4.8 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. Fig.4.8.1 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.4.8.1 (*i*). These electrostatic fields give rise to core-core capacitances *Cc* and conductor- earth capacitances C_e as shown in Fig.4.8.1 (*ii*). The three *Cc* are delta connected whereas the three C_e are star connected, the sheath forming the star point.

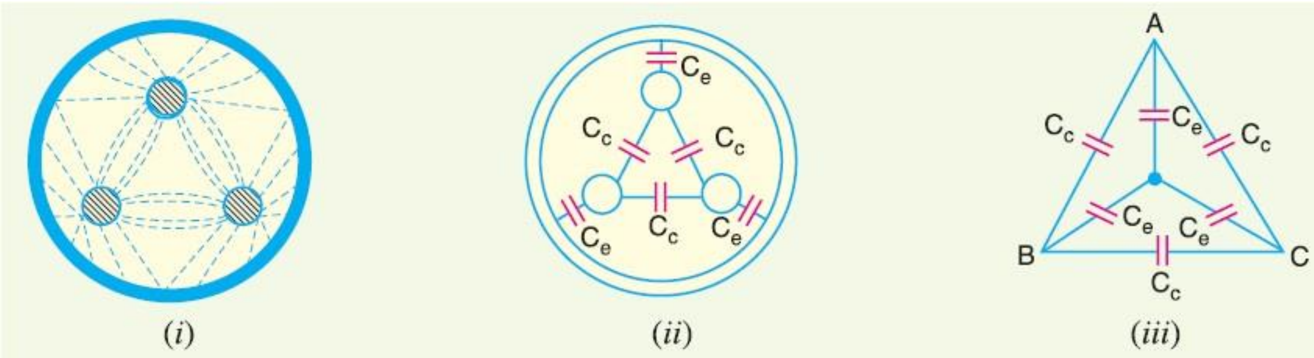


Figure 4.8.1 Capacitance of 3-Core Cables

[Source: "Principles of Power System" by V.K.Mehta Page: 288]

They lay of a belted cable makes it reasonable to assume equality of each *Cc* and each *Ce*. The three delta connected capacitances *Cc* [See Fig. 4.8.2 (*i*)] can be converted into equivalent star connected capacitances as shown in Fig. 4.8.2 (*ii*). It can be easily *shown that equivalent star capacitance *Ceq* is equal to three times the deltacapacitance

Cc i.e. Ceq = 3*Cc*.

The system of capacitances shown in Fig. 4.8.1 (*iii*) reduces to the equivalent circuit shown in Fig.4.8.3 (*i*). Therefore, the whole cable is equivalent to three star-connected capacitors each of capacitance,

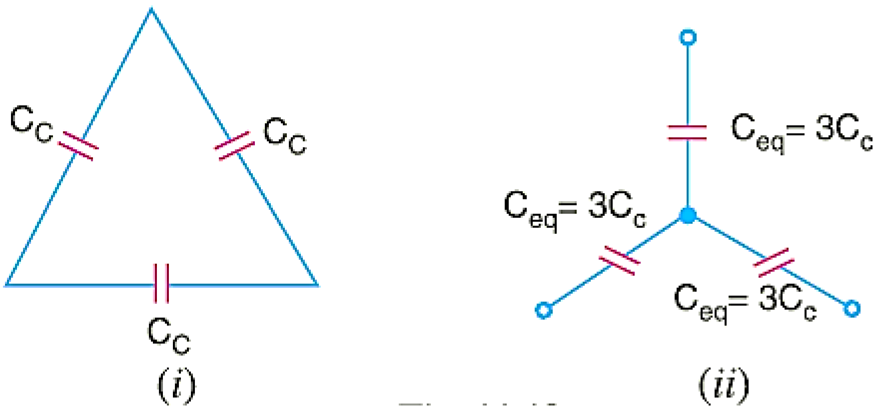


Figure 4.8.2 Delta Connected Capacitor of 3-Core Cables

[Source: "Principles of Power System" by V.K.Mehta Page: 288]

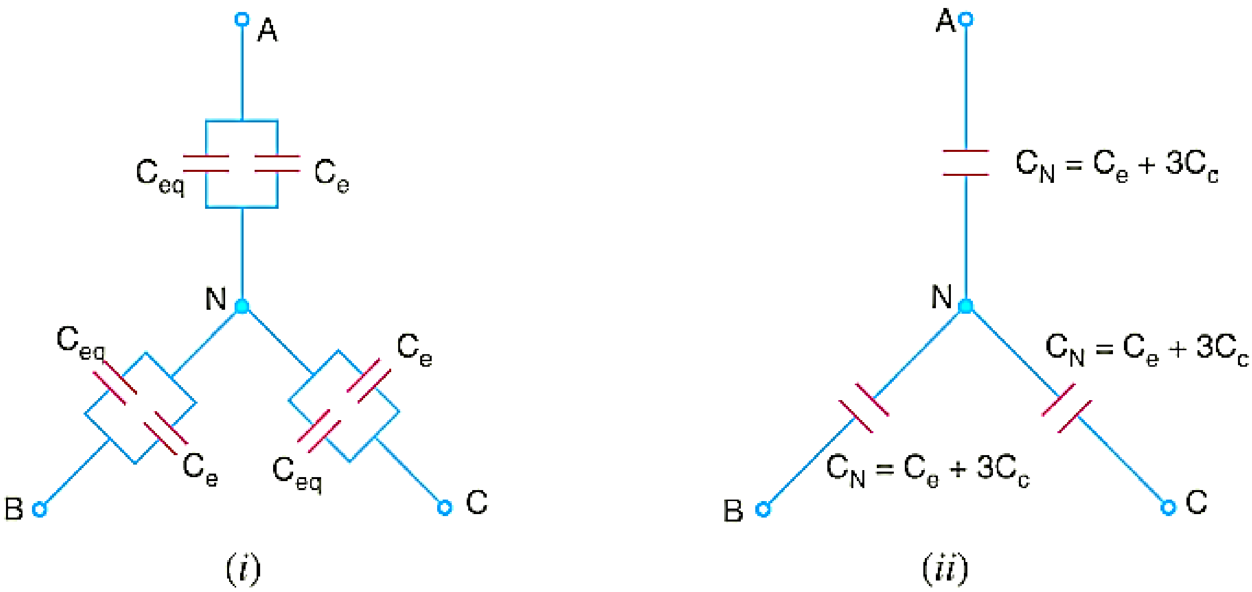


Figure 4.8.2 Star Connected Capacitor of 3-Core Cables

[Source: "Principles of Power System" by V.K.Mehta Page: 288]

$C_N = C_e + C_{eq}$

$= C_e + 3C_c$

If Vph is the phase voltage, then charging current I_C is given by ;

$$I_C = \frac{V_{ph}}{\text{Capacitive reactance per phasa}}$$

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

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

4.5 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 and ε be the permittivity of the insulation material between core and lead sheath.

Obviously *$\varepsilon = \varepsilon_0 \varepsilon_r$ where εr is the relative permittivity of the insulation.

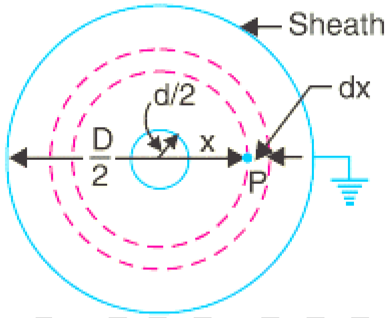


Figure 4.5.1 Single core cable

[Source: "Principles of Power System" by V.K.Mehta Page: 128]

Consider a cylinder of radius x metres and axial length 1 metre. The surface area of this cylinder is = 2 π x × 1 = 2 π x m^2

∴ Electric flux density at any point P on the considered cylinder is

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

$$\text{at point } P,\ E_x = \frac{D_x}{\varepsilon} = \frac{Q}{2\pi x \varepsilon} = \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r} \text{ volts/m}$$

The work done in moving a unit positive charge from point P through a distance dx in the direction of electric field is Ex 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 :

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

Capacitance of the cable is

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

$$= \frac{2\pi\, \varepsilon_o \varepsilon_r}{\log_e (D/d)} \text{ F/m}$$

$$= \frac{2\pi \times 8{\cdot}854 \times 10^{-12} \times \varepsilon_r}{2{\cdot}303 \log_{10}(D/d)} \text{ F/m}$$

$$= \frac{\varepsilon_r}{41{\cdot}4 \log_{10}(D/d)} \times 10^{-9} \text{ F/m}$$

If the cable has a length of l metres, then capacitance of the cable is

$$C = \frac{\varepsilon_r\, l}{41{\cdot}4 \log_{10} \frac{D}{d}} \times 10^{-9} \text{ F}$$

Problem 1

A single core cable has a conductor diameter of 1 cm and internal sheath diameter of 1·8 cm. If impregnated paper of relative permittivity 4 is used as the insulation, calculate the capacitance for 1 km length of the cable.

Solution:

$$C = \frac{\varepsilon_r\, l}{41{\cdot}4 \log_{10}(D/d)} \times 10^{-9} \text{ F}$$

$\varepsilon_r = 4$; $l = 1000$ m

$D = 1{\cdot}8$ cm ; $d = 1$ cm

$$C = \frac{4 \times 1000}{41{\cdot}4 \log_{10}(1{\cdot}8/1)} \times 10^{-9} \text{ F} = 0{\cdot}378 \times 10^{-6} \text{ F}$$

Problem 2

A 33 kV, 50 Hz, 3-phase underground cable, 4 km long uses three single core cables. Each of the conductor has a diameter of 2·5 cm and the radial thickness of insulation is 0·5 cm. Determine (i) capacitance of the cable/phase (ii) charging current/phase (iii) total charging kVAR. The relative permittivity of insulation is 3.

Solution:

$$C = \frac{\varepsilon_r \; l}{41 \cdot 4 \log_{10}(D/d)} \times 10^{-9} \text{ F}$$

$\varepsilon_r = 3$; $l = 4 \text{ km} = 4000 \text{ m}$

$d = 2{\cdot}5 \text{ cm}$; $D = 2.5 + 2 \times 0.5 = 3.5 \text{ cm}$

$$C = \frac{3 \times 4000 \times 10^{-9}}{41 \cdot 4 \times \log_{10}(3 \cdot 5 / 2 \cdot 5)}$$

$= 1.984 \times 10^{-6}$

(ii) Voltage/phase, V_{ph}

$$= \frac{33 \times 10^3}{\sqrt{3}} = 19{\cdot}05 \times 10^3 \text{ V}$$

Charging current/phase, I_C

$$I_C = \frac{V_{ph}}{X_C} = 2\pi f C V_{ph}$$

$$= 2\pi \times 50 \times 1984 \times 10^{-9} \times 19{\cdot}05 \times 10^3$$

$= 11.87$ A

Total charging kVAR

$$= 3 V_{ph} I_C = 3 \times 19{\cdot}05 \times 10^3 \times 11{\cdot}87$$

$= 678.4 \times 10^3$ KVAR

4.3 CONSTRUCTION OF CABLES

Fig. 4.3.1 shows the general construction of a 3-conductor cable. The various parts are,

a)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. is used for 3- phase service. The conductors are made of tinned copper or aluminum and are usually stranded in order to provide flexibility to the cable.

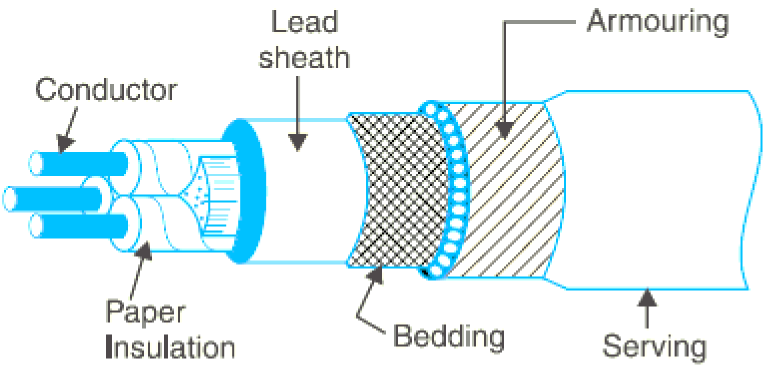


Figure 4.3.1 Construction of a Cable

[Source: "Principles of Power System" by V.K.Mehta Page: 265]

b) 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.

c)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 Fig.

d) 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.

e) 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.

f) 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.

4.10 DC CABLES

The DC cable has the following characteristics compared with the AC cable.

1. The system used is different. The DC cable is used in the rectified DC transmission system, and the AC cable is often used in the power frequency (domestic 50 Hz) power system.

2. Compared with the AC cable, the power loss during the transmission of the DC cable is small. The power loss of the DC cable is mainly the DC resistance loss of the conductor, and the insulation loss is small (the size depends on the current fluctuation after rectification); while the AC resistance of the low-voltage AC cable is slightly larger than the DC resistance, the high-voltage cable is obvious, mainly because The proximity effect and the skin effect, the loss of insulation resistance accounts for a large proportion, mainly the impedance generated by the capacitor and the inductor.

3. High transmission efficiency and low line loss.

4. It is convenient to adjust the current and change the power transmission direction.

5. Although the price of the converter equipment is higher than that of the transformer, the cost of using the cable line is much lower than that of the AC cable. The DC cable is positive and negative poles, and the structure is simple; the AC cable is three-phase four-wire or five-wire system, the insulation safety requirements are high, the structure is complex, and the cable cost is more than three times that of the DC cable.

6. DC cable is safe to use:

1) The inherent characteristics of DC transmission, it is difficult to generate induced current and leakage current, and it will not interfere with the electric field generated by other cables.

2) The single-core laying cable does not affect the cable transmission performance due to the hysteresis loss of the steel structure bridge.

3) It has higher interception capability and over-cut protection than DC cables of the same structure.

4) A straight, alternating electric field of the same voltage is applied to the insulation, and the DC electric field is much safer than the AC electric field.

7. The installation and maintenance of the DC cable is simple and the cost is low. Requirements for the same cable insulation for the same AC and DC voltage and current

When an AC and DC electric field of the same voltage is applied to the insulation, the electric field of the DC cable is much smaller than the AC electric field. Due to the large difference in the structure of the two electric fields, the maximum electric field when the AC cable is energized is concentrated near the conductor, and the maximum electric field when the DC cable is energized is mainly concentrated within the insulating surface layer, which is more secure (2.4 times).

Third, the mutual conversion relationship between AC and DC voltage

There are many different understandings on the mutual conversion of AC and DC voltages. However, our company is uniformly calculated according to GB12528.1, that is, the same AC cable, the rated voltage of the DC cable is 1.5 times the phase voltage of the AC cable. But our company's 1500V DC cable is designed according to the voltage of DC3000V, which has safe electrical insulation performance.

4.6 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 (gmax) 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 gmax 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 *gmax* . 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

(i)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 r of any layer is inversely proportional to its distance from the center. Under such conditions, the value of potential gradient any point in the dielectric is constant and is independent of its distance from the center. 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.

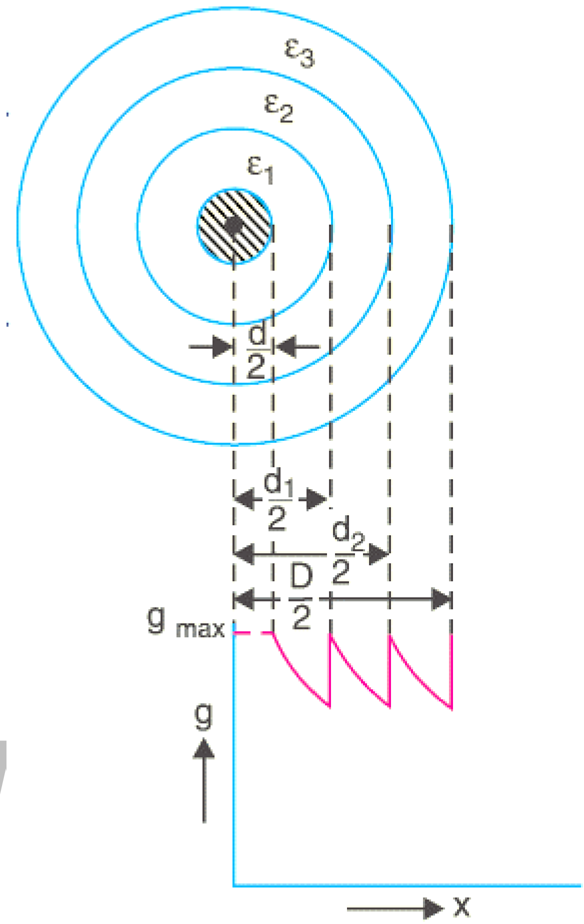


Figure 4.6.1 Capacitance Grading

[Source: "Principles of Power System" by V.K.Mehta Page: 281]

The capacitance grading can be explained beautifully by referring to Fig. There are three dielectrics of outer diameter d1, d2 and D and of relative permittivity 1, 2 and 3 respectively. If the permittivity are such that 1 > 2 > 3 and the three dielectrics are worked at the same maximum stress, then,

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

Potential difference across the inner layer is

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

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

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

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

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

Total p.d. between core and earthed sheath is

$V = V_1 + V_2 + V_3$

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

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,

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

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 *gmax* 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,

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

(ii) 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 im- proves 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.

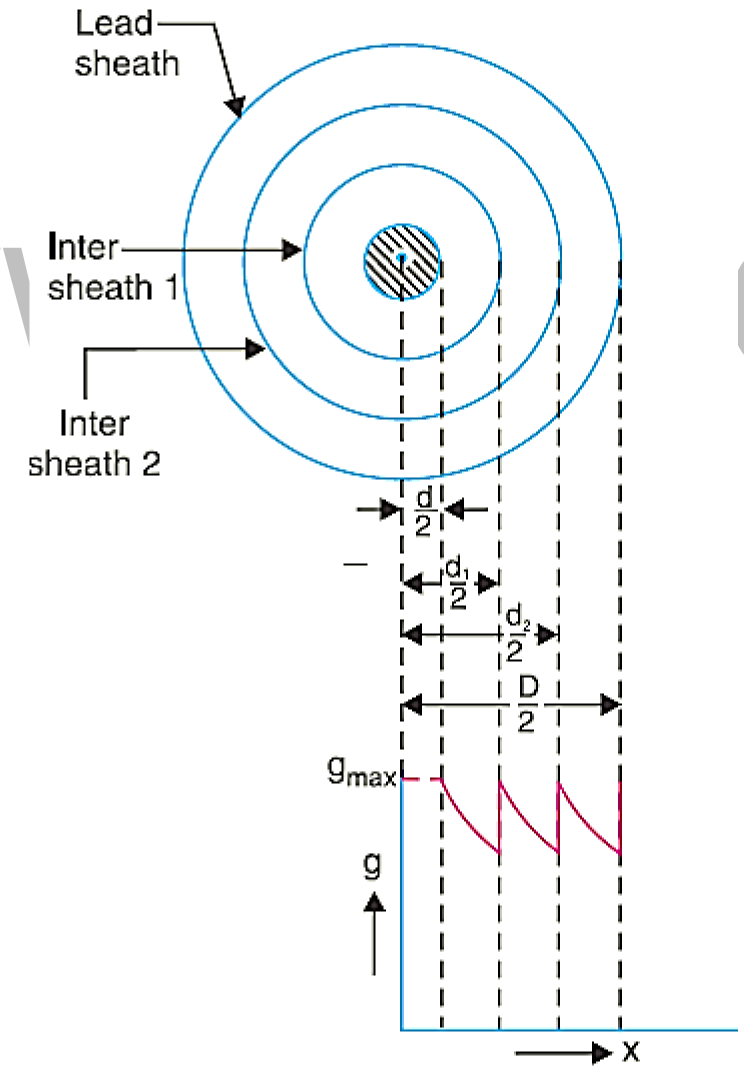


Figure 4.6.1 Intersheath Grading

[Source: "Principles of Power System" by V.K.Mehta Page: 285]

Let $V1$, $V2$ and $V3$ 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.

Maximum stress between core and intersheath 1 is

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

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

$$g_{3max} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}}$$

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

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

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

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.

Problem 1

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:

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

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

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

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

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

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

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

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

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

$$V_1 + V_2 + V_3 = V$$

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

$$V_1 = 53{\cdot}9/3{\cdot}192 = 16{\cdot}88 \text{ kV}$$

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

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

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

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

Problem 2

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.

Solution:

d = 2 cm ; d_1 = ? ; d_2 = ? ; D = 8 cm

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

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

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

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

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

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

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

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

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

Safe working voltage (r.m.s.) for cable

$$= \frac{81.808}{\sqrt{2}}$$

$$= 57.84$$ □□

4.4 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 r1 and internal sheath radius r2 as shown in Fig.4.4.1

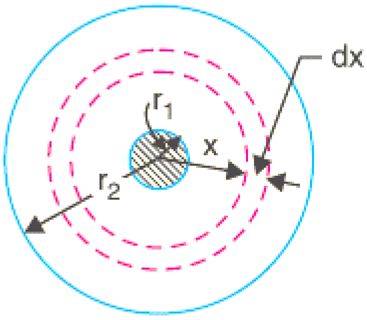


Figure 4.1.1 Single core cable

[Source: "Principles of Power System" by V.K.Mehta Page: 273]

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 2π x l.

Insulation resistance of considered layer

$$= \rho \frac{dx}{2\pi x l}$$

Insulation resistance of the whole cable is

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

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

Problem 1

The insulation resistance of a single-core cable is 495 MΩ per km. If the core diameter is 2·5 cm and resistivity of insulation is 4·5 × 1014 Ω-cm, find the insulation thickness.

Solution:

Length of cable, $l = 1\text{ km} = 1000\text{ m}$

Cable insulation resistance, $R = 495\text{ M}\Omega = 495 \times 10^6\,\Omega$

Conductor radius, $r_1 = 2{\cdot}5/2 = 1{\cdot}25\text{ cm}$

Resistivity of insulation, $\rho = 4{\cdot}5 \times 10^{14}\,\Omega\text{-cm} = 4{\cdot}5 \times 10^{12}\,\Omega\text{m}$

Let r_2 cm be the internal sheath radius.

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

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

$$= \frac{2\pi \times 1000 \times 495 \times 10^6}{4.5 \times 10^{12}}$$

$$= 0.69$$

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

$$\frac{r_2}{r_1} = \text{Anitilog} \frac{\quad}{2.3}$$

$$r_2 = 2r_1$$

$$r_2 = 2 \times 1.25$$

$$r_2 = 2.5\text{ cm}$$

∴ Insulation thickness $= r_2 - r_1$

$$= 2.5 - 1.25$$

$$= 1.25\text{ cm}$$

4.7 POTENTIAL GRADIENT

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*. The electric intensity at a point x metres from the centre of the cable is

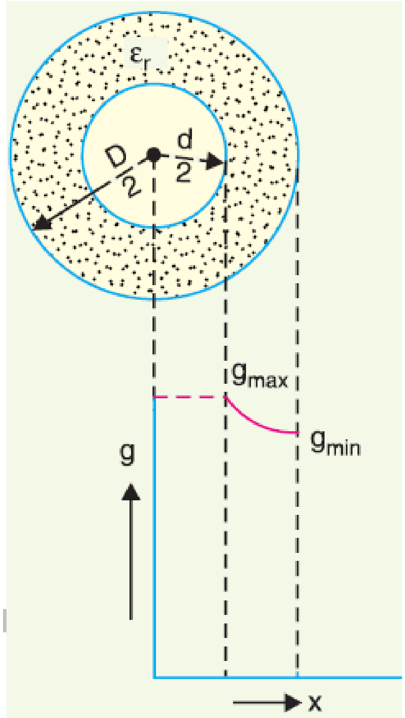


Figure 4.7.1 Potential Gradient – Cable

[Source: "Principles of Power System" by V.K.Mehta Page: 277]

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

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

$$g = E_x$$

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

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

$$Q = \frac{2\pi\,\varepsilon_o\varepsilon_r\,V}{\log_e\frac{D}{d}} \quad \text{.......(ii)}$$

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

$$g = \frac{\frac{2\pi\varepsilon_o\,\varepsilon_r\;V}{\log_e D/d}}{2\pi\varepsilon_o\,\varepsilon_r\;x} = \frac{V}{x\,\log_e\frac{D}{d}} \text{ volts/m} \quad \text{.......(iii)}$$

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,

$$g_{max} = \frac{2V}{d\log_e\frac{D}{d}} \text{ volts/m}$$

[Putting $x = d/2$ in exp. (*iii*)]

Minimum potential gradient is,

$$g_{min} = \frac{2V}{D\log_e\frac{D}{d}} \text{ volts/m}$$

4.9 POWER FACTOR OF CABLE

If the temperature continues to increase, the cable insulation will be damaged. a length of 6 km. The cable is operated at 60 Hz and 7.2 kV. The dielectric constant is 3.5, the dielectric power factor is 0.03 (δ=Cosϕ_d) and dielectric resistivity of the insulation is 1.3x10^7 MΩ.cm

4.9.1 HEATING OF CABLE

The temperature rise of cable depends on the following factors:

1. The production of heat within the external periphery of the cable.

2. The conveyance of the heat as far as the periphery - that is, up to the boundary of the surrounding medium.

3. The conveyance of the heat through this medium, and therefore away from the cable.

4. The current rating of the cables.

5. The nature of the load, i.e. whether continuous or intermittent; not infrequently the rating under short-circuit conditions has to be considered.

Heat generation in cable

Following are the sources of heat generation in the cable

a) I^2R losses in the conductors

b) Dielectric losses in the cable insulation

c) Sheath and armour loss

a) I^2R losses in the conductors

Copper loss is the term often given to heat produced by electrical currents in the conductors, or other electrical devices. Copper losses are an undesirable transfer of energy, as are core losses, which result from induced currents in adjacent components.

The term is applied regardless of whether the windings are made of copper or another conductor, such as aluminium.

Resistance of conductor at an temperature of 70 deg. C (assumed) is determined from the resistance given in standard table (usually at 20 deg,C) from the following relation-

R_h = Ra(1+α (70-20))

Where R_h, R_a are the hot resistance, resistance at 20deg.C.

b) Dielectric losses in the cable insulation

The energy losses occurring in the dielectric of cables are due to leakage and so called dielectric hysteresis.

The charging current of cable I_c is assumed to have two components –

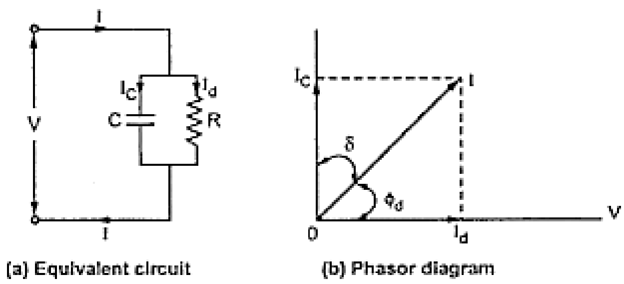


Figure 4.2.1 Belted Cable

[Source: https://bralpowerassociate.blogspot.com/2013/11/heating-in-cable.html

One being true capacitance current which is equal to ωC V and leads the applied voltage by 90deg.

· The other being the energy component which in phase with the applied voltage and represents the dielectric loss components of current.

If V is the applied voltage, C is the capacitance, of cable, Φ is the phase angle between voltage and current called the power factor of the cable and δ is the loss angle of the dielectric,

Charging current, $I_c = V/X_c = \omega C\ V$

The dielectric loss, due to leakage and hysteresis effects in the dielectric, is usually expressed in terms of the loss angle,δ:

$\delta = 90 - \varphi$

Where, φ is the dielectric power factor angle.

Dielectric loss $= \omega C V^2 \tan\delta$,

Where,

C= capacitance to neutral

V= phase voltage

A typical value of tanδ lies in the range 0.002 to 0.003. In low voltage cables the dielectric loss is negligible, but is appreciable in EHV cables.

c) Sheath loss

In 3 core cable the effect is negligible but for single core cable the effect is of great importance. The electromagnetic fields produced by the current flowing through the conductors induce emfs in sheath and under certain condition heavy currents are set up therein. The actual current flowing along the sheath depends magnitude and frequency of the current in the conductor, the arrangement and spacing between the cables. Two different cables having sheath electrically connected are bounded or unbounded. The induced sheath currents are of two types-

i) The currents, which have both outward and inward directions, called the sheath eddies.

ii) The currents, which have outward and inward current path in separate sheath called the sheath circuit eddies.

The approximate formulae for eddy loss for unbounded cables given by Arnold is as under-

$$\text{sheath loss} = I^2\left[\frac{78\omega^2}{R_S}\left(\frac{r}{d}\right)^2 \times 10^{-9}\right] \text{walts/phase}$$

Where,

I = current per conductor,

r = mean radius of sheath,

d=inter axial spacing of conductors

R_s = sheath resistance in ohm

4.2 TYPES OF UNDERGROUND CABLES

The classification of Underground cables can be done on the basis of several criteria. Various aspects are taken into account while classification and these include:

1. Number of conductors in the cable
2. Voltage rating of the cable
3. Construction of cable
4. Type and thickness of insulation used
5. Installation and Laying of the cables

4.2.1 Classification Based Upon Number Of Conductors In The Cable

1. Single core cable
2. Three core cable

Typically, an Underground cable has either one, three or four cores. These cables are of course, constructed accordingly. Underground cables are usually employed to deliver 3 phase power. A 3 cored cable is preferred up to 66 kV. Beyond that, insulation required for the cable is too much. For higher voltages, 3 cored constructions become too bulky, and hence, even with some limitations we employ single cored cables.

4.2.2 Classification Based Upon Voltage Rating Of The Cable

1. Low tension cables: These have a maximum voltage handling capacity of 1000 V (1 kV)
2. High tension cables: These have a maximum voltage handling capacity of 11 kV.
3. Super tension cables: These have a maximum voltage handling capacity of 33 kV.
4. Extra high tension cables: These have a maximum voltage handling capacity of 66 kV.
5. Extra super voltage cables: These are used for applications with voltage requirement above 132 kV.

4.2.3 Classification Based Upon Construction of The Cable

1. Belted Cable

In such cables, the conductors (usually three) are bunched together and then bounded with an insulating paper 'belt'. In such cables, each conductor is insulated using paper impregnated with a suitable dielectric. The gaps between the conductors and the insulating paper belt are filled with a fibrous dielectric material such as Jute or Hessian. This provides flexibility as well as a circular shape. As we discussed earlier (in Construction of Cables), the jute layer is then covered by a metallic sheath and armouring for protection. One particular speciality of this cable is that its shape may not be perfectly circular. It is kept non-circular to use the available space more effectively.

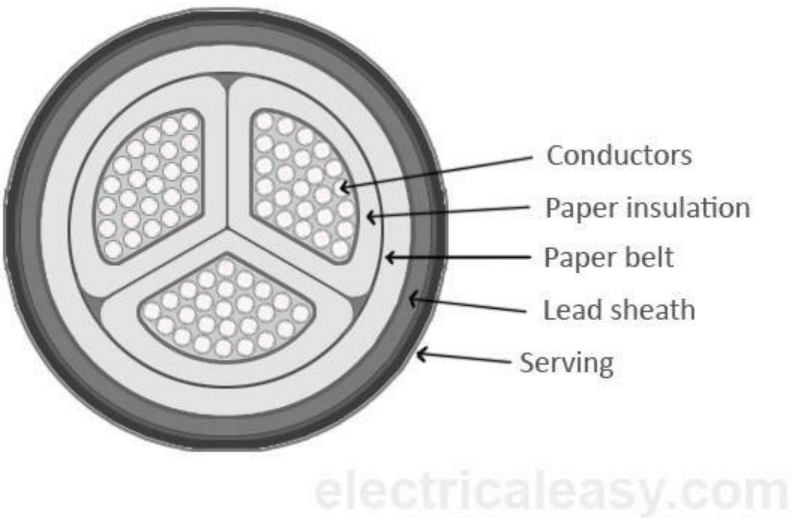


Figure 4.2.1 Belted Cable

[Source:https://www.electricaleasy.com/2017/03/types-of-underground-cables.html]

There are some limitations of such construction. Since the electric field is tangential, the insulation provided is stressed. As a result, the dielectric strength falls over time. Hence, such construction isn't preferred for voltage levels above 11 kV.

2. Screened Cable

Further divided as

1.H-type and

2.S.L. - type cables.

4.2.3 Classification Based Upon Construction of The Cable

1. Belted Cable

In such cables, the conductors (usually three) are bunched together and then bounded with an insulating paper 'belt'. In such cables, each conductor is insulated using paper impregnated with a suitable dielectric. The gaps between the conductors and the insulating paper belt are filled with a fibrous dielectric material such as Jute or Hessian.

1.H-Type Cables

It was first designed by M. Hochstadter. The three cores are individually insulated with paper and then covered by a metallic screen / cover. These metallic covers are perforated. As a result, such construction allows the three metallic screens to touch each other. These three metallic covers are then grouped together in a metallic tape usually made of copper. A lead sheath surrounds this construction. The metallic covers and the sheath are grounded.

The obvious advantage is the electric stresses are radial, not tangential and hence of lesser magnitudes. Also, the metallic covers improve the heat dissipation.

2. S.L Type Cables

It is similar to the H type cables, with the difference that each of the three cores has its own lead sheath. With this provision, the need for the overall sheath used previously is eliminated. The advantage of such a construction is that the chances of a core-to-core breakdown are greatly minimized. Also, the flexibility of the cable is improved.

The limitations are severe. Such construction is limited for voltages up to 66kV only. The individual sheaths are thinner, and if there are constructional defects, moisture may enter the cable and reduce its dielectric strength.

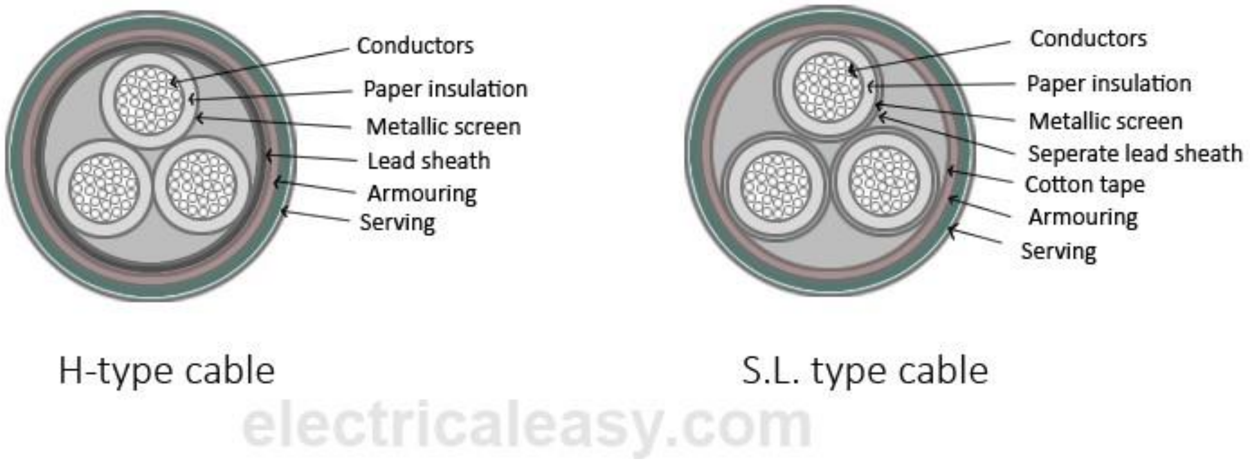


Figure 4.2.2 Screened Cable

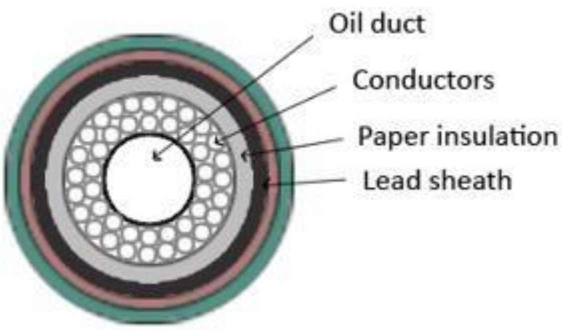
[Source:https://www.electricaleasy.com/2017/03/types-of-underground-cables.html]

- H.S.L. Type Cables: This type of cable is combination of H type and S.L. type cable. In these cables each core is insulated with impregnated paper and provided with separate lead sheaths.

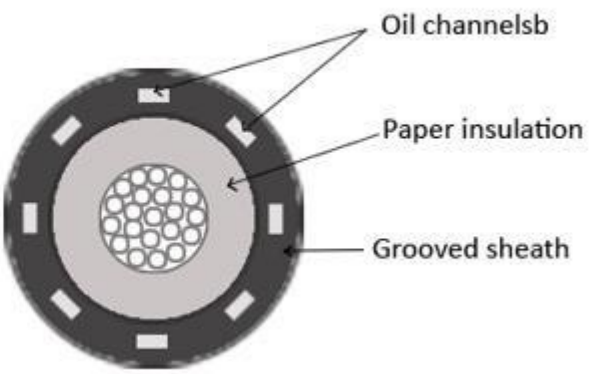
3. Pressure Cables

For voltages beyond 66 kV, the electrostatic stresses in the cables exceed the acceptable values and solid cables become unreliable. This occurs mainly because voids are created when voltages exceed 66 kV. Hence, instead of solid cables, we use Pressure cables. Typically, such cables are either oil filled or gas filled.

- Oil Filled Cables: Oil is circulated under suitable pressure through ducts provided for such purpose. This oil supply and pressure are maintained through reservoirs kept at proper distances. The oil used is the same that is employed for impregnation of paper insulators.
- Gas Filled Cables: Pressurized gas (usually dry nitrogen) is circulated around cables in an air-tight steel pipe. Such cables are cable of carrying higher values of load current and can operate at higher values of voltage. But the overall cost is more.



(i) Conductor channel



(ii) Sheath channel

Figure 4.2.2 Oil filled – Pressure Cable

[Source:https://www.electricaleasy.com/2017/03/types-of-underground-cables.html]

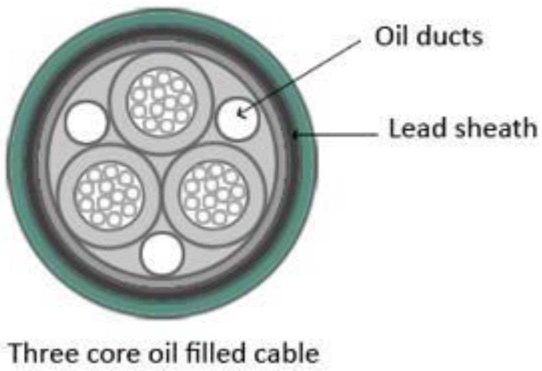


Figure 4.2.3 Oil filled – 3-Core Pressure Cable

[Source:https://www.electricaleasy.com/2017/03/types-of-underground-cables.html]

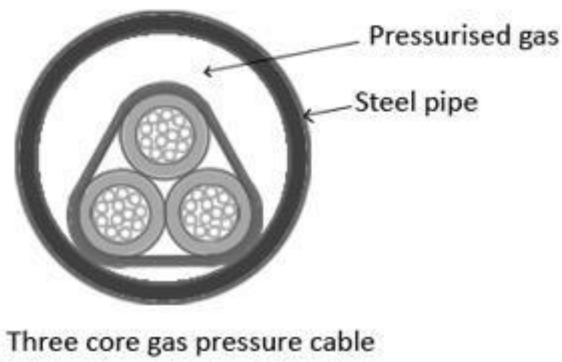


Figure 4.2.4 Gas filled – 3-Core Pressure Cable

[Source:https://www.electricaleasy.com/2017/03/types-of-underground-cables.html]

4.2.4 Classification Based Upon Insulation of the Cable

Various insulating materials used in cable construction are Rubber, Paper, PVC, XLPE (Cross linked Polyethene) etc. Such classification is based upon operating temperature limitations. Following are some insulating materials used and their maximum operating temperatures.

Insulation material	Max. operating temperature
PVC TYPE A	75°C
PVC TYPE B	85°C

PVC TYPE C	85°C
XLPE	90°C
RUBBER	90°C
RUBBER – EPR IE-2, EPR IE-3, EPR IE-4, SILICON IE-5	150°C

Table 4.2.3 Insulation Material used in cables under various temperature

[Source:https://www.electricaleasy.com/2017/03/types-of-underground-cables.html]

4.2.5 Classification Based Upon Installation and Laying of the Cable

- Direct Buried: As the name suggests, the conductors are buried underground in a trench without additional accessories. Sometimes cooling pipes are added if required. Once the cables are installed, there's no visible sign above the ground.
- Trough: Concrete troughs are dug and cables are installed in them. They're visible on the surface. Maintenance is easier.
- Tunnels: Sometimes, tunnels are dug up for this purpose. Such construction is mainly employed if a river needs to be crossed or if the intended power distribution is to a major city. Maintenance and future expansion is easier, but initial cost is higher.
- Gas Insulated Lines: This is a relatively new technology. For cables operating at higher voltages and currents, and handling high power, such gas insulated line construction is safer. It is being employed nowadays for advanced projects.

4.1 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 fulfill the following necessary requirements:

(i) The conductor used in cables should be tinned stranded copper or aluminum 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.