient g at a point x metres from the centre of cable is $g = E_x = \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r} Volts/m$
- As derived earlier, the potential gradient between conductor and the sheath is

$$V = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} ln\left(\frac{D}{d}\right)\ Volts$$

Or, $Q = \frac{2\pi \varepsilon_0 \varepsilon_r}{ln\left(\frac{D}{d}\right)} V$

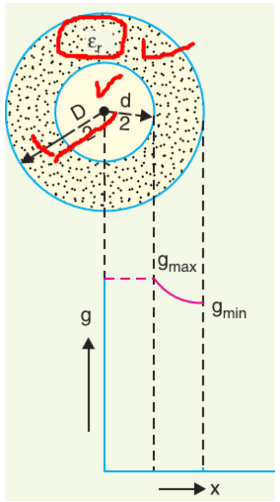


Figure 14

- Substituting the value of Q in the expression of g, we get

$$g = \frac{V}{x ln\left(\frac{D}{d}\right)}\ Volts/m$$

- It is clear that potential gradient varies inversely as the distance x. Therefore, potential gradient will be maximum when x is minimum *i.e.,* when $x = d/2$ or at the surface of the conductor. On the other hand, potential gradient will be minimum at $x = D/2$ or at sheath surface.
- Hence, maximum potential gradient is $g_{max} = \frac{2V}{d \times ln\left(\frac{D}{d}\right)}\ V/m$
- Minimum potential gradient is $g_{min} = \frac{2V}{D \times ln\left(\frac{D}{d}\right)}\ V/m$

$$\frac{g_{max}}{g_{min}} = \frac{\frac{2V}{d \log_e D/d}}{\frac{2V}{D \log_e D/d}} = \frac{D}{d}$$

Most Economical Conductor Size in a Cable:-

- It has already been shown that maximum stress in a cable occurs at the surface of the conductor. For safe working of the cable, dielectric strength of the insulation should be more than the maximum stress.
- Rewriting the expression for maximum stress, we get, $g_{max} = \frac{2V}{d \times ln\left(\frac{D}{d}\right)} \ V/m$
- The values of working voltage V and internal sheath diameter D have to be kept fixed at certain values due to design considerations. This leaves conductor diameter d to be the only variable. For given values of V and D, the most economical conductor diameter will be one for which g_{max} has a minimum value. The value of g_{max} will be minimum when $d \ln(D/d)$ is maximum *i.e.*

$$\frac{d[d \ln (D/d)]}{dd} = 0$$

Or, $\ln\left(\frac{D}{d}\right) + d.\frac{d}{D}.\frac{-D}{d^2} = 0$

Or, $\ln\left(\frac{D}{d}\right) = 1$

Or, $\frac{D}{d} = e = 2.718$

- Most economical conductor diameter is $d = \frac{D}{2.718}$ and the value of g_{max} under this condition is $g_{max} = \frac{2V}{d}$ Volts/m.
- For low and medium voltage cables, the value of conductor diameter arrived at by this method (*i.e.*, $d = 2V/g_{max}$) is often too small from the point of view of current density.
- Therefore, the conductor diameter of such cables is determined from the consideration of safe current density.
- For high voltage cables, designs based on this theory give a very high value of d, too large from the point of view of current carrying capacity and it is, therefore, advantageous to increase the conductor diameter to this value. There are three ways of doing this without using excessive copper :

(*i*) Using aluminium instead of copper because for the same current, diameter of aluminium will be more than that of copper.

(*ii*) Using copper wires stranded round a central core of hemp.

(*iii*) Using a central lead tube instead of hemp.

Grading of Cables:-

- *The process of achieving uniform electrostatic stress in the dielectric of cables is known as* **grading of cables.**
- It has already been shown that electrostatic stress in a single core cable has a maximum value (g_{max}) at the conductor surface and goes on decreasing as we move towards the sheath.
- The maximum voltage that can be safely applied to a cable depends upon g_{max} *i.e.,* electrostatic stress at the conductor surface. For safe working of a cable having homogeneous dielectric, the strength of dielectric must be more than g_{max}.
- If a dielectric of high strength is used for a cable, it is useful only near the conductor where stress is maximum. But as we move away from the conductor, the electrostatic stress decreases, so the dielectric will be unnecessarily overstrong.
- The unequal stress distribution in a cable is undesirable for two reasons. Firstly, insulation of greater thickness is required which increases the cable size.
- Secondly, it may lead to the breakdown of insulation. In order to overcome above disadvantages, it is necessary to have a uniform stress distribution in cables.
- This can be achieved by distributing the stress in such a way that its value is increased in the outer layers of dielectric. This is known as grading of cables. The following are the two main methods of grading of cables: **(*i*) Capacitance grading (*ii*) Intersheath grading**

Capacitance Grading

- In capacitance grading, the homogeneous dielectric is replaced by a composite dielectric.
- The composite dielectric consists of various layers of different dielectrics in such a manner that relative permittivity ε_r of any layer is inversely proportional to its distance from the centre.
- Under such conditions, the value of potential gradient at any point in the dielectric is constant and is independent of its distance from the centre.
- In other words, the dielectric stress in the cable is same everywhere and the grading is ideal one.
- However, ideal grading requires the use of an infinite number of dielectrics which is an impossible task.
- In practice, two or three dielectrics are used in the decreasing order of permittivity ; the dielectric of highest permittivity being used near the core.
- The capacitance grading can be explained by referring to Figure 15. There are three dielectrics of outer diameter d_1, d_2 and D and of relative permittivity $\varepsilon_1, \varepsilon_2$ and ε_3 respectively.
- If the permittivity are such that $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$ and the three dielectrics are worked at the same maximum stress, then,

$$\frac{1}{\varepsilon_1 d} = \frac{1}{\varepsilon_2 d_1} = \frac{1}{\varepsilon_3 d_2}$$

Or, $\varepsilon_1 d = \varepsilon_2 d_1 = \varepsilon_3 d_2$

- Potential difference across the inner layer is

$$V_1 = \int_{d/2}^{d_1/2} g dx = \int_{d/2}^{d_1/2} \frac{Q}{2\pi\varepsilon_0\varepsilon_1 x} dx = \frac{Q}{2\pi\varepsilon_0\varepsilon_1} \ln\left(\frac{d_1}{d}\right) = \frac{g_{max}}{2} d \ln\left(\frac{d_1}{d}\right)$$

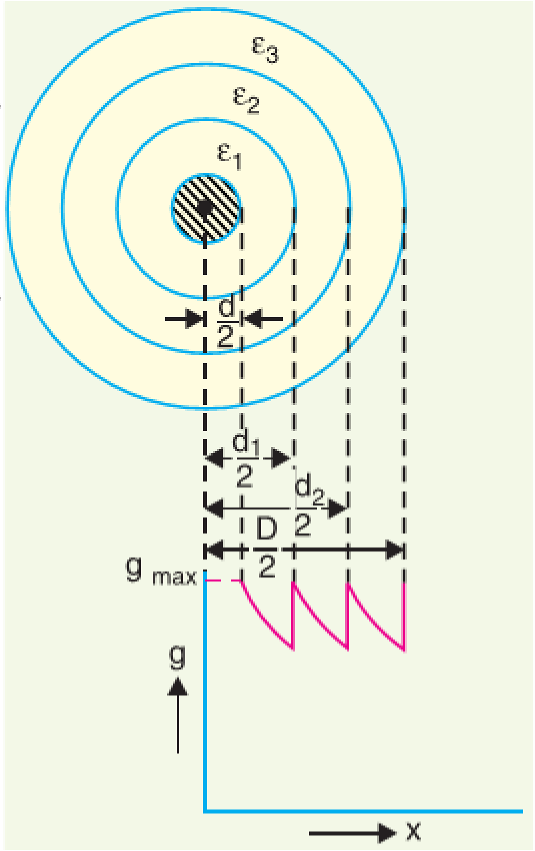


Figure 15

Capacitance Grading

- Similarly, potential across second layer (V_2) and third layer (V_3) is given by:

$$V_2 = \frac{g_{max}}{2} d_1 \ln(\frac{d_2}{d_1});\ V_3 = \frac{g_{max}}{2} d_2 \ln(\frac{D}{d_2})$$

- Total potential difference between core and earthed sheath is

$$V = \frac{g_{max}}{2}\left[d \ln\left(\frac{d_1}{d}\right) + d_1 \ln\left(\frac{d_2}{d_1}\right) + d_2 \ln(\frac{D}{d_2})\right]$$

- If the cable had homogeneous dielectric, then, for the same values of d, D and g_{max}, the permissible potential difference between core and earthed sheath would have been

$$V' = \frac{g_{max}}{2} d \ln(\frac{D}{d})$$

- Obviously, $V > V'$ *i.e.,* for given dimensions of the cable, a graded cable can be worked at a greater potential than non-graded cable.
- Alternatively, for the same safe potential, the size of graded cable will be less than that of non-graded cable.
- The following points may be noted:

(i) As the permissible values of $\boldsymbol{g_{max}}$ are peak values, therefore, all the voltages in above expressions should be taken as peak values and not the r.m.s. values.

(ii) If the maximum stress in the three dielectrics is not the same, then,

$$\boldsymbol{V} = \frac{\boldsymbol{g_{1max}}}{\boldsymbol{2}} d \ln\left(\frac{d_1}{d}\right) + \frac{\boldsymbol{g_{2max}}}{\boldsymbol{2}} d_1 \ln\left(\frac{d_2}{d_1}\right) + \frac{\boldsymbol{g_{3max}}}{\boldsymbol{2}} d_2 \ln\left(\frac{D}{d_2}\right)$$

- The principal disadvantage of this method is that there are a few high grade dielectrics of reasonable cost whose permittivities vary over the required range.

Intersheath Grading

- In this method of cable grading, a homogeneous dielectric is used, but it is divided into various layers by placing metallic intersheaths between the core and lead sheath.
- The intersheaths are held at suitable potentials which are in between the core potential and earth potential. This arrangement improves voltage distribution in the dielectric of the cable and consequently more uniform potential gradient is obtained.
- Consider a cable of core diameter d and outer lead sheath of diameter $D.$ Suppose that two intersheaths of diameters d_1 and d_2 are inserted into the homogeneous dielectric and maintained at some fixed potentials.
- Let V_1, V_2 and V_3 respectively be the voltage between core and intersheath 1, between intersheath 1 and 2 and between intersheath 2 and outer lead sheath.
- As there is a definite potential difference between the inner and outer layers of each intersheath, therefore, each sheath can be treated like a homogeneous single core cable. As proved already, Maximum stress between core and intersheath 1 is

$$g_{1max} = \frac{V_1}{\frac{d}{2}\ln(\frac{d_1}{d})}$$

$$g_{2max} = \frac{V_2}{\frac{d_1}{2}\ln(\frac{d_2}{d_1})}$$

$$g_{3max} = \frac{V_3}{\frac{d_2}{2}\ln(\frac{D}{d_2})}$$

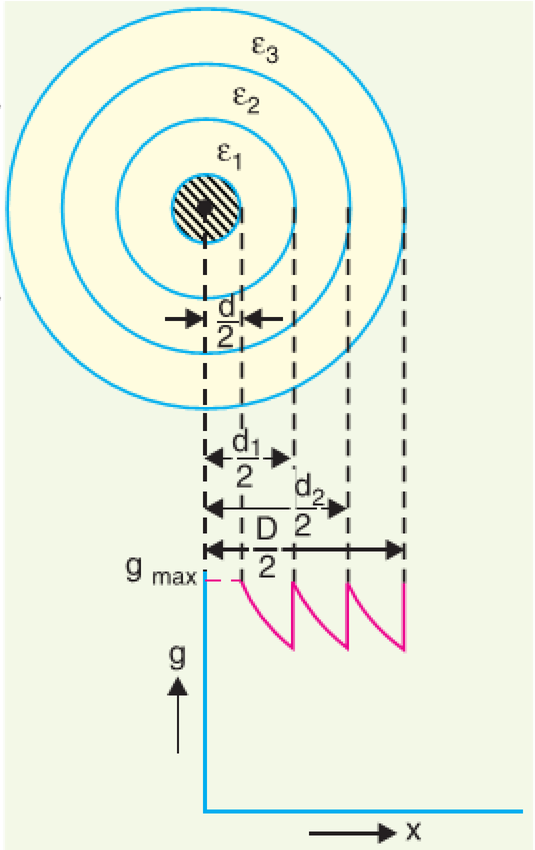


Figure 15

Intersheath Grading

- Since the dielectric is homogeneous, the maximum stress in each layer is the same *i.e.,*

$$g_{1max} = g_{2max} = g_{3max} = g_{max} \text{ (say)}$$

$$\therefore \quad \frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}} = \frac{V_2}{\frac{d_1}{2}\log_e \frac{d_2}{d_1}} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}}$$

- As the cable behaves like three capacitors in series, therefore, all the potentials are in phase *i.e.* Voltage between conductor and earthed lead sheath is $V = V_1 + V_2 + V_3$
- Intersheath grading has three principal disadvantages.
  - Firstly, there are complications in fixing the sheath potentials.
  - Secondly, the intersheaths are likely to be damaged during transportation and installation which might result in local concentrations of potential gradient.
  - Thirdly, there are considerable losses in the intersheaths due to charging currents.
- For these reasons, intersheath grading is rarely used.

Capacitance of 3-Core Cables

- The capacitance of a cable system is much more important than that of overhead line because in cables (*i*) conductors are nearer to each other and to the earthed sheath (*ii*) they are separated by a dielectric of permittivity much greater than that of air.
- Figure 16 shows a system of capacitances in a 3-core belted cable used for 3-phase system. Since potential difference exists between pairs of conductors and between each conductor and the sheath, electrostatic fields are set up in the cable as shown in Fig. 16 (*i*).
- These electrostatic fields give rise to core-core capacitances C_c and conductor-earth capacitances C_e as shown in Figure 16(*ii*).
- The three C_c are delta connected whereas the three C_e are star connected, the sheath forming the star point as shown in Figure 16 (*iii*).

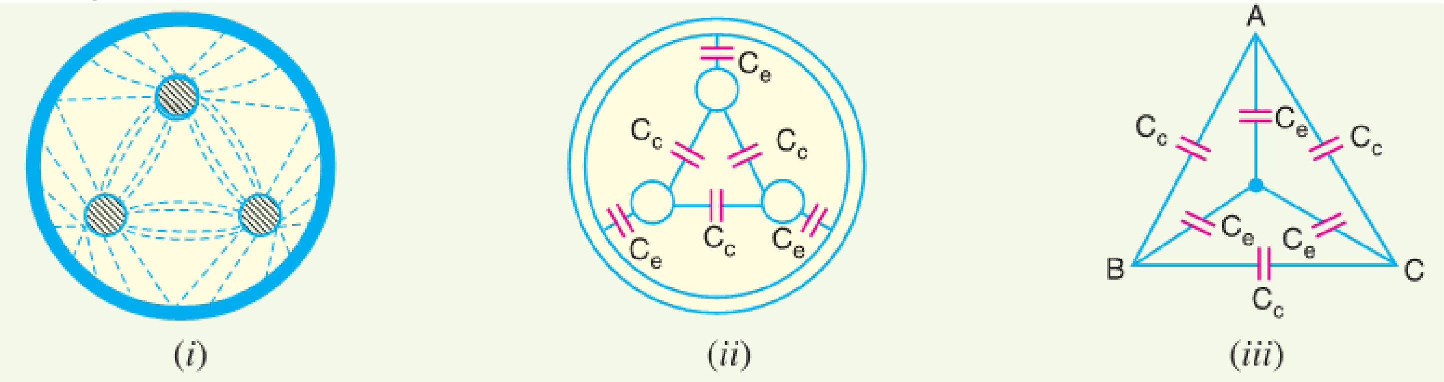


Figure 16

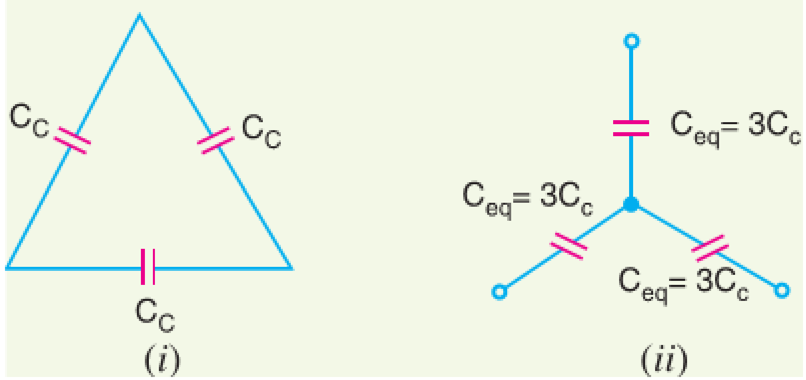


Figure 17

- They lay of a belted cable makes it reasonable to assume equality of each C_c and each C_e. The three delta connected capacitances C_c as shown in Figure 17 (*i*) can be converted into equivalent star connected capacitances as shown in Fig. 17(*ii*). It can be easily shown that equivalent star capacitance C_{eq} is equal to three times the delta capacitance C_c *i.e.* $C_{eq} = 3C_c$.

Capacitance of 3-Core Cables

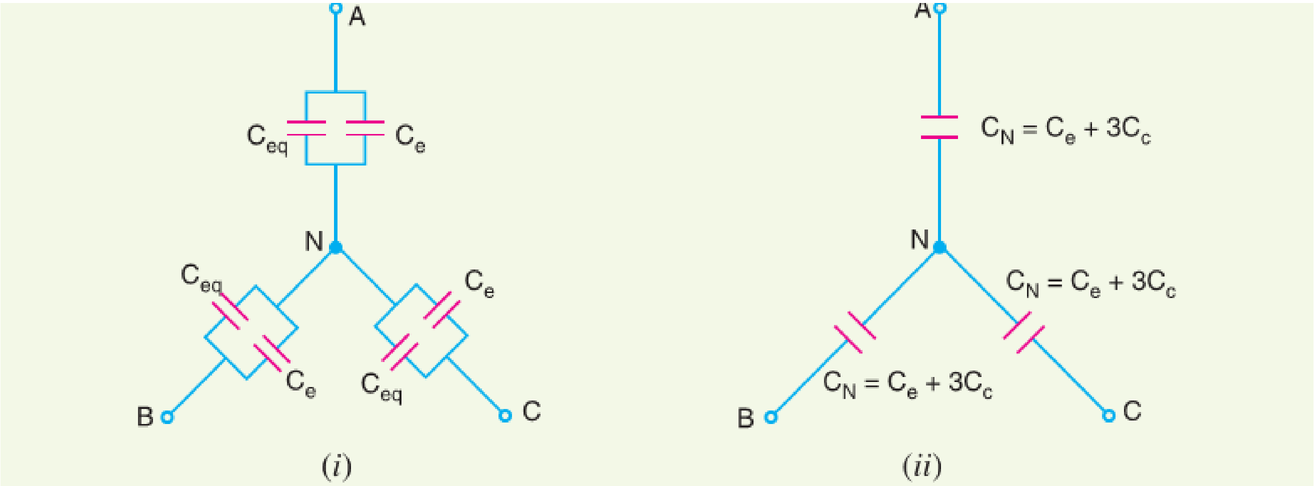


Figure 18

- Figure 16 (*iii*) reduces to the equivalent circuit shown in Figure 17 (*i*). Therefore, the whole cable is equivalent to three star-connected capacitors each of capacitance $C_N = C_e + C_{eq} = C_e + 3Cc$

- If V_{ph} is the phase voltage, then charging current I_C is given by:

$$I_C = V_{ph}/\ Capacitive\ reactance\ per\ phase = 2\pi f V_{ph} C_N = 2\pi f V_{ph}(C_e + 3Cc)$$

Measurements of C_e and C_c

- Although core-core capacitance C_c and core-earth capacitance C_e can be obtained from the empirical formulas for belted cables, their values can also be determined by measurements.
- For this purpose, the following two measurements are required:

(*i*) In the first measurement, the three cores are bunched together (*i.e.* commoned) and the capacitance is measured between the bunched cores and the sheath. The bunching eliminates all the three capacitors C_c, leaving the three capacitors C_e in parallel. Therefore, if C_1 is the measured capacitance, this test yields: $C_1 = 3Ce$ or $C_e = C_1/3$. Knowing the value of C_1, the value of C_e can be determined.

(*ii*) In the second measurement, two cores are bunched with the sheath and capacitance is measured between them and the third core. This test yields $2Cc + Ce$. If C_2 is the measured capacitance, then, $C_2 = 2Cc + Ce$. As the value of C_e is known from first test and C_2 is found experimentally, therefore, value of C_c can be determined.

- It may be noted here that if value of C_N $(= \ C_e \ + \ 3Cc)$ is desired, it can be found directly by another test. In this test, the capacitance between two cores or lines is measured with the third core free or connected to the sheath. This eliminates one of the capacitors C_e so that if C_3 is the measured capacitance, then,

$$C_3 = CC + \frac{C_C}{2} + \frac{C_e}{2} = \frac{1}{2}(Ce + 3CC) = \frac{1}{2}C_N$$

The capacitances per kilometre of a 3-phase cable are 0·63μF between the three cores bunched together and the sheath and 0·37 μF between one core and the other two connected to the sheath. Calculate the charging current taken by eight kilometres of this cable when connected to a 3-phase, 50 Hz, 6600 V supply.

$3C_e = 0.63\mu f$

$C_e = 0.21\mu f$

$2C_c + C_e = 0.37\mu f$

$2C_c + 0.21 = 0.37$

$2C_c = 0.16\mu f$

$C_c = 0.08\mu f$

$C_N = 3C_c + C_e$

$= (0.24 + 0.21)\mu f$

$= 0.45\mu f$

$I_c = \frac{6600}{\sqrt{3}} \times 2 \times \pi \times 50 \times 0.45\times10^{6} \times 8\times10^{3}$

$= 4.31$ Amp.

Types of Cable Faults

- Cables are generally laid directly in the ground or in ducts in the underground distribution system. For this reason, there are little chances of faults in underground cables. However, if a fault does occur, it is difficult to locate and repair the fault because conductors are not visible. Nevertheless, the following are the faults most likely to occur in underground cables :
  (i) Open-circuit fault
  (ii) Short-circuit fault
  (iii) Earth fault.

(*i*) ***Open-circuit fault*:-** When there is a break in the conductor of a cable, it is called open circuit fault. The open-circuit fault can be checked by a megger. For this purpose, the three conductors of the 3-core cable at the far end are shorted and earthed. Then resistance between each conductor and earth is measured by a megger. The megger will indicate zero resistance in the circuit of the conductor that is not broken. However, if the conductor is broken, the megger will indicate infinite resistance in its circuit.

(*ii*) ***Short-circuit fault:-*** When two conductors of a multi-core cable come in electrical contact with each other due to insulation failure, it is called a short-circuit fault. Again, we can seek the help of a megger to check this fault. For this purpose, the two terminals of the megger are connected to any two conductors. If the megger gives zero reading, it indicates short circuit fault between these conductors. The same step is repeated for other conductors taking two at a time.

(*iii*) ***Earth fault:-*** When the conductor of a cable comes in contact with earth, it is called earth fault or ground fault. To identify this fault, one terminal of the megger is connected to the conductor and the other terminal connected to earth. If the megger indicates zero reading, it means the conductor is earthed. The same procedure is repeated for other conductors of the cable.


GUARD
Megger. MIT1025
10kV INSULATION TESTER
TEST
OK
500V
1kV
2.5kV
5kV
10kV
OFF
DAR
PI
DD
SV
IR

CIE INSULATION TESTER
A CAMBRIDGE ENGINEERING PRODUCT
EARTH
LINE

Permissible Current Loading

- The safe current-carrying capacity of an underground cable is determined by the maximum permissible temperature rise. The cause of temperature rise is the losses that occur in a cable which appear as heat. These losses are :
  - **(*i*) Copper losses in the conductors**
  - **(*ii*) Hysteresis losses in the dielectric**
  - **(*iii*) Eddy current losses in the sheath**
- The safe working conductor temperature is 65ºC for armoured cables and 50ºC for lead-sheathed cables laid in ducts.
- The maximum steady temperature conditions prevail when the heat generated in the cable is equal to the heat dissipated.
- The heat dissipation of the conductor losses is by conduction through the insulation to the sheath from which the total losses (including dielectric and sheath losses) may be conducted to the earth.
- Therefore, in order to find permissible current loading, the thermal resistivities of the insulation, the protective covering and the soil must be known.

Permissible Current Loading

- When considering heat dissipation in underground cables, the various thermal resistances providing a heat dissipation path are in series. Therefore, they add up like electrical resistances in series.
- Consider a cable laid in soil.
- Let I = permissible current per conductor
- n = number of conductors
- R = electrical resistance per metre length of the conductor at the working temperature
- S= total thermal resistance (*i.e.* sum of thermal resistances of dielectric and soil) per metre length
- t = temperature difference (rise) between the conductor and the soil
- Neglecting the dielectric and sheath losses, we have,

$$Power\ dissipated\ =\ nI^2R$$

$$Power\ dissipated\ =\ Temperature\ rise/Thermal\ resistance$$

or, $nI^2R = \frac{t}{S}$ $\qquad$ $\left[S = \frac{Resistivity}{2\pi} ln\left(\frac{d_1}{d}\right)\ Thermal\ ohm\ per\ meter\right]$

or, $I = \sqrt{\frac{t}{nRS}}$

It should be noted that when cables are laid in proximity to each other, the permissible current is reduced further on account of mutual heating.

Dielectric Loss

- Dielectrics (insulating materials for example) when subjected to a varying electric field, will have some energy loss.
- The varying electric field causes small realignment of weakly bonded molecules, which lead to the production of heat.
- The amount of loss increases as the voltage level is increased. For low voltage cables, the loss is usually insignificant and is generally ignored.
- For higher voltage cables, the loss and heat generated can become important and needs to be taken into consideration.
- Dielectric loss is measured using what is known as the loss tangent or tan delta ($\tan\delta$).
- In simple terms, tan delta is the tangent of the angle between the alternating field vector and the loss component of the material. The higher the value of $\tan\delta$ the greater the dielectric loss will be.
- Given the tan δ and capacitance of the cable, the dielectric loss is easily calculated:
$$Loss = \omega C V^2 tan\delta$$

An 11 kV, ~~50 Hz~~, single phase cable ~~2.5~~ km long, has a diameter of 20 mm and internal sheath radius of 15 mm. If the dielectric has a relative permittivity of 2.4, determine (*i*) capacitance (*ii*) charging current (*iii*) total charging kVAR.

$d = 20\,mm$

$D = 2 \times 15\,mm = 30\,mm$

$\epsilon_r = 2.4$

$\epsilon_0 = 8.854 \times 10^{-12}\,F/m$

$$C_T = \frac{2\pi \epsilon_0 \epsilon_r \cdot l}{\ln\left(\frac{D}{d}\right)}$$

$$= \frac{2 \times \pi \times 8.854 \times 10^{-12} \times 2.4 \times 2.5 \times 10^{3}}{\ln\left(\frac{30}{20}\right)}\,F$$

$$= 8.2285 \times 10^{-7}\,F = 0.82285\,\mu f$$

$$I_{ph} = I_C = \frac{V/\sqrt{3}}{X_C} = 11 \times 10^{3} \times 2 \times \pi \times 50 \times 0.82285 \times 10^{-6} = 2.8436\,Amp$$

$$3 \times \frac{V}{\sqrt{3}} I_C = 11 \times 10^{3} \times 2.8436 = 31.279\,KVAR$$

$3 V_{ph} I_{ph}$

$= ??$

A ~~single core~~ cable for use on 11 kV, 50 Hz system has conductor area of 0·645 cm² and internal diameter of sheath is 2·18 cm. The permittivity of the dielectric used in the cable is 3·5. Find (i) the maximum electrostatic stress in the cable (ii) minimum electrostatic stress in the cable (iii) capacitance of the cable per km length (iv) charging current.

$A_c = 0.645\,cm^2$

$\frac{\pi d^2}{4} = A_c$

$d = \sqrt{\frac{4A_c}{\pi}}$

$= \sqrt{\frac{4 \times 0.645}{\pi}}$

$= 0.9062\,cm$

$D = 2.18\,cm$

$\epsilon_r = 3.5$

$g = \frac{V}{x \ln\left(\frac{D}{d}\right)}$

$\frac{D}{2}$

$g_{max} = \frac{2V}{d \ln\left(\frac{D}{d}\right)}$

$= 27.6562\,kV$

$g_{min} = \frac{2V}{D \ln\left(\frac{D}{d}\right)}$

$= 11.4963\,kV$

$C = \frac{2\pi \times 8.854 \times 10^{-12} \times 3.5}{\ln\left(\frac{2.18}{0.9062}\right)}\ F/m$

$= 0.2218\,\mu f$

$I_c = 2\pi \times 50 \times 0.2218 \times 10^{-6} \times 11 \times 10^3$

$= 0.7664\,Amps$

Find the most economical size of a single-core cable working on a 132 kV, 3-phase system, if a dielectric stress of 60 kV/cm can be allowed.

$g_{max} = 60 kV/cm$

$$g_{max} = \frac{2V}{d \ln_e\left(\frac{D}{d}\right)}$$

$$= \frac{2V}{d}$$

$$60 \times 10^3 = \frac{2 \times 132 \times 10^3 \times \sqrt{2}}{\sqrt{3} \times d}$$

$$d = \frac{2 \times 132 \sqrt{2} \times 10^3}{\sqrt{3} \times 60 \times 10^3} cm$$

$$= 3.5926 cm$$

$$\boxed{\frac{D}{d} = e}$$

d

$$D = ed$$

$$= 9.7657 cm$$

A single-core 66 kV cable has a conductor diameter of 2 cm and a sheath of inside diameter 5·3 cm. The cable has an inner layer of 1 cm thick of rubber of dielectric constant 4·5 and the rest impregnated paper of dielectric constant 3·6. Find the maximum stress in the rubber and in the paper.

$d = 2\,cm$.

$D = 5.3\,cm$

$\epsilon_1 = 4.5$

$\epsilon_2 = 3.6$

$d_1 = 4\,cm$.

$$g_{max} = \frac{Q}{2\pi\epsilon_0\epsilon_r x}.$$

$$g_{1max} = \frac{Q}{2\pi\epsilon_0\epsilon_1 \frac{d}{2}} \quad \text{--- (1)}$$

$$g_{2max} = \frac{Q}{2\pi\epsilon_0\epsilon_2 \frac{d_1}{2}} \quad \text{--- (2)}$$

$$\boxed{\frac{1}{\epsilon_1 \frac{d}{2}} = \frac{1}{\epsilon_2 \frac{d_1}{2}}}$$

$$\frac{g_{1max}}{g_{2max}} = \frac{\epsilon_2 d_1}{\epsilon_1 d} = \frac{3.6 \times 4/2}{4.5 \times 2} = \frac{7.2}{4.5}$$

$$g_{1max} = 1.6\, g_{2max}$$

$$g_{max} = \frac{2V_1}{d \ln\left(\frac{d_1}{d}\right)} \Rightarrow V_1 = \frac{d}{2} g_{1max} \ln\left(\frac{d_1}{d}\right)$$

$$g_{2max} = \frac{2V_2}{d_1 \ln\left(\frac{D}{d_1}\right)} \Rightarrow V_2 = \frac{d_1}{2} g_{2max} \ln\left(\frac{D}{d_1}\right)$$

$66 \times 10^3/2$

$$V = V_1 + V_2 = \frac{d}{2} g_{1max} \ln\left(\frac{d_1}{d}\right) + \frac{d_1}{2} g_{2max} \ln\left(\frac{D}{d_1}\right)$$

$g_{2max} = 39.476\,kV/cm$ (rms)

$g_{1max} = 63.1631\,kV/cm$ (rms).

A single-core cable working on 66 kV on 3-phase system has a conductor diameter of 2 cm and a sheath of inside diameter 5·3 cm. If two intersheaths are used, find the best positions, maximum stress and the voltage on the intersheaths.

$d = 2\,cm.$

$D = 5.3\,cm.$

$d_1 = ?$

$d_2 = ?$

$$g_{1max} = \frac{2V_1}{d \ln\left(\frac{d_1}{d}\right)} = 39.0516\,kV/cm\ (peak)$$

$$g_{2max} = \frac{2V_2}{d_1 \ln\left(\frac{d_2}{d_1}\right)}$$

$$g_{3max} = \frac{2V_3}{d_2 \ln\left(\frac{D}{d_2}\right)}$$

$g_{1min} = g_{2m} = g_{3m}$

$$\boxed{\frac{d_1}{d} = \frac{d_2}{d_1} = \frac{D}{d_2}}$$

$$\frac{d_1}{2} = \frac{d_2}{d_1} = \frac{5.3}{d_2}$$

$d_1 d_2 = 10.6$

$d_1^2 = 2d_2$

$d_2 = \frac{d_1^2}{2}$

$\frac{d_1^3}{2} = 10.6$

$d_1 = 2.76\,cm$

$d_2 = \frac{d_1^2}{2} = 3.8088$

$$\frac{2V_1}{d \cancel{\ln\left(\frac{d_1}{d}\right)}} = \frac{2V_2}{d_1 \cancel{\ln\left(\frac{d_2}{d_1}\right)}} = \frac{2V_3}{d_2 \cancel{\ln\left(\frac{D}{d_2}\right)}}$$

$$\frac{2V_1}{2} = \frac{2V_2}{2.76} = \frac{2V_3}{3.8088}$$

$$V_3 = \frac{3.8088}{2} V_1$$

$$V_2 = \frac{2.76}{2} V_1$$

$$V_1 + V_2 + V_3 = \frac{66\sqrt{2}}{\sqrt{3}}$$

$V_1 = 12.5779\,kV.$

$V_2 = 17.39\,kV.$

$V_{int1} = V - V_1 = \cancel{50}\ 41.3108\,kV\ (peak)$

$V_{int2} = V - V_1 - V_2 = 23.91\,kV\ (peak)$

Determine the insulation resistance of a single-core cable of length 3 km and having conductor radius 12·5 mm, insulation thickness 10 mm and specific resistance of insulation of $5 \times 10^{12}\Omega$m.

$$R = \frac{\rho}{2\pi L} \ln\left(\frac{r_2}{r_1}\right)$$

$$= \frac{5 \times 10^{12}}{2\pi \times 3 \times 10^3} \ln\left(\frac{22 \cdot 5}{12 \cdot 5}\right) \Omega$$

$$= 155915255 \cdot 3 \, \Omega$$

$$= 155 \cdot 9152 \, M\Omega$$

$$R_{in} \propto \frac{1}{l}$$

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

$$R \propto l$$

Capacitance Grading

Example 11.12. *A single-core lead sheathed cable is graded by using three dielectrics of relative permittivity 5, 4 and 3 respectively. The conductor diameter is 2 cm and overall diameter is 8 cm. If the three dielectrics are worked at the same maximum stress of 40 kV/cm, find the safe working voltage of the cable.*

What will be the value of safe working voltage for an ungraded cable, assuming the same conductor and overall diameter and the maximum dielectric stress ?

Here, $d = 2$ cm ; $d_1 = ?$; $d_2 = ?$; $D = 8$ cm

$\varepsilon_1 = 5$; $\varepsilon_2 = 4$; $\varepsilon_3 = 3$; $g_{max} = 40$ kV/cm

Graded cable. As the maximum stress in the three dielectrics is the same,

$$\therefore \quad \varepsilon_1 d = \varepsilon_2 d_1 = \varepsilon_3 d_2$$

$$\text{or} \quad 5 \times 2 = 4 \times d_1 = 3 \times d_2$$

$$\therefore \quad d_1 = 2{\cdot}5 \text{ cm} \quad \text{and } d_2 = 3{\cdot}34 \text{ cm}$$

Permissible peak voltage for the cable

$$= \frac{g_{max}}{2}\left[d \log_e \frac{d_1}{d} + d_1 \log_e \frac{d_2}{d_1} + d_2 \log_e \frac{D}{d_2}\right]$$

$$= \frac{40}{2}\left[2 \log_e \frac{2{\cdot}5}{2} + 2{\cdot}5 \log_e \frac{3{\cdot}34}{2{\cdot}5} + 3{\cdot}34 \log_e \frac{8}{3{\cdot}34}\right]$$

$$= 20\,[0{\cdot}4462 + 0{\cdot}7242 + 2{\cdot}92] \text{ kV}$$

$$= 20 \times 4{\cdot}0904 = 81{\cdot}808 \text{ kV}$$

$\therefore$ Safe working voltage (r.m.s.) for cable

$$= \frac{81{\cdot}808}{\sqrt{2}} = \mathbf{57{\cdot}84 \text{ kV}}$$

Ungraded cable. Permissible peak voltage for the cable

$$= \frac{g_{max}}{2}\, d \log_e \frac{D}{d} = \frac{40}{2} \times 2 \log_e \frac{8}{2} \text{ kV} = 55{\cdot}44 \text{ kV}$$

$\therefore$ Safe working voltage (r.m.s.) for the cable

$$= \frac{55{\cdot}44}{\sqrt{2}} = \mathbf{39{\cdot}2 \text{ kV}}$$

This example shows the utility of grading the cable. Thus for the same conductor diameter (d) and the same overall dimension (D), the graded cable can be operated at a voltage $(57{\cdot}84 - 39{\cdot}20) = 18{\cdot}64$ kV (r.m.s.) higher than the homogeneous cable — an increase of about 47%.

Intersheath Grading

Example 11.15. *A single core cable of conductor diameter 2 cm and lead sheath of diameter 5.3 cm is to be used on a 66 kV, 3-phase system. Two intersheaths of diameter 3·1 cm and 4·2 cm are introduced between the core and lead sheath. If the maximum stress in the layers is the same, find the voltages on the intersheaths.*

Here, $d = 2$ cm ; $d_1 = 3\cdot 1$ cm ; $d_2 = 4\cdot 2$ cm

$$D = 5.3 \text{ cm} ; V = \frac{66 \times \sqrt{2}}{\sqrt{3}} = 53\cdot 9 \text{ kV}$$

$$g_{1max} = \frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}} = \frac{V_1}{1 \times \log_e \frac{3\cdot 1}{2}} = 2\cdot 28\, V_1$$

$$g_{2max} = \frac{V_2}{\frac{d_1}{2}\log_e \frac{d_2}{d_1}} = \frac{V_2}{1\cdot 55 \log_e \frac{4.2}{3.1}} = 2\cdot 12\, V_2$$

$$g_{3max} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}} = \frac{V_3}{2\cdot 1 \log_e \frac{5\cdot 3}{4\cdot 2}} = 2\cdot 04\, V_3$$

As the maximum stress in the layers is the same,

$\therefore$ $g_{1max} = g_{2max} = g_{3max}$

or $2\cdot 28\, V_1 = 2\cdot 12\, V_2 = 2\cdot 04\, V_3$

$\therefore$ $V_2 = (2\cdot 28/2\cdot 12)\, V_1 = 1\cdot 075\, V_1$

and $V_3 = (2\cdot 28/2\cdot 04)\, V_1 = 1\cdot 117\, V_1$

Now $V_1 + V_2 + V_3 = V$

or $V_1 + 1\cdot 075\, V_1 + 1\cdot 117\, V_1 = 53\cdot 9$

or $V_1 = 53\cdot 9/3\cdot 192 = 16\cdot 88$ kV

and $V_2 = 1\cdot 075\, V_1 = 1\cdot 075 \times 16\cdot 88 = 18\cdot 14$ kV

$\therefore$ Voltage on first intersheath (*i.e.*, near to the core)

$= V - V_1 = 53\cdot 9 - 16\cdot 88 =$ **37·02 kV**

Voltage on second intersheath $= V - V_1 - V_2 = 53\cdot 9 - 16\cdot 88 - 18\cdot 14 =$ **18·88 kV**

Intersheath Grading

Example 11.16. *A single-core 66 kV cable working on 3-phase system has a conductor diameter of 2 cm and a sheath of inside diameter 5.3 cm. If two intersheaths are introduced in such a way that the stress varies between the same maximum and minimum in the three layers, find :*

(*i*) *positions of intersheaths*

(*ii*) *voltage on the intersheaths*

(*iii*) *maximum and minimum stress*

Here, $d = 2$ cm ; $D = 5.3$ cm ; $V = \frac{66\times\sqrt{2}}{\sqrt{3}} = 53.9$ kV

(*i*) **Positions of intersheaths.** Suppose that diameters of intersheaths are d_1 and d_2 cm respectively. Let V_1, V_2 and V_3 respectively be the voltage between conductor and intersheath 1, between intersheath 1 and 2 and between intersheath 2 and outer lead sheath.

$$g_{1max} = \frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}} \quad ; \quad g_{2max} = \frac{V_2}{\frac{d_1}{2}\log_e \frac{d_2}{d_1}} \quad ; \quad g_{3max} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}}$$

As the maximum stress in the three layers is the same,

$$\therefore \quad \frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}} = \frac{V_2}{\frac{d_1}{2}\log_e \frac{d_2}{d_1}} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}} \quad \text{...}(i)$$

In order that stress may vary between the same maximum and minimum in the three layers, we have,

$$d_1/d = d_2/d_1 = D/d_2 \quad \text{...}(ii)$$

$$\therefore \quad \frac{V_1}{d} = \frac{V_2}{d_1} = \frac{V_3}{d_2} \quad \text{...*}(iii)$$

From exp. (*ii*), we get,

$$d_1^2 = d \times d_2 = 2d_2 \qquad [\because d = 2 \text{ cm}]$$

or $$d_2 = d_1^2/2$$

and $$d_1 d_2 = D \times d = 5{\cdot}3 \times 2 = 10.6 \text{ cm}$$

or $$d_1 \times d_1^2/2 = 10{\cdot}6$$

or $$d_1 = (21{\cdot}2)^{1/3} = \mathbf{2{\cdot}76\ cm}$$

$$\therefore \quad d_2 = d_1^2/2 = (2{\cdot}76)^2/2 = \mathbf{3{\cdot}8\ cm}$$

Hence intersheaths of diameters 2.76 cm and 3.8 cm are required to be used.

(*ii*) **Voltage on intersheaths**

$$V = V_1 + V_2 + V_3$$

or $$53{\cdot}9 = V_1 + \frac{d_1}{d}V_1 + \frac{d_2}{d}V_1 \qquad [\text{From eq. } (iii)]$$

$$= V_1\left(1 + \frac{2{\cdot}76}{2} + \frac{3{\cdot}8}{2}\right) = 4{\cdot}28\, V_1$$

$$\therefore \quad V_1 = 53{\cdot}9/4{\cdot}28 = 12{\cdot}6 \text{ kV}$$

and $$V_2 = \frac{d_1}{d} \times V_1 = \frac{2.76}{2} \times 12{\cdot}6 = 17{\cdot}39 \text{ kV}$$

Voltage on first intersheath $= V - V_1 = 53{\cdot}9 - 12.6 =$ **41·3 kV *max***

Voltage on second intersheath $= V - V_1 - V_2 = 53{\cdot}9 - 12{\cdot}6 - 17{\cdot}39 =$ **23·91 kV *max***

(*iii*) **Stresses in dielectrics**

$$\text{Maximum stress} = \frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}} = \frac{12{\cdot}6}{1 \times \log_e \frac{2{\cdot}76}{2}} \text{ kV/cm} = \mathbf{39\ kV/cm}$$

$$\text{Minimum stress} = \frac{V_1}{\frac{d_1}{2}\log_e \frac{d_1}{d}} = \frac{12{\cdot}6}{1{\cdot}38 \log_e \frac{2{\cdot}76}{2}} \text{ kV/cm} = \mathbf{28{\cdot}35\ kV/cm}$$