UNIT-IV

UNDERGROUND CABLES.

An Underground Cable essentially Consists of one or more Conductors Covered with suitable insulation and surrounded by a protecting Cover.

The Underground Cables have Several advantages
→ less liable to damage through storms (or) lightning, low maintenance Cost, less chances of faults, smaller voltage drop and better general appearance.

The major drawback of underground Cables are.
→ Greater Installation Cost and introduce insulation problems at high voltages Compared with equivalent Overhead systems.

The reason Underground Cables employed.
→ If place where it is impracticable to use Overhead lines. such locations may be thickly populated areas where municipal authorities prohibit Overhead lines for reasons for safety (or) around plants (or) where maintenance Conditions donot permit the Use of overhead Construction.

However, recent improvements in design and manufacture have lead to development of cables suitable for use at high voltages.

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 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 the causes voltage drop within permissible limits.

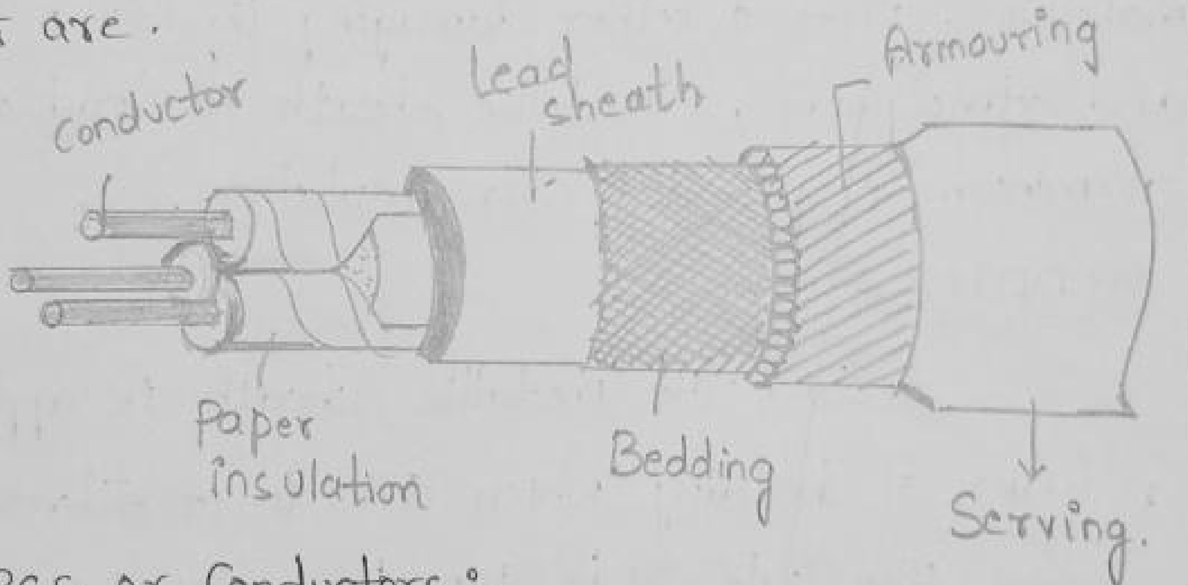
iii) The cable must have proper thickness of insulation in order to give high degree of safety and reliability at voltage for which it is designed.

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

v) The materials used in manufacture of Cables should be such that there is Complete chemical and physical stability throughout.

CONSTRUCTION OF CABLES:

The General Construction 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 above figure. 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, thickness of layer depending upon voltage to be withstood by 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 in soil and atmosphere, a metallic sheath of lead (or) aluminium is provided Over insulation.

BEDDING:

Over the metallic sheath is applied a layer of bedding which Consists of fibrous material like jute (or) hessian tape. the purpose of bedding is to protect the metallic sheath aganist 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 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 cables for the protection of conductor insulation and to protect the metallic sheath from mechanical injury.

INSULATING MATERIALS FOR CABLES:

The Satisfactory Operation of Cable depends to a great extent upon characteristics of insulation Used. Therefore, the prioper choice of Insulating material for Cables is of Considerable importance. In general, the insulating materials Used in Cables should have following properties:

i) High insulation resistance to avoid leakage Current.

ii) High dielectric strength to avoid electrical breakdown of the Cable.

iii) High mechanical strength to withstand the mechanical handling of Cables.

iv) Non-hygroscopic ie., it should not absorb moisture from air (or) Soil. The moisture tends to decrease the insulation resistance.

v) Non inflammable.

vi) low Cost as to make the underground system a Variable proposition.

vii) Unaffected by acids and alkalies to avoid any chemical actions.

The type of insulating material depends upon purpose for which cable is required and quality of insulation to be aimed at.

The insulating materials used in cables are.

1) RUBBER :-

Rubber may be obtained from milky sap of tropical trees (or) it may be produced from oil products. It has relative permittivity varies between 2 & 3, dielectric strength is 30 kv/mm and resistivity of insulation is 10^{17} Ω cm. Major drawbacks is readily absorbs moisture, soft and liable to damage due to rough handling.

2) Vulcanised India Rubber:

It is prepared by mixing pure rubber with mineral mater such as Zinc Oxide, redlead e.tc and 3 to 5 % of Sulphur. The rubber compound is then applied to conductor and is heated to temperature about 150°C. The whole process is called vulcanisation.

Vulcanised India rubber has greater mechanical strength, durability. Its main drawback is that sulphur reacts very quickly with copper.

3) Impregnated Paper :-

It consists of chemically pulped paper made from wood chippings and impregnated with some compound such as paraffinics.

It has advantages of low Cost, low Capacitance, high dielectric strength and high insulation resistance.

The only disadvantage is paper is hygroscopic and even it lowers the insulation resistance of cable.

Polyvinyl chloride (PVC):-

This insulating material is a synthetic Compound. It is obtained from the polymerisation of actylene.

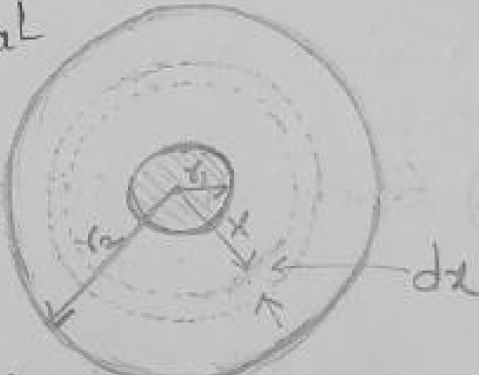
Polyvinyl chloride has high insulation resistance, good dielectric strength and mechanical toughness over a wide range of temperatures.

It is inert to Oxygen and almost inert to many alkalies and acids. This type of insulation is preferred Over VIR (Vulcanised India Rubber) in extreme environmental Conditions.

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.

Consider a Single Core Cable of Conductor radius r_1 and internal sheath radius r_2 as figure.



Let l be the length of Cable.

'ρ' be resistivity of insulation.

Consider a Very small layer of insulation of thickness dx at radius x. The length through which leakage current tends to flow is dx and area of cross section offered to this flow $= 2\pi x l$.

$\therefore$ Insulation resistance of Considered layer $= \rho \dfrac{dx}{2\pi x l}$.

$$\left[\because R = \frac{\rho l}{A}\right]$$

Insulation resistance of the whole Cable is

$$R = \int_{r_1}^{r_2} \rho \frac{dx}{2\pi x l} = \frac{\rho}{2\pi l} \int_{r_1}^{r_2} \frac{1}{x} dx.$$

$$\boxed{R = \frac{\rho}{2\pi l} \log_e \frac{r_2}{r_1}}$$

This shows that insulation resistance of a Cable is inversely proportional to its length.

NUMERICAL PROBLEMS:

1) A Single Core Cable has Conductor diameter of 1cm & insulation thickness of 0.4cm. If the specific ~~res~~ resistance of insulation is $5\times10^{14}\,\Omega\cdot cm$. Calculate insulation resistance for a 2 km length of Cable?

A) Given $r_1 = 0.5cm$, $l = 2km = 2000m$.

$\rho = 5\times10^{14}\,\Omega\text{-}cm$, $r_2 = 0.5 + 0.4 = 0.9cm$.

Insulation resistance of Cable is.

$$R = \frac{\rho}{2\pi l} \log_e \frac{r_2}{r_1}$$

$$= \frac{5\times10^{12}}{2\pi\, 2000} \log_e \frac{0.9}{0.5}$$

$$= 0.234\times10^{9}\,\Omega$$

$$\boxed{R = 234 M\Omega.}$$

2) A Single Core Cable 5 km long has an insulation resistance of 0.4 MΩ. The Core diameter is 20mm and diameter of Cable over insulation is 50mm. Calculate resistivity of insulating material.

Sol: length of Cable, $l = 5\ km = 5000\ m$.

$R = 0.4 M\Omega = 0.4 \times 10^6 \Omega$, $r_1 = 10mm$, $r_2 = 25mm$

∴ Insulation resistance $R = \frac{\rho}{2\pi l} \log \frac{r_2}{r_1}$.

$$0.4 * 10^6 = \frac{\rho}{2\pi \times 5000} \log \frac{25}{10}.$$

$$\rho = 13.72 * 10^9 \Omega m.$$

3) The insulation resistance of single Core Cable is 495 MΩ/km. If Core diameter is 2.5cm & ρ is $4.5 \times 10^{14} \Omega cm$. find insulation thickness.

Sol. length of Cable $l = 1km$, Cable insulation Resistance, $R = 495 M\Omega$

Conductor radius $= r_1 = \frac{2.5}{2} = 1.25cm$, $\rho = 4.5 \times 10^{14} \Omega cm$.

Let r_2 cm be internal sheath radius.

$$R = \frac{\rho}{2\pi l} \log_e \frac{r_2}{r_1}.$$

$$\log_e \frac{r_2}{r_1} = \frac{2\pi l R}{\rho} = \frac{2\pi \times 1000 \times 495 \times 10^6}{4.5 \times 10^{12}} = 0.69.$$

$$2.3 \log_{10} \frac{r_2}{r_1} = 0.69.$$

$$r_2/r_1 = \text{antilog } 0.69/2.3 = 2.$$

$$r_2 = 2r_1 = 2 \times 1.25 = 2.5 cm.$$

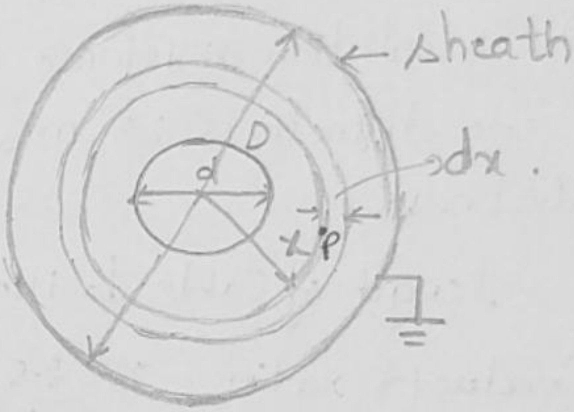
∴ Insulation thickness $= r_2 - r_1$

$= 2.5 - 1.25 = 1.25\ cm$ //.

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`.



Let the charge per metre axial length of the Cable be `Q` Coulombs. `ε` be permittivity of the insulation material between Core and lead sheath.

Obviously $\varepsilon = \varepsilon_0 \varepsilon_r$, where ε_r is the relative permittivity of insulation.

Consider a cylinder of radius x meter and axial length 1 metre. The surface area of this cylinder is $= 2\pi x l = 2\pi x \ m^2$.

$\therefore$ electric flux density at any point p on Considered cylinder $D_x = \dfrac{Q}{2\pi x} \ C/m^2$.

Electric Intensity at point P, $E_x = \frac{D_x}{\varepsilon} = \frac{Q}{2\pi x \varepsilon}$

$$E_x = \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r} \text{ volts/m.}$$

The work done in moving a unit positive charge from point p through a distance dx in direction of electric field is $E_x dx$

Hence 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.

$$V = \int_{d/2}^{D/2} E_x dx = \int_{d/2}^{D/2} \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r} dx$$

$$= \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} \log_e \frac{D}{d}.$$

Capacitance of Cable is.

$$C = \frac{Q}{V} = \frac{Q}{\frac{Q}{2\pi\varepsilon_0\varepsilon_r} \log_e \frac{D}{d}} \text{ f/m}$$

$$= \frac{2\pi\varepsilon_0\varepsilon_r}{\log_e \frac{D}{d}} \text{ f/m.}$$

$\varepsilon_0 = 8.854 \times 10^{-12}$, $\log_e = 2.303 \log_{10}$.

$$C = \frac{2\pi \times 8.854 \times 10^{-12} \times \varepsilon_r}{2.303 \log_{10} D/d} \text{ f/m.}$$

$$= \frac{\varepsilon_r}{41.4 \log_{10}(D/d)} * 10^{-9} \text{ f/m.}$$

If the Cable has length of l meters, then Capacitance of the Cable is.

$$\boxed{C = \frac{\varepsilon_r l}{41.4 \log_{10}\frac{D}{d}} * 10^{-9}} \text{ farad.}$$

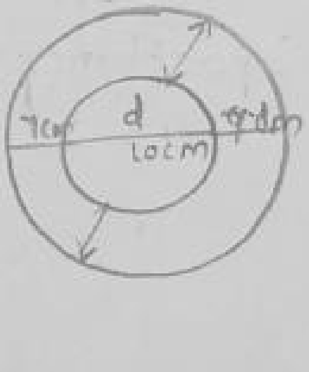
Numericals:

1) Calculate the Capacitance and charging Current of single core cable used on a 3 phase, 66kv system. the cable is 1km long having a core diameter of 10cm and an impregnated paper insulation of thickness 7cm. The relative permittivity of insulation may be taken as 4 and supply at 50Hz.

Sol. Capacitance of Cable $C = \frac{\varepsilon_r l}{41.4 \log_{10}\left(\frac{D}{d}\right)} * 10^{-9}$ f

Here $\varepsilon_r = 4$, $d = 10$cm, $l = 1000$ m.

$D = 10 + (2 \times 7) = 24$ cm.



$$C = \frac{4 \times 1000}{41.4 \times \log_{10}\left(\frac{24}{10}\right)} \times 10^{-9}$$

$= 0.254\ \mu f$.

Voltage between core and sheath is.

$V_{ph} = 66/\sqrt{3} = 38.1$kv

Charging Current $= V_{ph}/X_C = 2\pi f C V_{ph}$

$\Rightarrow 2\pi(50)(0.254) \times 10^{-6} \times 38.1 \times 10^{3}$

$\Rightarrow 3.04$A.

Total charging kVAR $= 3 V_{ph} I_c$.

$= 3 \times 38.1 \times 3.04 \times 10^{3}$

$= 347.47 \times 10^{3}$ kVAR.

CAPACITANCE OF 3 CORE CABLES.

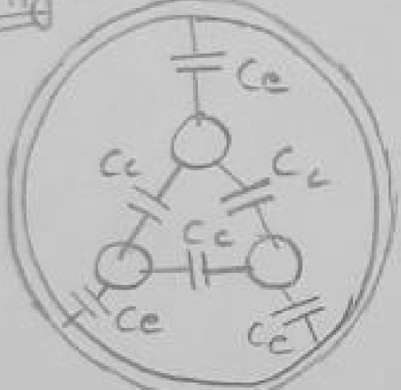
The Capacitance of a Cable system is much more important than that of overhead line because in Cables.

i) Conductors are nearer to each other and to the earthed sheath.

ii) They are seperated by a dielectric of permitivity much greater than that of air.

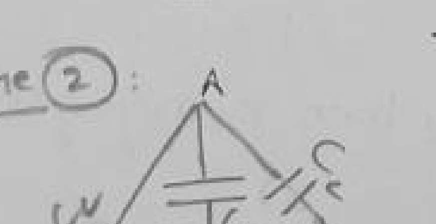
figure (1) shows a system of Capacitances in a 3 Core belted Cable Used for 3 phase system.

fig: 1



The electrostatic fields in Cable give rise to Core-Core Capacitances C_c and Conductor-earth Capacitances C_e.

figure (2):



The three C_c are delta Connected whereas the three C_e are star Connected, the sheath forming the start point in figure (2)

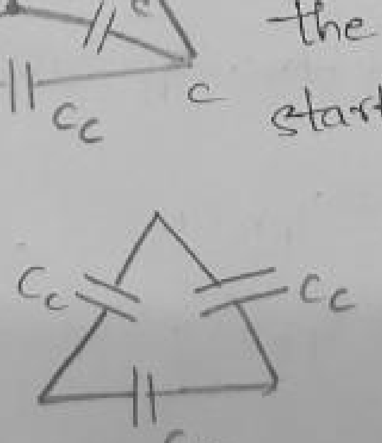


figure (3)

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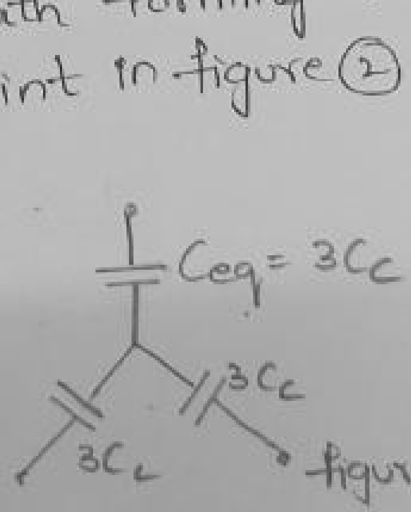
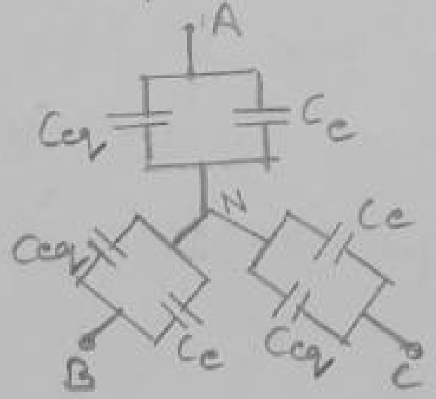
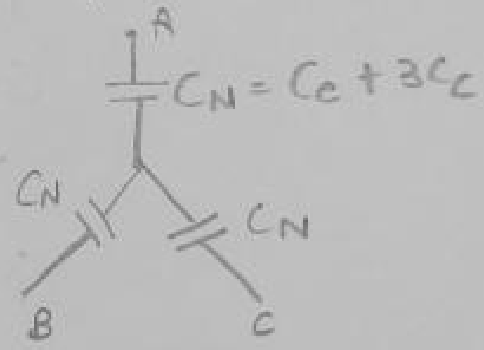


figure (4)

The three delta Connected Capacitances C_c [see in fig ③] can be converted into equivalent star connected capacitance as shown in fig ④. It can be easily shown that equivalent star capacitance C_{eq} is equal to three times the delta capacitance C_c ie., $C_{eq} = 3C_c$.

The System of Capacitances shown in fig ② reduces to equivalent ~~Con figur~~ Circuit shown in figure ⑤. Therefore, the whole cable is equivalent to three star connected capacitors each of Capacitance. [see in figure ⑥]





$$C_N = C_e + C_{eq} = C_e + 3C_c.$$

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

$$I_c = \frac{V_{ph}}{\text{~~Capacitance~~ Capacitive reactance per phase}}$$

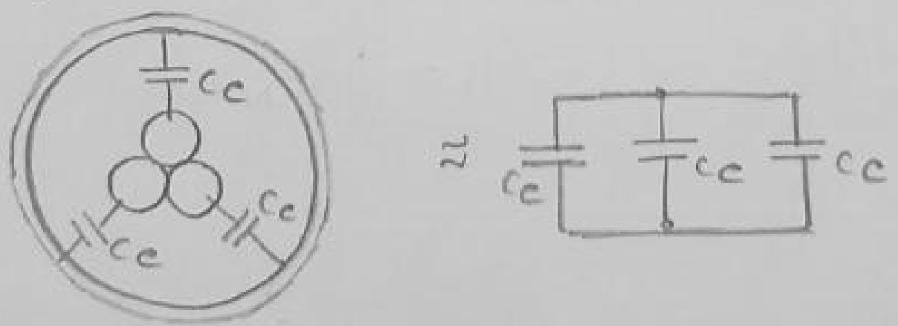
$$I_c = 2\pi f V_{ph} C_N$$

$$\boxed{I_c = 2\pi f V_{ph} (C_e + 3C_c)}$$

Measurements of C_e and C_c.

Although Core-Core Capacitance C_c and Core earth capacitance C_e can be obtained from empirical formulas for belted Cables, their values Can also be determined by measurements. for this purpose, the following two measurements are required.

i) The first measurement, the three Cores are bunched together (ie., Commoned) and Capacitance is measured between bunched Cores and sheath. The bunching eliminates all the three Capacitors C_c, leaving the three Capacitors C_e in parallel. Therefore, if C_1 is measured Capacitance, this test yields.



$$C_1 = 3C_e$$

$$C_e = \frac{C_1}{3}.$$

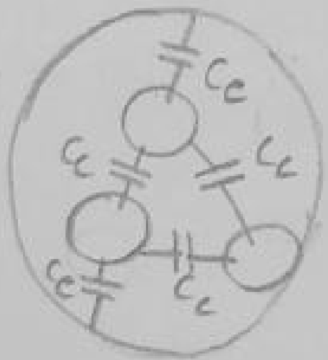
knowing the value of C_1, the value of C_e Can be determined.

(ii) In the second measurement, two cores are bunched with sheath and capacitance is measured between them and third core. This test yields

$$C_2 = C_e + 2C_c.$$

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.

(iii) In this test, the capacitance between two core is measured with third core connected to sheath. This eliminates one of capacitors C_e so that if C_3 is measured capacitance then,



$$C_3 = C_c + \frac{C_c}{2} + \frac{C_e}{2}$$

$$= \frac{1}{2}(C_e + 3C_c)$$

$$C_3 = \frac{1}{2} C_N.$$

Numerical Problems on Capacitance of three Core Cable:

1) The capacitance per km of 3 phase belted cable is 0.3 μf between the two cores with third core connected to lead sheath. Calculate the charging current taken by 5 km. of this cable when connected to 3 phase, 50Hz, 11kV supply?

Sol.: The capacitance between a pair of cores with third core earthed for a length of 5 km is.

$$C_3 = 0.3 \times 5 = 1.5\,\mu f.$$

$$V_{ph} = \frac{11 \times 10^3}{\sqrt{3}} = 6351V, \quad f = 50\,Hz.$$

Core to neutral capacitance C_N of this cable (as per measurement test ③) is given by.

$$C_N = 2C_3 = 2 \times 1.5 = 3\,\mu f.$$

∴ charging current, $I_c = 2\pi f V_{ph} C_N$.

$$= 2\pi(50)(6351)(3 \times 10^{-6}) = 5.98\,A.$$

2) The capacitances of 3 phase belted cable are 12.6 μf between the 3 core bunched together & lead sheath and 7.4 μf between one core and other two connected to sheath. find the charging current drawn by cable when connected to 66kV, 50Hz supply.

Sol. $$V_{ph} = \frac{66 \times 10^3}{\sqrt{3}} = 38105V, \quad f = 50\,Hz,$$

$$C_1 = 12.6\,\mu f, \quad C_2 = 7.4\,\mu f.$$

let Core-Core and Core-earth Capacitances of Cable be C_e & C_c respectively.

$$C_1 = 3C_e \; ; \; C_e = C_1/3 = \frac{12.6}{3} = 4.2 \mu f.$$

$$C_2 = 2C_c + C_e.$$

$$C_c = \frac{C_2 - C_e}{2} = \frac{7.4 - 4.2}{2} = 1.6 \mu f.$$

Core to neutral capacitance.

$$C_N = C_e + 3C_c = 4.2 + 3 \times 1.6 = 9 \mu f.$$

charging Current, $I_C = 2\pi f V_{ph} C_N$

$$= 2\pi (50)(38105)(9) \times 10^{-6}$$

$$= 107.74 \text{ A}.$$

3) The Capacitance/km of 3 ϕ belted cable is 0.18 μf. between two Core with third core Connect to sheath. Calculate kVA taken by 20km long cable when connected to 3 phase, 50Hz, 3300V supply.

Sol: The Capacitance between pair of Core with third Core earth for length of 20km ; f = 50Hz.

$$C_3 = 0.18 \times 20 = 3.6 \mu f \; , \; V_{ph} = \frac{3300}{\sqrt{3}} = 1905 V$$

Core to neutral Capacitance, $C_N = 2C_3 = 2 \times 3.6$

$$= 7.2 \mu f.$$

charging Current, $I_C = 2\pi f V_{ph} C_N$

$$= 2\pi (50)(1905)(7.2) \times 10^{-6}.$$

$$= 4.3 \text{ A}.$$

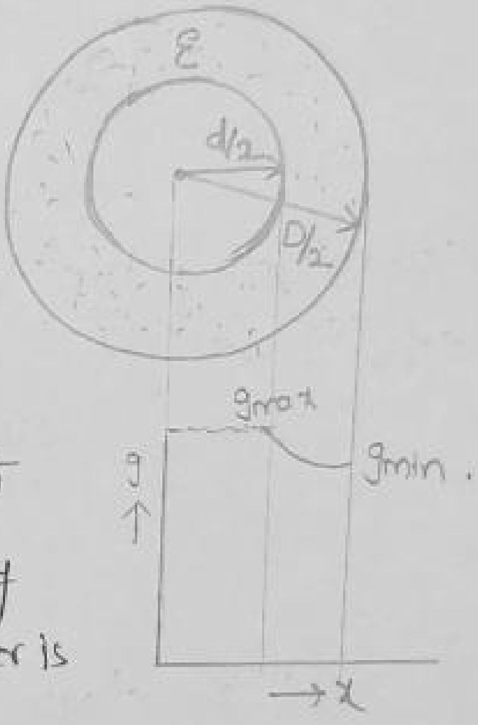
KVA taken by Cable $= 3 V_{ph} I_c$

$$= 3 \times 1905 \times 4.3 \times 10^{-3}$$

$$= 24.57 \text{ kVA}.$$

DIELECTRIC STRESS IN 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 infact the potential gradient (or) electric intensity) at that point.



Consider a Single Core cable with core diameter d and internal sheath diameter D.

Consider a Cylinder of radius x meters. The surface area of this cylinder = $2\pi x \, m^2$

$\therefore$ Electric flux density at any point p on Considered cylinder is

$$D_x = \frac{Q}{2\pi x} \; C/m^2.$$

Electric intensity at a point x meters from the centre of the Cable is.

$$E_x = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r x} \quad \text{volts/m}.$$

By definition, electric intensity is equal to potential gradient. Therefore, potential gradient g at a point x meters from the Centre of Cable is.

$$g = E_x.$$

$$\boxed{g = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r x}} \text{ volts/m} \quad \longleftarrow (1)$$

Potential difference V between Conductor and sheath is.

$$V = \int_d^D E \cdot dx. = \int_d^D \frac{Q}{2\pi \varepsilon_0 \varepsilon_r x} dx.$$

$$= \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} \log_e \frac{D}{d} \text{ volts}$$

$$\boxed{Q = \frac{2\pi \varepsilon_0 \varepsilon_r V}{\log_e \frac{D}{d}}} \quad \longleftarrow (2)$$

Substituting the value of Q from exp (ii) in exp (i) we get.

$$g = \frac{2\pi \varepsilon_0 \varepsilon_r V}{\frac{\log_e D/d}{2\pi \varepsilon_0 \varepsilon_r x}} = \frac{V}{x \log_e D/d} \text{ volts/m} \quad \longleftarrow (3)$$

It is clear from exp (3) that potential gradient varies inversely at the distance x. Therefore, potential gradient will be maximum when x is minimum i.e., when $x = d/2$ (or) at surface of Conductor. On the other hand, potential gradient will be minimum at $x = D/2$ (or) at sheath surface.

∴ Maximum potential gradient is

$$g_{max} = \frac{2V}{d \log_e D/d} \text{ volts/m} \quad [\because x = d/2]$$

Minimum potential gradient is

$$g_{min} = \frac{2V}{D \log_e D/d} \text{ volts/m} \quad [\because x = D/2]$$

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

It is clear that dielectric stress is maximum at conductor surface and its value goes on decreasing as we move away from the conductor.

It may be noted that maximum stress is an important consideration in design of a cable. for instance, if a cable is to be operated at such a voltage that maximum stress is 5 kV/mm, then the insulation used must have a dielectric strength of atleast 5 kV/mm, otherwise breakdown of the cable will become inevitable.

NUMERICALS ON DIELECTRIC STRESS

1) A 33kv single core cable has a conductor diameter of 1cm and a sheath of inside ~~Condu~~ diameter 4cm. find the maximum and minimum stress in the insulation ?

Sol: The maximum stress occurs at conductor surface and its value is given by.

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

Here,

$V = 33kv$ (rms) ; $d = 1$ cm ; $D = 4$ cm

Substituting the values in above expression, we get.

$$g_{max} = \frac{2 \times 33}{1 \times \log_e 4} \text{ kv/cm} = 47.61 \text{ kv/cm}.$$

The minimum stress occurs at sheath and its value is given by.

$$g_{min} = \frac{2V}{D \log \frac{D}{d}} = \frac{2 \times 33}{4 \log_e 4} \text{ kv/cm}$$

$$= 11.9 \text{ kv/cm rms}$$

Alternatively,

$$g_{min} = g_{max} * \frac{d}{D}$$

$$= 47.61 \times 1/4 = 11.9 \text{ Kv/cm}.$$

2) The maximum and minimum stresses in dielectric of a single core cable are 40 kv/cm (rms) and 10 kv/cm (rms) respectively. If the conductor diameter is 2cm. find i) thickness of insulation ii) Operating voltage.

Sol: Here, $g_{max} = 40\ kv/cm$; $g_{min} = 10\ kv/cm$; $d = 2cm$

$D = ?$

i) $$\frac{g_{max}}{g_{min}} = \frac{D}{d}$$

$$D = \frac{g_{max}}{g_{min}} \times d = \frac{40}{10} \times 2 = 8\ cm.$$

$\therefore$ Insulation thickness $= \frac{D-d}{2} = \frac{8-2}{2} = 3cm$

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

$$V = \frac{g_{max}\ d \cdot \log_e D/d}{2} = \frac{40 \times 2 \log_e 4}{2}\ kV$$

$$= 55.45\ kV\ rms.$$

3) A single core cable for use on 11kv, 50Hz system has conductor area of 0.645 cm^2 and internal diameter of sheath is 2.18 cm. The permittivity of dielectric used in the cable is 3.5.

find i) the maximum electrostatic stress in cable.

ii) Minimum electrostatic stress in the cable.

iii) Capacitance of the cable per km length.

iv) charging current.

Sol: Area of Cross section of Conductor, $a = 0.645\ cm^2$

Diameter of the Conductor, $d = \sqrt{\frac{4a}{\pi}}$.

$(\pi r^2 = a)$

$$d = \sqrt{\frac{4 \times 0.645}{\pi}} = 0.906\ cm$$

Internal diameter of sheath, $D = 2.18$ cm.

i) Maximum electrostatic stress in Cable is.

$$g_{max} = \frac{2V}{d \log_e \frac{D}{d}} = \frac{2 \times 11}{0.906 \log_e \frac{2.18}{0.906}}\ kV/cm.$$

$$= 27.65\ kV/cm \text{ rms}$$

ii) Minimum electrostatic stress in Cable.

$$g_{min} = \frac{2V}{D \log_e \frac{D}{d}} = \frac{2 \times 11}{2.18 \log_e \frac{2.19}{0.906}}\ kV/cm$$

$$= 11.5\ kV/cm.$$

iii) Capacitance of Cable

$$C = \frac{\varepsilon_r l}{41.4 \log_{10} \frac{D}{d}} \times 10^{-9}.$$

$\varepsilon_r = 3.5$, $l = 1km \Rightarrow 1000\ m$.

$$C = \frac{3.5 \times 1000}{41.4 \log_{10} \frac{2.18}{0.906}} \times 10^{-9}$$

$$= 0.22 \times 10^{-6}\ f.$$

iv) charging Current.

$$I_c = \frac{V}{X_c} = 2\pi f C V$$

$$= 2\pi(50)(0.22) \times 10^{-6} \times 11000$$

$$= 0.76\ A.$$

GRADING OF CABLES:

The process of achieving Uniform electrostatic stress in the dielectric of Cables is known as grading of Cables.

The Unequal stress distribution in a Cable is Undesirable for two reasons.

1) Insulation of greater thickness is required which increases the Cable size.
2) It may lead to 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 stress in such a way that its value is increased in Outer layers of dielectric. This is known as grading of Cables.

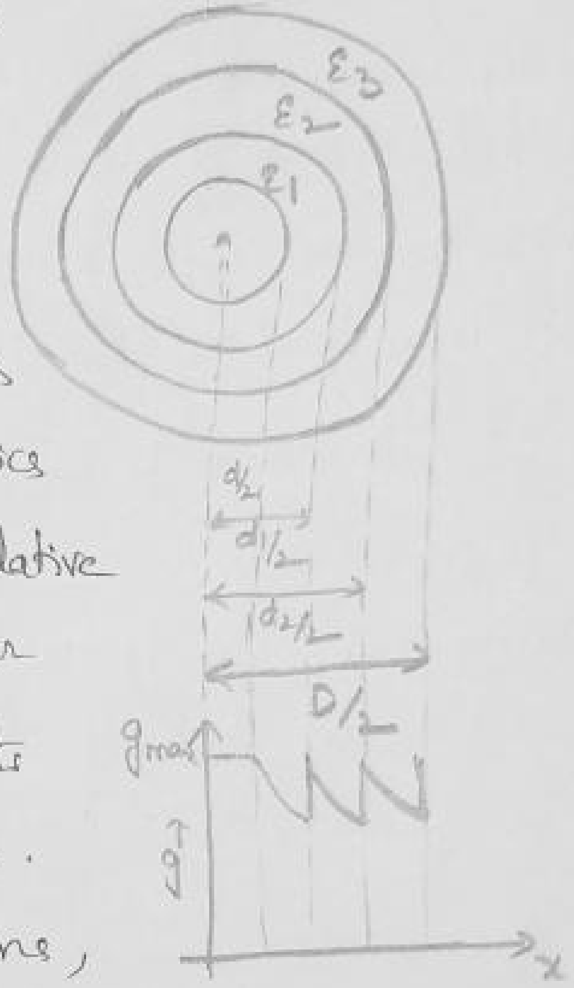
The following are the two main methods of grading of Cables :

1) Capacitance grading.
2) Intersheath grading.

CAPACITANCE GRADING:

The process of achieving uniformity in dielectric stress by using layers of different dielectrics is known as capacitance grading.

In capacitance grading, the homogeneous dielectric is replaced by 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 dielectric is constant and it is independent of distance from the centre.

As $\varepsilon_r \propto \frac{1}{x}$, $\Rightarrow \varepsilon_r = \frac{k}{x}$, k is constant.

Potential gradient at a distance x from centre

$$g = \frac{Q}{2\pi\varepsilon_0\varepsilon_r x} = \frac{Q}{2\pi\varepsilon_0\left(\frac{k}{x}\right)x} = \frac{Q}{2\pi\varepsilon_0 k}$$

$$= \text{Constant.}$$

This shows if Condition $\varepsilon_r \propto \frac{1}{x}$ is fulfilled, potential gradient will be Constant.

In otherwords, the dielectric stress in Cable is same everywhere and grading is ideal one.

In practice, two (or) three dielectrics are Used in decreasing order of permittivity; the dielectric of high permitivity being Used near the Core.

There are three dielectrics of outer diameter d_1, d_2 & D are of relative permitivity ε_1, ε_2 and ε_3 respectively. If the permittivities are such that $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$.

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

$$\boxed{\varepsilon_1 d = \varepsilon_2 d_1 = \varepsilon_3 d_2}$$

Potential difference across inner layer is

$$V_1 = \int_{d/2}^{d_1/2} g\, dx = \int_{d/2}^{d_1/2} \frac{Q}{2\pi\varepsilon_0\varepsilon_1 x} dx.$$

$$= \frac{Q}{2\pi\varepsilon_0\varepsilon_1} \log_e \frac{d_1}{d}. \quad \text{--- (1)}$$

$$\because \; g_{max} = \frac{Q}{\pi\varepsilon_0\varepsilon_1 d}$$

$$\frac{g_{max}\, d}{2} = \frac{Q}{2\pi\varepsilon_0\varepsilon_1} \quad \text{--- (2)}$$

Substitute (2) in (1)

$$V_1 = \frac{g_{max}}{2} d \log_e \frac{d_1}{d}$$

Similarly, potential difference across second & third layer.

$$V_2 = \frac{g_{max}}{2} d_1 \log_e \frac{d_2}{d_1}$$

$$V_3 = \frac{g_{max}}{2} d_2 \log_e \frac{D}{d_2}.$$

Total potential difference between core & earthed sheath

$$V = V_1 + V_2 + V_3.$$

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

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

$$V' = \frac{g_{max}}{2} d \log_e \frac{D}{d}.$$

obviously, $\boxed{V > V'}$ ie., for given dimensions of the cable, a graded cable can be worked at a greater potential than non graded cable.

If the maximum stress in the three dielectrics is not the same, then.

$$V = \frac{g_{1max}}{2} d \log_e \frac{d_1}{d} + \frac{g_{2max}}{2} d_1 \log_e \frac{d_2}{d_1} + \frac{g_{3max}}{2} d_2 \log_e \frac{D}{d_2}.$$

1) A single core lead sheathed cable is graded by using three dielectrics of relative permittivity 5, 4 and 3 respectively. The conductor diameter is 2cm and overall diameter is 8cm. If three dielectrics are worked at same maximum stress of 40kV/cm. find safe working voltage of cable? 16

What will be value of safe working voltage for an ungraded cable.

Sol: $d = 2cm,\ d_1 = ?\ ,\ d_2 = ?\ ,\ D = 8cm,\ \varepsilon_1 = 5,\ \varepsilon_2 = 4,$

$\varepsilon_3 = 3;\ g_{max} = 40\ kV/cm.$

Graded Cable: As the maximum stress in the three dielectrics is the same.

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

$$5 \times 2 = 4 \times d_1 = 3 \times d_2$$

$$d_1 = 2.5\ cm \quad \text{and} \quad d_2 = 3.34 cm.$$

Permissible peak voltage for cable.

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

$$= \frac{40}{2}\left[2 \log_e \frac{2.5}{2} + 2.5 \log_e \frac{3.34}{2.5} + 3.34 \log_e \frac{8}{3.34}\right]$$

$$= 20\ [0.4462 + 0.7242 + 2.92]\ kV$$

$$= 81.808\ kV.$$

$\therefore$ Safe working voltage (rms) of cable.

$$= \frac{81.808}{\sqrt{2}} = 57.84\ kV.$$

Ungraded Cable : permissible peak voltage for Cable.

$$= \frac{g_{max}}{2} d \log_e \frac{D}{d} = \frac{40}{2} \times 2 \log_e \frac{8}{2} = 55.4 \text{ kv.}$$

∴ Safe working voltage (rms) for the cable.

$$= \frac{55.44}{\sqrt{2}} = 39.2 \text{ kv.}$$

Thus for same conductor diameter (d) and same overall dimension (D), the graded cable can be operated at voltage $(57.84 - 39.2) = 18.64$ kV (rms)

2) A single core lead sheathed cable has a conductor diameter of 3cm, the diameter of the cable being 9cm. The cable is graded by using two dielectrics of relative permittivity 5 and 4 respec. with corresponding safe working stresses of 30 kv/cm and 20 kv/cm. Calculate the radial thickness of each insulation and safe working voltage of cable?

sol.

$d = 3\text{cm}$, $d_1 = ?$, $D = 9\text{cm}$, $\varepsilon_1 = 5$, $\varepsilon_2 = 4$.

$g_{1max} = 30 \text{ kv/cm}$, $g_{2max} = 20 \text{ kv/cm}$, $g_{1max} \propto \frac{1}{\varepsilon_1 d}$

$g_{2max} \propto \frac{1}{\varepsilon_2 d_1}$

$$\frac{g_{1max}}{g_{2max}} = \frac{\varepsilon_2 d_1}{\varepsilon_1 d}$$

$$d_1 = \frac{g_{1max}}{g_{2max}} \times \frac{\varepsilon_1 d}{\varepsilon_2} = \frac{30}{20} \times \frac{5 \times 3}{4}$$

$$= 5.625 \text{ cm.}$$

$\therefore$ Radial thickness of inner dielectric.

$$= \frac{d_1 - d}{2} = \frac{5.625 - 3}{2} = 1.312 \text{ cm.}$$

Radial thickness of outer dielectric

$$= \frac{D - d_1}{2} = \frac{9 - 5.625}{2} = 1.68 \text{ cm.}$$

Permissible peak voltage for the Cable.

$$= \frac{g_{1max}}{2} d \log_e \frac{d_1}{d} + \frac{g_{2max}}{2} d_1 \log_e \frac{D}{d_1}$$

$$= \frac{30}{2} \times 3 \log_e \frac{5.625}{3} + \frac{20}{2} \times 5.625 \log_e \frac{9}{5.625}$$

$$= 28.28 + 26.43 = 54.71 \text{ kV.}$$

$\therefore$ Safe working voltage (rms) for Cable.

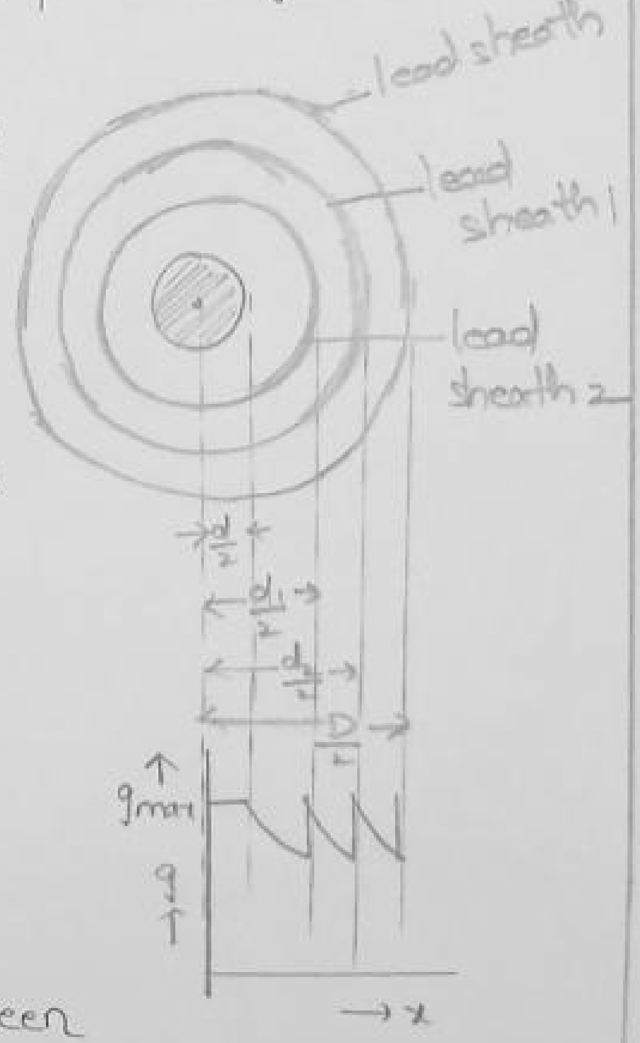
$$= \frac{54.71}{\sqrt{2}} = 38.68 \text{ kV.}$$

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 inbetween the Core potential and earth potential. This arrangement Improves voltage distribution in 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 homogeneous dielectric and maintained at some fixed potentials.



let V_1, V_2 and V_3 respectively be 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.

Maximum stress between core and intersheath:

$$g_{1max} = \frac{V_1}{\frac{d}{2}\log_e\frac{d_1}{d}}.$$

Similarly, $g_{2max} = \dfrac{V_2}{\frac{d_1}{2}\log_e\frac{d_2}{d_1}}$, $g_{3max} = \dfrac{V_3}{\frac{d_2}{2}\log_e\frac{D}{d_2}}$

Since, the dielectric is homogeneous, the maximum stress in each layer is same, ie.,

$$g_{1max} = g_{2max} = g_{3max} = g_{max}.$$

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

As the cable behaves like three capacitors in series, therefore, all potentials are in phase ie. voltage between conductor and earthed lead sheath

$$V = V_1 + V_2 + V_3.$$

Intersheath grading has three principal disadvantages.

1) There are complications in fixing sheath potentials

2) Intersheaths are likely to be damaged during transportation and installation which might

Numericals on Intersheath Grading:-

1) A single core cable of conductor diameter 2cm and lead sheath of diameter 5.3cm is to be used on a 66kV, 3phase system. Two intersheaths of diameter 3.1cm and 4.2cm are introduced between core and lead sheath. If the maximum stress in layers is same, find the voltages on intersheaths.

Sol: $d = 2cm$, $d_1 = 3.1 cm$, $d_2 = 4.2 cm$, $D = 5.3 cm$

$$V = \frac{66 \times \sqrt{2}}{\sqrt{3}} = 53.9 \text{ kV}$$

$$g_{1max} = \frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}} = \frac{V_1}{1 \times \log_e \frac{3.1}{2}} = 2.22 V_1$$

$$g_{2max} = \frac{V_2}{\frac{d_1}{2}\log_e \frac{d_2}{d_1}} = \frac{V_2}{1.55 \log_e \frac{4.2}{3.1}} = 2.12 V_2$$

$$g_{3max} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}} = \frac{V_3}{2.1 \log_e \frac{5.3}{4.2}} = 2.04 V_3$$

As the maximum layers is same.

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

$$2.28 V_1 = 2.12 V_2 = 2.04 V_3$$

$$V_2 = \left(\frac{2.28}{2.12}\right) V_1 = 1.075 V_1$$

$$V_3 = \left(\frac{2.28}{2.04}\right) V_1 = 1.117 V_1.$$

Now

$$V = V_1 + V_2 + V_3$$

$$53.9 = V_1 + 1.075 V_1 + 1.117 V_1$$

$$V_1 = \frac{53.9}{3.192} = 16.88 \text{ kV}$$

$$V_2 = 1.075 V_1 = 1.075 * 16.88 = 18.14 \text{ kV}$$

∴ Voltage on first intersheath

$$= V - V_1 = 53.9 - 16.88$$
$$= 37.02 \text{ kV}$$

∴ Voltage on second intersheath

$$= V - V_1 - V_2$$
$$= 53.9 - 16.88 - 18.14$$
$$= 18.88 \text{ kV}$$