Course: Transmission and Distribution– BEE402

Module-4: Corona and Underground Cable

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Corona

- When an alternating potential difference is applied across two conductors whose spacing is large as compared to their diameters, there is no apparent change in the condition of atmospheric air surrounding the wires if the applied voltage is low.
- However, when the applied voltage exceeds a certain value, called ***critical disruptive voltage,*** the conductors are surrounded by a faint violet glow called corona.
- The phenomenon of corona is accompanied by a hissing sound, production of ozone, power loss and radio interference.
- The higher the voltage is raised, the larger and higher the luminous envelope becomes, and greater are the sound, the power loss and the radio noise.
- If the applied voltage is increased to breakdown value, a flash-over will occur between the conductors due to the breakdown of air insulation.
- *The phenomenon of violet glow, hissing noise and production of ozone gas in an overhead transmission line is known as* ***corona.***

- If the conductors are polished and smooth, the corona glow will be uniform throughout the length of the conductors, otherwise the rough points will appear brighter.
- With DC voltage, there is difference in the appearance of the two wires. The positive wire has uniform glow about it, while the negative conductor has spotty glow.

Theory of corona formation:

- Some ionisation is always present in air due to cosmic rays, ultraviolet radiations and radioactivity.
- Therefore, under normal conditions, the air around the conductors contains some ionised particles (*i.e.*, free electrons and +ve ions) and neutral molecules.
- When the potential gradient at the conductor surface reaches about 30 kV per cm (max. value), the velocity acquired by the free electrons is sufficient to strike a neutral molecule with enough force to dislodge one or more electrons from it.
- This produces another ion and one or more free electrons, which is turn are accelerated until they collide with other neutral molecules, thus producing other ions.

- Thus, the process of ionisation is cumulative. The result of this ionisation is that either corona is formed or spark takes place between the conductors.

Factors Affecting Corona

The phenomenon of corona is affected by the physical state of the atmosphere as well as by the conditions of the line. *The following are the factors upon which corona depends :*

(i) ***Atmosphere:*** As corona is formed due to ionisation of air surrounding the conductors, therefore, it is affected by the physical state of atmosphere.

In the stormy weather, the number of ions is more than normal and as such corona occurs at much less voltage as compared with fair weather.

(ii) ***Conductor size:*** The corona effect depends upon the shape and conditions of the conductors.

The rough and irregular surface will give rise to more corona because unevenness of the surface decreases the value of breakdown voltage. Thus a stranded conductor has irregular surface and hence gives rise to more corona that a solid conductor.

(iii) *Spacing between conductors:*

If the spacing between the conductors is made very large as compared to their diameters, there may not be any corona effect.

It is because larger distance between conductors reduces the electro-static stresses at the conductor surface, thus avoiding corona formation.

(iv) *Line voltage:*

The line voltage greatly affects corona. If it is low, there is no change in the condition of air surrounding the conductors and hence no corona is formed.

However, if the line voltage has such a value that electrostatic stresses developed at the conductor surface make the air around the conductor conducting, then corona is formed.

Important Terms

- The phenomenon of corona plays an important role in the design of an overhead transmission line.

Therefore, it is profitable to consider the following terms much used in the analysis of corona effects:

(*i*) Critical Disruptive Voltage: *It is the minimum phase-neutral voltage at which corona occurs.*

Consider two conductors of radii *r* cm and spaced *d* cm apart. If *V* is the phase-neutral potential, then potential gradient at the conductor surface is given by:

$$g = \frac{V}{r \log_e \frac{d}{r}} \text{ volts / cm}$$

In order that corona is formed, the value of g must be made equal to the breakdown strength of air.

The breakdown strength of air at 76 cm pressure and temperature of 25ºC is 30 kV/cm (max) or 21.2 kV/cm (*r.m.s.*) and is denoted by g_o.

$$g_o = \frac{V_c}{r \log_e \frac{d}{r}}$$

g_o = breakdown strength of air at 76 cm of mercury and 25ºC

= 30 kV/cm (*max*) or 21.2 kV/cm (*r.m.s.*)

$$V_c = g_o \, r \log_e \frac{d}{r}$$

The above expression for disruptive voltage is under standard conditions *i.e.*, at 76 cm of Hg and 25ºC. However, if these conditions vary, the air density also changes, thus altering the value of g_o.

The value of *go* is directly proportional to air density. Thus the breakdown strength of air at a barometric pressure of *b* cm of mercury and temperature of t^{o} C becomes δ*go* where

$$\delta = \text{air density factor} = \frac{3\cdot 92b}{273+t}$$

Under standard conditions, the value of δ = 1.

$$\therefore \text{Critical disruptive voltage, } V_c = g_o\,\delta\, r \log_e \frac{d}{r}$$

Correction must also be made for the surface condition of the conductor. This is accounted for by multiplying the above expression by irregularity factor *mo*.

$$\therefore \text{Critical disruptive voltage, } V_c = m_o\, g_o\,\delta\, r \log_e \frac{d}{r} \text{ kV/phase}$$

where *mo* = 1 for polished conductors

= 0·98 to 0·92 for dirty conductors

= 0·87 to 0·8 for stranded conductors

(*ii*) Visual critical voltage:

It is the minimum phase-neutral voltage at which corona glow appears all along the line conductors.

It has been seen that in case of parallel conductors, the corona glow does not begin at the disruptive voltage *Vc* but at a higher voltage *Vv* called ***Visual Critical Voltage***. The phase-neutral effective value of visual critical voltage is given by the following empirical formula :

$$V_v = m_v g_o \delta r \left(1 + \frac{0 \cdot 3}{\sqrt{\delta r}}\right) \log_e \frac{d}{r} \text{ kV/phase}$$

where m_v is another irregularity factor having a value of 1·0 for polished conductors and 0·72 to 0·82 for rough conductors.

(*iii*) Power loss due to corona:

Formation of corona is always accompanied by energy loss which is dissipated in the form of light, heat, sound and chemical action. When disruptive voltage is exceeded, the power loss due to corona is given by :

$$P = 242{\cdot}2\left(\frac{f+25}{\delta}\right)\sqrt{\frac{r}{d}}\,(V-V_c)^2\times 10^{-5}\ \text{kW / km / phase}$$

Where f = supply frequency in Hz

V = phase-neutral voltage (*r.m.s.*)

Vc = disruptive voltage (*r.m.s.*) per phase

Advantages and Disadvantages of Corona

Corona has many advantages and disadvantages.

In the correct design of a high voltage overhead line, a balance should be struck between the advantages and disadvantages.

Advantages

(i) Due to corona formation, the air surrounding the conductor becomes conducting and hence virtual diameter of the conductor is increased.

The increased diameter reduces the electrostatic stresses between the conductors.

(ii) Corona reduces the effects of transients produced by surges.

Disadvantages

(*i*) Corona is accompanied by a loss of energy. This affects the transmission efficiency of the line.

(*ii*) Ozone is produced by corona and may cause corrosion of the conductor due to chemical action.

(*iii*) The current drawn by the line due to corona is non-sinusoidal and hence non-sinusoidal voltage drop occurs in the line. This may cause inductive interference with neighboring communication lines.

Methods of Reducing Corona Effect

- It has been seen that intense corona effects are observed at a working voltage of 33 kV or above.
- Therefore, careful design should be made to avoid corona on the sub-stations or bus-bars rated for 33 kV and higher voltages otherwise highly ionised air may cause flash-over in the insulators or between the phases, causing considerable damage to the equipment.

The corona effects can be reduced by the following methods :

(i) By increasing conductor size:

- By increasing conductor size, the voltage at which corona occurs is raised and hence corona effects are considerably reduced.
- This is one of the reasons that *ACSR* conductors which have a larger cross-sectional area are used in transmission lines.

(ii) By increasing conductor spacing:

- By increasing the spacing between conductors, the voltage at which corona occurs is raised and hence corona effects can be eliminated.
- However, spacing cannot be increased too much otherwise the cost of supporting structure (*e.g.*, bigger cross arms and supports) may increase to a considerable extent.

Example 4.1. *A 3-phase line has conductors 2 cm in diameter spaced equilaterally 1 m apart. If the dielectric strength of air is 30 kV (max) per cm, find the disruptive critical voltage for the line. Take air density factor δ = 0·952 and irregularity factor m_o = 0·9.*

Solution.

Conductor radius, r = 2/2 = 1 cm

Conductor spacing, d = 1 m = 100 cm

Dielectric strength of air, g_o = 30 kV/cm (*max.*) = 21·2 kV (*r.m.s.*) per cm

Disruptive critical voltage, $V_c = m_o \, g_o \, \delta \, r \log_e (d/r)$ kV*/phase (*r.m.s.* value)

$= 0·9 \times 21·2 \times 0·952 \times 1 \times \log_e 100/1$

$= 83·64$ kV/phase

∴ Line voltage (*r.m.s.*) = $\sqrt{3} \times 83·64 =$ **144·8 kV**

Example 4.2. *A 132 kV line with 1·956 cm dia. conductors is built so that corona takes place if the line voltage exceeds 210 kV (r.m.s.). If the value of potential gradient at which ionisation occurs can be taken as 30 kV per cm, find the spacing between the conductors.*

Solution.

Assume the line is 3-phase.

Conductor radius, $r = 1{\cdot}956/2 = 0{\cdot}978$ cm

Dielectric strength of air, $g_o = 30/\sqrt{2} = 21{\cdot}2$ kV (*r.m.s.*)

Disruptive voltage/phase, $V_c = 210/\sqrt{3} = 121{\cdot}25$ kV

Assume smooth conductors (*i.e.*, irregularity factor *mo* = 1) and standard pressure and temperature for which air density factor $\delta = 1$. Let *d* cm be the spacing between the conductors.

$\therefore$ Disruptive voltage (*r.m.s.*) per phase is

$$V_c = m_o\, g_o\, \delta\, r \log_e (d/r) \text{ kV}$$

$$= 1 \times 21{\cdot}2 \times 1 \times 0{\cdot}978 \times \log_e (d/r)$$

$$121{\cdot}25 = 20{\cdot}733 \log_e (d/r)$$

$$\log_e \frac{d}{r} = \frac{121 \cdot 25}{20 \cdot 733} = 5{\cdot}848$$

$$2{\cdot}3 \log_{10} d/r = 5{\cdot}848$$

$$\log_{10} d/r = 5{\cdot}848/2{\cdot}3 = 2{\cdot}5426$$

$$d/r = \text{Antilog } 2{\cdot}5426$$

$$d/r = 348{\cdot}8$$

$\therefore$ Conductor spacing, $d = 348{\cdot}8 \times r = 348{\cdot}8 \times 0{\cdot}978 =$ **341 cm**

Introduction to Underground Cable

- The transmission and distribution of an electrical power can be with the help of overhead transmission lines or by underground cables.
- In thickly populated are like towns and cities, the use of overhead lines is not practicable.
- In such cases electrical energy is transmitted and distributed with the help of underground cables.
- In its basic form, an underground cable is a conductor provided with proper insulation.
- As the voltage level increases, the cost of the insulation increases rapidly and thus the use of underground cables is restricted to low and medium voltage distribution.

Underground Cables

An **underground cable** *essentially consists of one or more conductors covered with suitable insulation and surrounded by a protecting cover.*

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 and causes voltage drop within permissible limits.

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

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

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

Construction of Cables

Fig. 4.1 shows the general construction of a 3-conductor cable. The various parts are :

(i) Cores or Conductors:

- A cable may have one or more than one core (conductor) depending upon the type of service for which it is intended.
- For instance, the 3-conductor cable shown in Fig. 4.1 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.

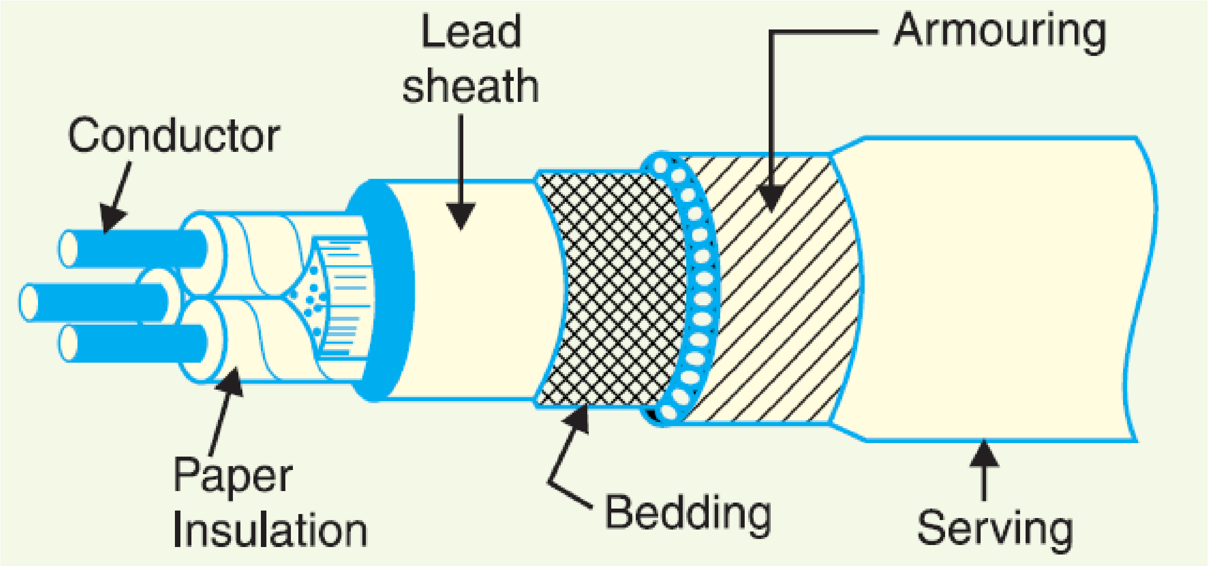


Fig 4.1: Construction of Under Ground Cable

(ii) *Insulation:*

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

(iii) *Metallic sheath:*

- In order to protect the cable from moisture, gases or other damaging liquids (acids or alkalies) in the soil and atmosphere, a metallic sheath of lead or aluminium is provided over the insulation as shown in Fig. 4.1.

(iv) *Bedding:*

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

(v) *Armouring:*

- Over the bedding, armouring is provided which consists of one or two layers of galvanized steel wire or steel tape.
- Its purpose is to protect the cable from mechanical injury while laying it and during the course of handling. Armouring may not be done in the case of some cables.

(vi) *Serving:*

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

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.

Comparison of Underground cables and Overhead lines

Context	Overhead line	Underground cable
Fault location	As the overhead line is visible, it is easy to find the location of the fault.	As the underground cable is invisible, it is very difficult to find the location of the fault.
Initial cost	There is no requirement of digging, manholes, and trench. So, the overhead line system is cheaper than the underground system.	The initial cost of the underground transmission system is more compared to the overhead line because it needs digging, trenching, etc.
Chance of fault	As overhead line exposed to the environment, the chances of faults are more.	The cables are not exposed to the environment, there is less chance of fault.
Safety	This system is less safe as the conductors placed on the towers.	This system is safer as the cables placed underground.

Context	Overhead line	Underground cable
Appearance	The general appearance of this system is not good because of all lines are visible.	The general appearance of this system is good because of all lines are invisible.
Maintenance cost	In this system, no need to dig at the time of maintenance. Hence, for the same number of faults, the maintenance cost is less.	In this system, to find the fault, digging is compulsory. It increases labor cost. Hence, for the same number of faults, the maintenance cost is more.
Useful life	In this system, useful life is approximately 20 to 25 years.	Useful life is approximately 40 to 50 years.
Flexibility	This system is more flexible. Because the expansion of the system is easily possible.	This system is not flexible. The expansion cost is nearly equal to the new erection of the system.

Context	Overhead line	Underground cable
Conductor size	The conductors placed in atmosphere. So, the heat dissipation is better. Therefore the size of the conductor is small compared to the underground system.	Because of the poor heat dissipation, the size of the cables is more.
Interference with the communication line	The communication lines are run along the transmission line. In this case, it is possible to cause electromagnetic interference.	In this case, there is no chance of interference with communication lines.
Proximity effect	The distance between the conductor is very high. So, proximity effect does not affect.	As the distance between cables is very less, the proximity effect is very high.

Context	Overhead line	Underground cable
Application	The cost of this system is low. Therefore overhead lines used in the long transmission system and in rural areas for the distribution system.	Because of the high cost, it uses in the short distance and in populated areas. Where space is a major problem for the overhead transmission line.

- The only drawbacks of underground cables are the extremely high initial cost and insulation problems at high voltages.
- Thus the use of underground cables is mainly for the distribution of an electrical power at low and medium voltages.
- Its use is almost compulsory at the location where use of overhead lines is not practicable due to the safety reasons such as congested urban area, crossing of wide roads, near gas plants and refineries, near substation etc.

Dielectric Stress in 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

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

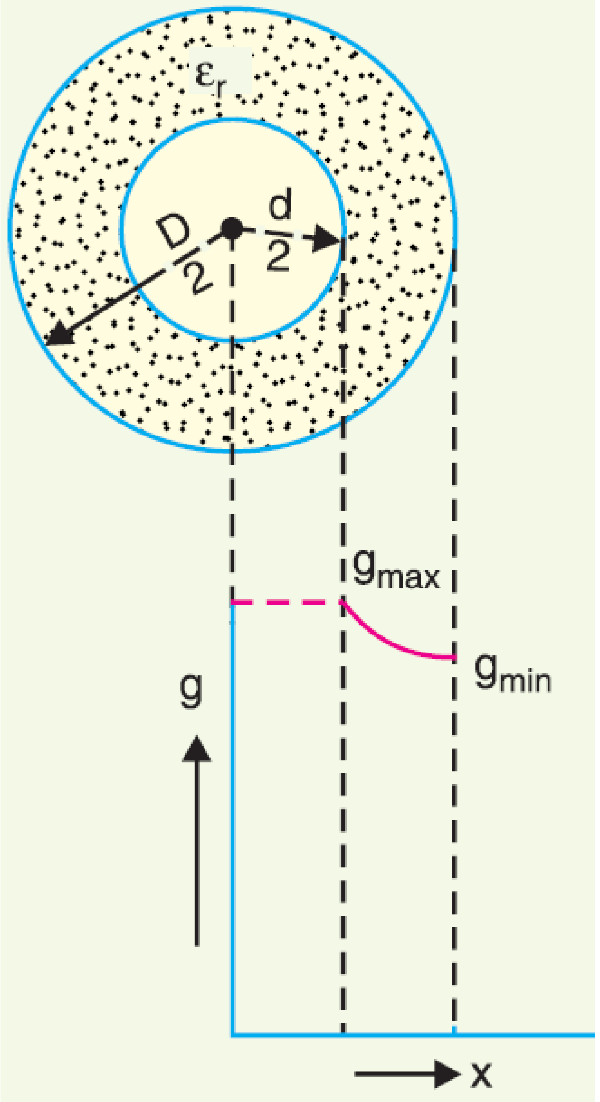


Fig 4.2

By definition, electric intensity is equal to potential gradient. Therefore, potential gradient g at a point x metres from the centre of cable is

$$g = E_x$$

$$g = \frac{Q}{2\pi\,\varepsilon_o\,\varepsilon_r\,x} \text{ volts/m} \qquad \ldots(i)$$

Potential difference V between conductor and sheath is

$$V = \frac{Q}{2\,\pi\varepsilon_o\,\varepsilon_r} \log_e \frac{D}{d} \text{ volts}$$

$$Q = \frac{2\pi\,\varepsilon_o\varepsilon_r\,V}{\log_e \frac{D}{d}} \qquad \ldots(ii)$$

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

$$g = \frac{\dfrac{2\pi\varepsilon_o\varepsilon_r V}{\log_e D/d}}{2\pi\varepsilon_o\varepsilon_r x}$$

$$= \frac{V}{x\log_e \dfrac{D}{d}} \text{ volts/m} \qquad \ldots(iii)$$

It is clear from exp. (*iii*) 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.

∴ Maximum potential gradient is

$$g_{max} = \frac{2V}{d\log_e \dfrac{D}{d}} \text{ volts/m} \qquad [\text{Putting } x = d/2 \text{ in exp. } (iii)]$$

Minimum potential gradient is

$$g_{min} = \frac{2V}{D \log_e \frac{D}{d}} \text{ volts/m} \qquad \text{[Putting } x = D/2 \text{ in exp. } (iii)]$$

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

The variation of stress in the dielectric is shown in Fig. 4.2. It is clear that dielectric stress is maximum at the 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 the design of a cable.

Example 4.3. A 33 kV single core cable has a conductor diameter of 1 cm and a sheath of inside diameter 4 cm. Find the maximum and minimum stress in the insulation.

Solution.

The maximum stress occurs at the conductor surface and its value is given by;

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

$$V = 33 \text{ kV (r.m.s)} ; \; d = 1 \text{ cm} ; \; D = 4 \text{ cm}$$

Substituting the values in the above expression, we get,

$$g_{max} = \frac{2 \times 33}{1 \times \log_e 4} \text{ kV}^{\dagger}\text{/cm} = \mathbf{47{\cdot}61 \text{ kV/cm}} \; r.m.s.$$

The minimum stress occurs at the sheath and its value is give by ;

$$g_{min} = \frac{2V}{D \log_e \frac{D}{d}} = \frac{2 \times 33}{4 \times \log_e 4} \text{ kV/cm} = \mathbf{11{\cdot}9 \text{ kV/cm}} \; r.m.s$$

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

The process of achieving uniformity in the dielectric stress by using layers of different dielectrics is known as **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 εr 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.

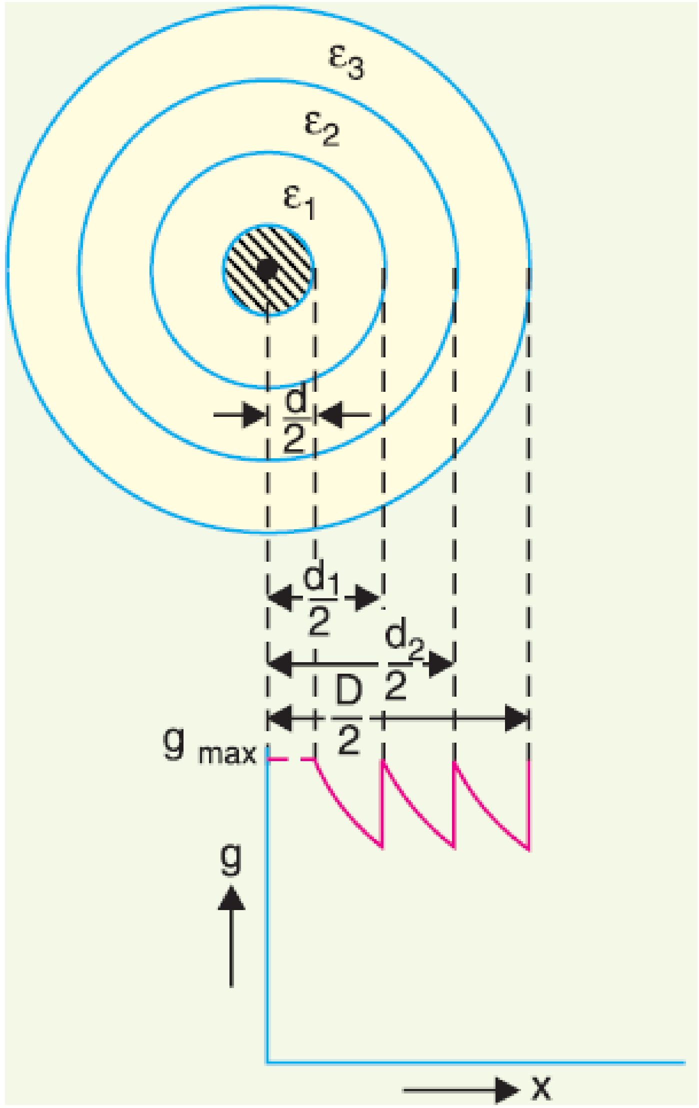


Fig 4.3

- 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 beautifully by referring to Fig. 4.3.
- There are three dielectrics of outer diameter *d*1, *d*2 and *D* and of relative permittivity ε_1, ε_2 and ε_3 respectively.
- If the permittivities are such that $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$ and the three dielectrics are worked at the same maximum stress, then,

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

$$\text{or} \quad \varepsilon_1 d = \varepsilon_2 d_1 = \varepsilon_3 d_2$$

$$\dagger \quad g_{1max} = \frac{Q}{\pi \varepsilon_0 \varepsilon_1 d}$$

Potential difference across the inner layer is

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

$$= \frac{Q}{2\pi\varepsilon_0\varepsilon_1}\log_e\frac{d_1}{d} = \frac{g_{max}}{2}\,d\log_e\frac{d_1}{d}\quad\left[\because\ \frac{Q}{2\pi\varepsilon_0\varepsilon_1} = {}^{*}\frac{g_{max}}{2}\,d\right]$$

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

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

Total p.d. between core and earthed sheath is

$$V = V_1 + V_2 + V_3 = \frac{g_{max}}{2}\left[d\log_e\frac{d_1}{d} + d_1\log_e\frac{d_2}{d_1} + d_2\log_e\frac{D}{d_2}\right]$$

$$^{*}\,g_{max} = \frac{Q}{\pi\varepsilon_0\varepsilon_1 d}$$

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.

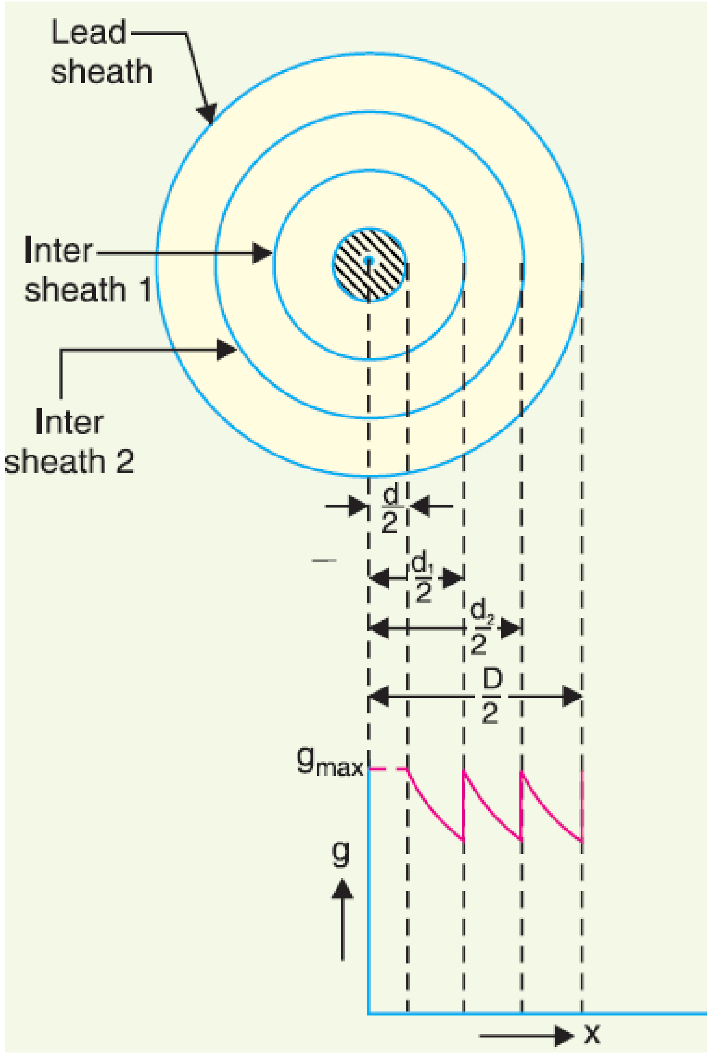


Fig 4.4

Maximum stress between core and intersheath 1 is

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

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

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.

Example 4.4. 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.

Solution. $d = 2\text{ cm}\ ; \quad d_1 = 3{\cdot}1\text{ cm}\ ; d_2 = 4{\cdot}2\text{ cm} \quad D = 5.3\text{ cm}$

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

$$g_{1max} = \frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}} = \frac{V_1}{1 \times \log_e \frac{3\cdot1}{2}} = 2{\cdot}28\ V_1$$

$$g_{2max} = \frac{V_2}{\frac{d_1}{2}\log_e \frac{d_2}{d_1}} = \frac{V_2}{1\cdot55\ \log_e \frac{4.2}{3.1}} = 2{\cdot}12\ V_2$$

$$g_{3max} = \frac{V_3}{\frac{d_2}{2}\log_e\frac{D}{d_2}} = \frac{V_3}{2\cdot1\log_e\frac{5\cdot3}{4\cdot2}} = 2\cdot04\ V_3$$

As the maximum stress in the layers is the same,

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

$$\text{or}\quad 2\cdot28\ V_1 = 2\cdot12\ V_2 = 2\cdot04\ V_3$$

$$\therefore\ V_2 = (2\cdot28/2\cdot12)\ V_1 = 1\cdot075\ V_1$$

$$\text{and}\quad V_3 = (2\cdot28/2\cdot04)\ V_1 = 1\cdot117\ V_1$$

$$\text{Now}\quad V_1 + V_2 + V_3 = V \quad \text{or} \quad V_1 + 1\cdot075\ V_1 + 1\cdot117\ V_1 = 53\cdot9$$

$$\therefore\ V_1 = 53\cdot9/3\cdot192 = 16\cdot88\ \text{kV}$$

$$V_2 = 1{\cdot}075\, V_1 = 1{\cdot}075 \times 16{\cdot}88 = 18{\cdot}14 \text{ kV}$$

∴ Voltage on first intersheath (*i.e.*, near to the core)

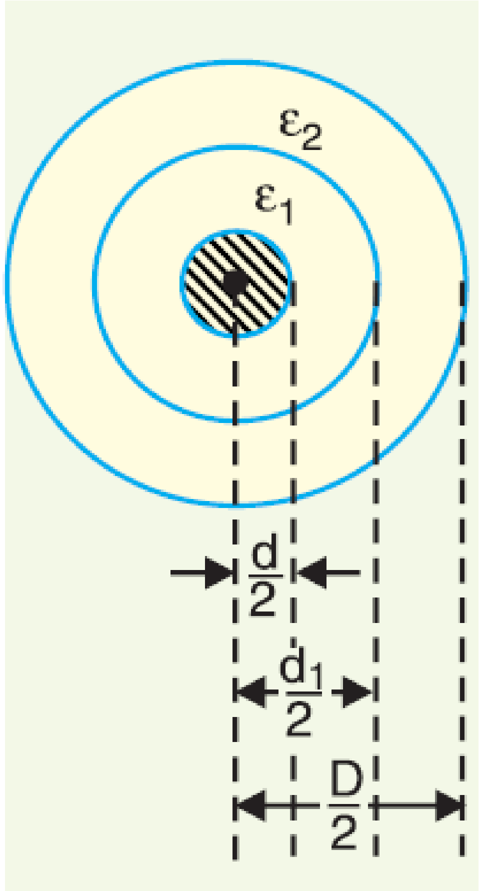
$$= V - V_1 = 53{\cdot}9 - 16{\cdot}88 = \mathbf{37{\cdot}02\ kV}$$

∴ Voltage on second intersheath

$$= V - V_1 - V_2$$

$$= 53{\cdot}9 - 16{\cdot}88 - 18{\cdot}14 = \mathbf{18{\cdot}88\ kV}$$

Example 4.5. A 66-kV single-core lead sheathed cable is graded by using two dielectrics of relative permittivity 5 and 3 respectively; thickness of each being 1 cm. The core diameter is 2 cm. Determine the maximum stress in the two dielectrics.



Solution. Figure shows the composite dielectric of a capacitance graded cable. The potential difference V between conductor and earthed sheath is given by ;

$$V = \int_{d/2}^{d_1/2} g_1\, dx + \int_{d_1/2}^{D/2} g_2\, dx = \int_{d/2}^{d_1/2} \frac{Q}{2\pi \varepsilon_0 \varepsilon_1 x}\, dx + \int_{d_1/2}^{D/2} \frac{Q}{2\pi \varepsilon_0 \varepsilon_2 x}\, dx$$

$$= \frac{Q}{2\pi \varepsilon_0}\left[\frac{1}{\varepsilon_1}\log_e \frac{d_1}{d} + \frac{1}{\varepsilon_2}\log_e \frac{D}{d_1}\right] \quad \ldots(i)$$

Now, $$g_{1max} = \frac{Q}{\pi \varepsilon_0 \varepsilon_1 d} \quad \ldots(ii)$$

Putting the value of $Q = g_{1max}\, \pi\, \varepsilon_0\, \varepsilon_1\, d$ from exp. (*ii*) in exp. (*i*), we get,

$$V = \frac{g_{1max}\, \varepsilon_1 d}{2}\left[\frac{1}{\varepsilon_1}\log_e \frac{d_1}{d} + \frac{1}{\varepsilon_2}\log_e \frac{D}{d_1}\right]$$

$$g_{1max} = \frac{2V}{d\left[\log_e \frac{d_1}{d} + \frac{\varepsilon_1}{\varepsilon_2}\log_e \frac{D}{d_1}\right]}$$

Here, $d = 2$ cm, $d_1 = 4$ cm, $D = 6$ cm ; $V = \frac{66}{\sqrt{3}} \times \sqrt{2} = 53.9$ kV, $\varepsilon_1 = 5$, $\varepsilon_2 = 3$

Substituting the values, we get,

$$g_{1max} = \frac{2 \times 53 \cdot 9}{2\,[\log_e 4/2 + 5/3\log_e 6/4]}\ \text{kV/cm} = \frac{2 \times 53.9}{2\,[0 \cdot 6931 + 0 \cdot 6757]} = \mathbf{39 \cdot 38\ kV/cm}$$

Similarly, it can be *proved that :

$$g_{2max} = \frac{2V}{d_1\left[\frac{\varepsilon_2}{\varepsilon_1}\log_e\frac{d_1}{d} + \log_e\frac{D}{d_1}\right]} \qquad ...(iii)$$

$$= \frac{2 \times 53.9}{4[3/5 \log_e 4/2 + \log_e 6/4]} \text{ kV/cm}$$

$$= \frac{2 \times 53 \cdot 9}{4[0 \cdot 4158 + 0 \cdot 4054]} = \mathbf{32 \cdot 81 \text{ kV/cm}}$$

* $g_{2max} = \dfrac{Q}{\pi \varepsilon_0 \varepsilon_2 d_1}$. Putting the value of $Q = g_{2max}\, \pi\, \varepsilon_0\, \varepsilon_2 d_1$ in exp. (i), we get the exp. (iii).

Example 4.6. 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.

Solution. Area of cross-section of conductor, $a = 0.645 \text{ cm}^2$

Diameter of the conductor, $d = \sqrt{\dfrac{4a}{\pi}} = \sqrt{\dfrac{4 \times 0 \cdot 645}{\pi}} = 0 \cdot 906 \text{ cm}$

Internal diameter of sheath, $D = 2 \cdot 18 \text{ cm}$

(*i*) Maximum electrostatic stress in the cable is

$$g_{max} = \frac{2V}{d \log_e \dfrac{D}{d}} = \frac{2 \times 11}{0 \cdot 906 \log_e \dfrac{2 \cdot 18}{0 \cdot 906}} \text{ kV/cm} = \mathbf{27 \cdot 65 \text{ kV/cm } \textit{r.m.s.}}$$

(*ii*) Minimum electrostatic stress in the cable is

$$g_{min} = \frac{2\,V}{D\log_e \dfrac{D}{d}} = \frac{2\times 11}{2\cdot 18\ \log_e \dfrac{2\cdot 18}{0\cdot 906}}\ \text{kV/cm} = \mathbf{11{\cdot}5\ kV/cm}\ \boldsymbol{r.m.s.}$$

(*iii*) Capacitance of cable, $C = \dfrac{\varepsilon_r\ l}{41\cdot 4\ \log_{10}\dfrac{D}{d}} \times 10^{-9}\ \text{F}$

Here $\varepsilon_r = 3.5$; $l = 1\ \text{km} = 1000\ \text{m}$

$$\therefore\quad C = \frac{3.5\times 1000}{41\cdot 4\ \log_{10}\dfrac{2\cdot 18}{0\cdot 906}} \times 10^{-9} = \mathbf{0{\cdot}22\times 10^{-6}\ F}$$

(*iv*) Charging current, $I_C = \dfrac{V}{X_C} = 2\pi f C V = 2\pi \times 50 \times 0{\cdot}22 \times 10^{-6} \times 11000 = \mathbf{0{\cdot}76\ A}$

Example 4.7. A single core lead sheathed cable has a conductor diameter of 3 cm; the diameter of the cable being 9 cm. The cable is graded by using two dielectrics of relative permittivity 5 and 4 respectively with corresponding safe working stresses of 30 kV/cm and 20 kV/cm. Calculate the radial thickness of each insulation and the safe working voltage of the cable.

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

$$g_{1max} = 30 \text{ kV/cm} \qquad g_{2max} = 20 \text{ kV/cm}$$

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

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

$$d_1 = \frac{g_{1max}}{g_{2max}} \times \frac{\varepsilon_1 d}{\varepsilon_2} = \frac{30}{20} \times \frac{5 \times 3}{4} = 5{\cdot}625 \text{ cm}$$

$\therefore$ Radial thickness of inner dielectric $= \dfrac{d_1 - d}{2} = \dfrac{5 \cdot 625 - 3}{2}$ $=$ **1.312 cm**

Radial thickness of outer dielectric $= \dfrac{D - d_1}{2} = \dfrac{9 - 5 \cdot 625}{2}$ $=$ **1.68 cm**

Permissible peak voltage for the cable

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

$$= \frac{30}{2} \times 3 \log_e \frac{5 \cdot 625}{3} + \frac{20}{2} \times 5 \cdot 625 \log_e \frac{9}{5 \cdot 625}$$

$$= 28{\cdot}28 + 26{\cdot}43 = 54{\cdot}71 \text{ kV}$$

$\therefore$ Safe working voltage (r.m.s.) for the cable $= 54.71/\sqrt{2}$ $=$ **38·68 kV**

Comparison of AC and DC Cables

When a cable is used for DC transmission then its voltage rating and current carrying capacity increases. This is because,

i) In DC system, there is no charging current hence the corresponding copper losses are absent.

ii) In DC system the dielectric hysteresis loss is absent. The only loss present is copper loss due to leakage current. Hence for the same temperature rise of the insulation, DC cables can carry much more current.

iii) The skin effect is absent in DC hence corresponding power losses absent.

iv) In DC system, no voltage gets induced in the sheath hence sheath losses due to the induced current is zero.

Due to all these reasons, the current carrying capacity of DC cable is higher than AC cables. Also the DC breakdown stress of the dielectric is more than the AC breakdown stress hence the voltage rating of DC cables is much higher compared to AC cables.

Proximity effect (Electromagnetism)

Proximity Effect: The alternating flux in a conductor is caused by the current of the other nearby conductor. This flux produces a circulating current or eddy current in the conductor which results an apparent increase in the resistance of the wire and; thus, more power losses in the windings. This phenomenon is proximity effect.

THANK YOU