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.

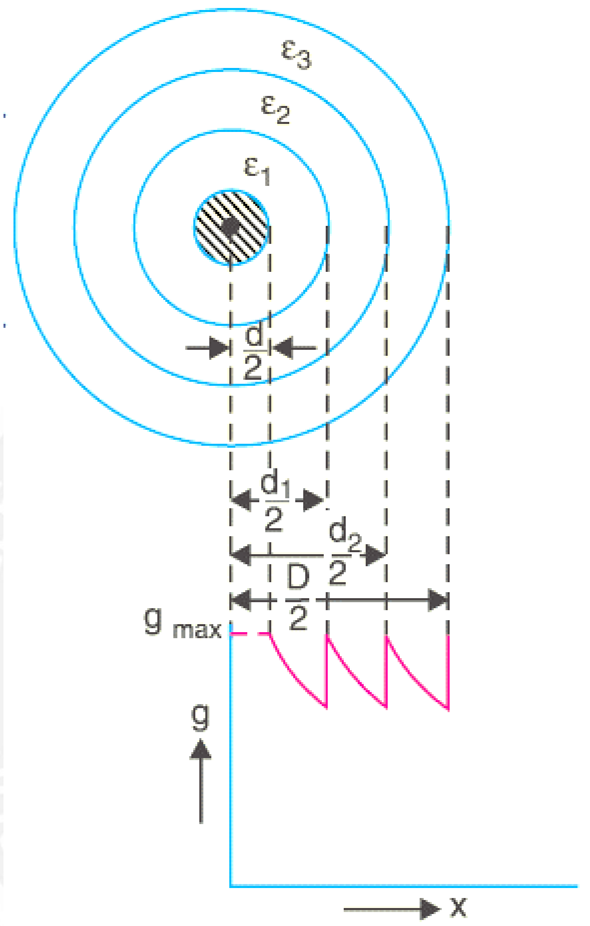

Figure 4.6.1 Capacitance Grading

[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.

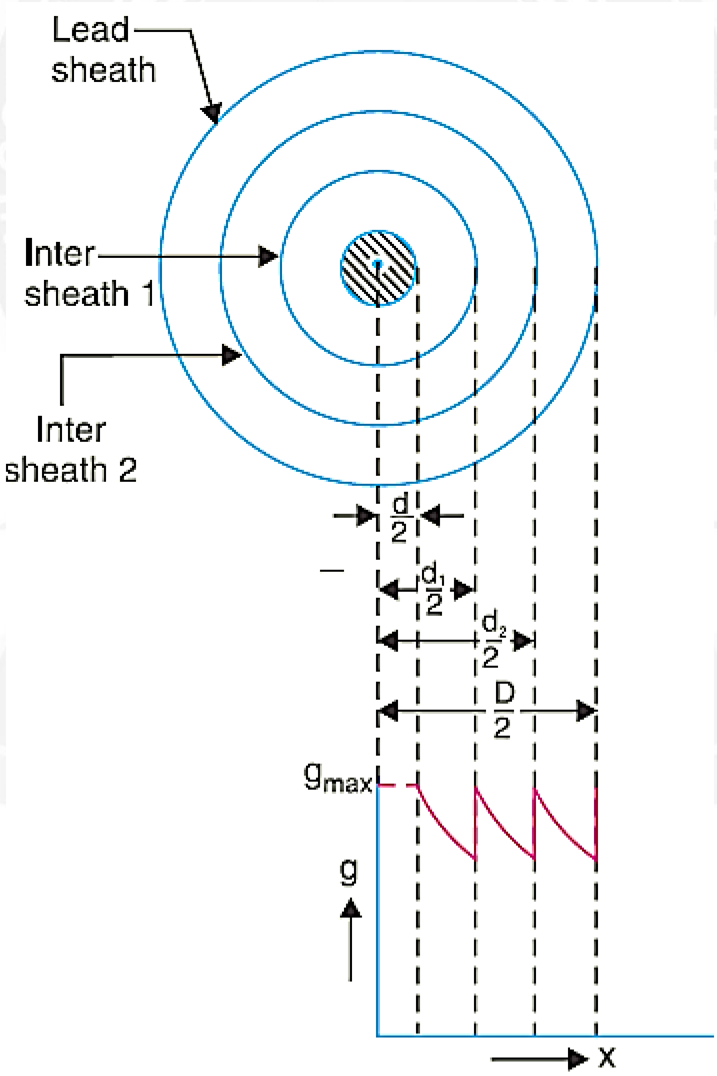

Figure 4.6.1 Intersheath Grading

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

Let *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.

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:

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

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

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

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

$$g_{3max} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}} = \frac{V_3}{2\cdot1\log_e \frac{5\cdot3}{4\cdot2}} = 2{\cdot}04\ V_3$$

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

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

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

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

$$V_1 + V_2 + V_3 = V$$

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

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

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

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

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

$$= \frac{40}{2}\left[2 \log_e \frac{2\cdot5}{2} + 2\cdot5 \log_e \frac{3\cdot34}{2\cdot5} + 3\cdot34 \log_e \frac{8}{3\cdot34}\right]$$

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

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

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

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

$$= 57.84\ KV$$