4. Electrical insulation and breakdown

The preceding analysis has provided the means to calculate the electric field surrounding a conductor which has a defined charge density (note: not a defined voltage as such). This provides a means of establishing the clearance required between two charged conductors or between a conductor and ground plane (by using the method of images). If we revisit the earlier analysis of a conductor located above a ground plane, we can estimate the minimum clearance required to avoid breakdown of the air. However, in order to establish this clearance, it is necessary to understand something about the insulation properties of air. The breakdown electrical strength is defined as the electric field at which arcing or breakdown of the air is likely to be initiated, leading to a significant current flow through the arc, often resulting in catastrophic damage to components and systems. The mechanism by which arc is initiated and sustained in a gas is rather complex, and for this purposes of this course, it is adequate to appreciate that this mechanism places an upper limit on the electric field which can be sustained by a given material.

A reasonable working estimate of the breakdown strength of dry air at sea level is 3×10^{6} V/m (often quoted as 3kV/mm). However, it is dependent on many of the properties of air, most notably the air pressure. The relationship between the breakdown electric field strength and pressure of air (indeed any gas) is not straightforward. This relationship can be calculated by Paschen's Law which provide a means of calculating the electric field breakdown strength in terms of a series of gas specific constants. Having established the constants for a particular gas, it is possible to calculate a so-called Paschen curve for the case of two parallel plates. In the case of air, as would be expected, there is some variation in the breakdown properties with temperature and humidity. Adopting typical values for dry air at 20^{o}C, a representative Paschen curve for air is shown in Figure 1. As will be apparent, at 1 atmosphere (to a reasonable assumption the pressure at sea-level) the breakdown electric field strength is ~3kV/m. The breakdown electric field strength initially drops as the pressure is reduced. However, it reaches a minimum as the so-called Paschen minimum beyond which is start to increase again dramatically. One important consequence of the general shape of the Paschen curve for air is that the breakdown strength of air drops with increasing altitude. This has significant implications for aircraft electrical systems which may well operate up to 40,000ft or so, where air pressure is only some 20% of that at sea level. In order to avoid electrical insulation problems in aircraft equipment, where there is also a desire for lightweight thin insulation on cables to save weight and the need to place cables in close contact, the voltage levels are low in comparison to those for mainstream land based applications, e.g. 115Vrms ac and 270VDC even up to installed powers of 1MW on the latest Boeing 787.

It is also worth noting that in high-voltage systems a small amount of modest electrical discharge can occur, a phenomena called corona discharge. This often leads to a visible blue glow around particular regions of high electrical component. Although not usually destructive in the short term, care is taken to manage such phenomena wherever practical and cost-effective as it can reduce lifetime of insulating components.

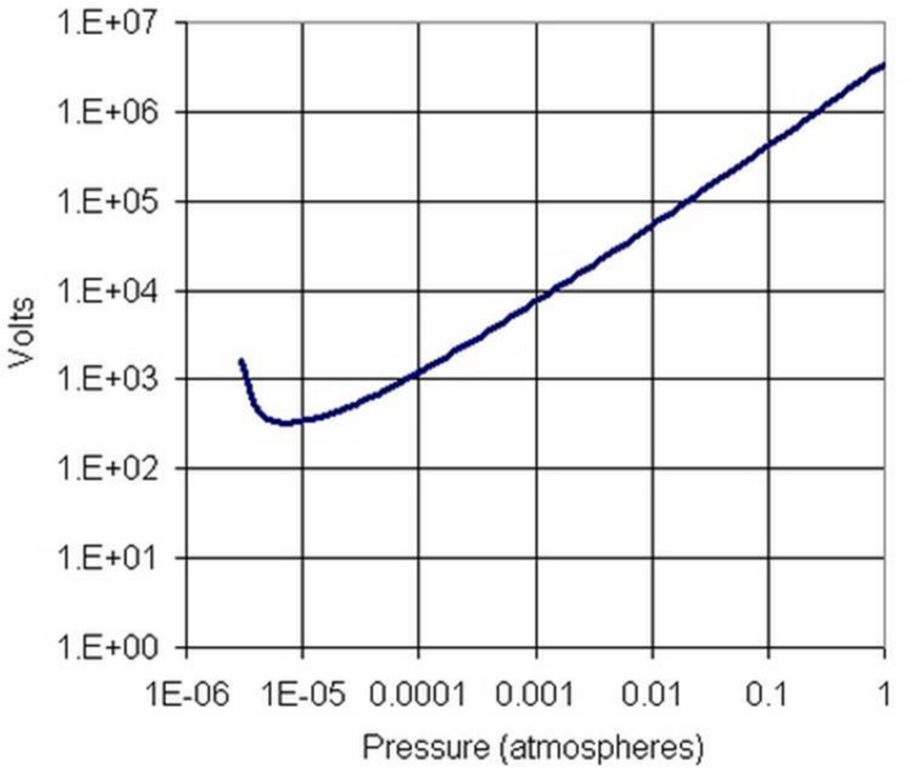

Figure 1 Paschen curve for dry air at 20^{0}C with a 1m gap

If we revisit the expression for the electric field surrounding a conductor above a ground plane, and using the method of images, the electric field is given by:

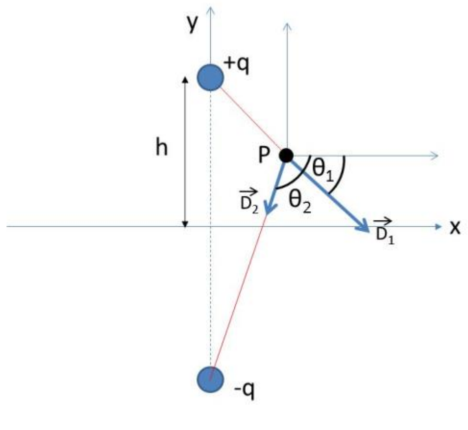

Figure 2 Definition of coordinate system

$$\overrightarrow{E_{net}} = \frac{\overrightarrow{D_{net}}}{\varepsilon} = \frac{R_c^2 q}{2l\varepsilon}\left(\left(\frac{cos\theta_1}{r_1} + \frac{cos\theta_2}{r_2}\right)\overrightarrow{e_x} + \left(\frac{sin\theta_1}{r_1} + \frac{sin\theta_2}{r_2}\right)\overrightarrow{e_y}\right)$$

Taking a vertical path from the conductor down to the ground plane (θ_1 = -90^0; θ_2=-90^0), the electric field along this path is simplified to:

$$\overrightarrow{E_{net}} = \frac{\overrightarrow{D_{net}}}{\varepsilon} = \frac{R_c^2 q}{2l\varepsilon}\left(\frac{-1}{r_1} - \frac{1}{r_2}\right)\overrightarrow{e_y} = -\frac{R_c^2 q}{2l\varepsilon}\left(\frac{1}{r_1} + \frac{1}{r_2}\right)\overrightarrow{e_y}$$

The simple vertical path followed also simplifies the expressions for r_1 and r_2, i.e r_1 = h-y_p and r_2 = h+y_p, which gives:

$$\overrightarrow{E_{net}} = -\frac{R_c^2 q}{2l\varepsilon}\left(\frac{1}{h - y_p} + \frac{1}{h + y_p}\right)\overrightarrow{e_y}$$

We can integrate the electric field from the surface of the physical conductor (of radius R_c) down to the ground plane, to give the voltage difference.

$$V = -\int_{h-R_c}^{0} \overrightarrow{E_{net}}\, dy = \left[\frac{R_c^2 q}{2l\varepsilon}\left(-log_e\left(h - y_p\right) + log_e\left(h + y_p\right)\right)\right]_{h-R_c}^{0}$$

$$V = \frac{R_c^2 q}{2l\varepsilon}\left(log_e(R_c) - log_e(2h - R_c)\right) = \frac{R_c^2 q}{2l\varepsilon}\left(log_e\left(\frac{R_c}{2h - R_c}\right)\right)$$

Example

Supposing we wish to establish the maximum voltage that a conductor of radius 15mm can sustain if it located a distance of 4m from a ground plane (which might also be considered as an approximation to a large grounded structure such as a transmission tower).

$$\overrightarrow{E_{net}} = -\frac{R_c^2 q}{2l\varepsilon}\left(\frac{1}{h - y_p} + \frac{1}{h + y_p}\right)\overrightarrow{e_y}$$

This has a maximum value when y_p = h-R_c, i.e. on the surface of the conductor since the electric field falls off as 1/distance outside the conductor and increases linearly with conductor radius within the conductor itself (see tutorial sheet).

$$\overrightarrow{E_{net}} = -\frac{R_c^2 q}{2l\varepsilon}\left(\frac{1}{R_c} + \frac{1}{2h - R_c}\right)\overrightarrow{e_y}$$

This can be rearranged to derive an expression for the maximum value of volume charge density per unit length which correspond to the breakdown electric field strength of air (3×10^6 V/m) for the conductor radius and distance from the ground plane.

$$\frac{q}{l} = -\frac{2\varepsilon E_{max}}{\left(\frac{1}{R_c} + \frac{1}{2h - R_c}\right) R_c^2}$$

But since h>>R_c, in this case then this expression simplifies to:

$$\frac{q}{l} = -\frac{2\varepsilon E_{max}}{R_c} = 3.54 \times 10^{-2} Cm^{-2}$$

(recalling that $\varepsilon = 8.85 \times 10^{-12}$ Fm^{-1} for air)

It is interesting to note that providing h>>Rc (4m versus 15mm in this case) the electric field for a given charge density does not depend in any meaningful sense on h, but is dependent on the cross-sectional area of the conductor itself (see later example in these notes). This however does not mean that the voltage which can be applied to the conductor is independent of the distance h, even when this condition is satisfied, since the link between charge on the conductor and the voltage is governed by the capacitance which is influenced by the distance to the ground, albeit with a logarithmic relationship. This can be seen by returning to the expression for the voltage:

$$V = \frac{R_c^2 q}{2l\varepsilon}\left(log_e(R_c) - log_e(2h - R_c)\right) = \frac{R_c^2 q}{2l\varepsilon}\left(log_e\left(\frac{R_c}{2h - R_c}\right)\right)$$

Substituting in the various values yields:

V = 251.5kV for a separation of 4m from the ground plane and a 15mm radius conductor

Supposing we reduce the conductor radius to 10mm. Applying the same procedure yields a reduced voltage of 180kV, which illustrates the importance of specifying an appropriate conductor diameter to manage localised electrical fields. Similarly, if we maintain the same 15mm radius, but decrease the separation to 1m, the maximum voltage is 188kV.

Insulated cables

The preceding analysis has demonstrated that if we wish to avoid localised breakdown around a bare conductor at some specified voltage in air that we have to ensure some clearance to the ground plane (or indeed another charged conductor). In some cases, such a underground high voltage cables, it may not be possible to realise such clearances. This then requires the use of some surrounding insulation (often solid, but could be oil) which ideally has both a high breakdown voltage and a higher permittivity than air.

Consider the simplified cable shown in Figure 3, in which the core conductor has a radius R_c and the surrounding insulation has a radius R_i.

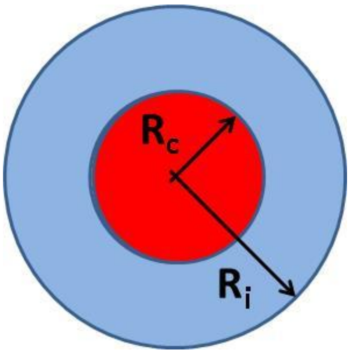

Figure 3 Simplified cross-section through a high voltage cable

The electric field profile across the insulated cable can be established from Gauss's Law, with a maximum value at the surface of the conductor. The magnitude of the electric field falls away as 1/distance in the insulation but a rate determined by 1/ε. Most polymers that are used as solid insulation materials in both low voltage and high voltage cables have relative permittivities of 2-6 or so, thus realising a more rapid off in voltage with distance. Moreover, they have extremely high breakdown voltages of at least ~100kV/mm (i.e. at least 30 times better than air). A variety of polymers can be used, a common one being XLPE which is widely used in high voltage cables up to 550kV.

Recalling from Lecture Notes 3 that the electric field in the region outside the core is given by:

$$\overrightarrow{E_r} = \frac{R_c^2 q}{2\varepsilon r}$$

A typical electric field variation across a cable is shown in Figure 4.

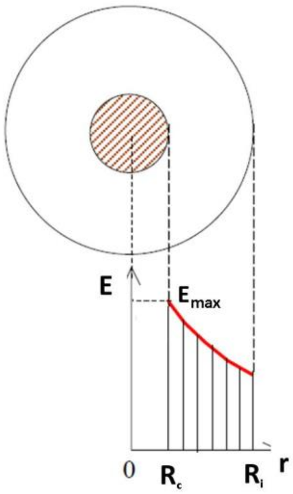

Figure 4 Typical electric field variation across an insulated cable

The voltage across the insulation layers is given by:

$$V = \frac{R_c^2 q}{2\varepsilon} log_e\left(\frac{R_c}{R_i}\right)$$

The electric field has a maximum value at R_c

$$E_{Rc} = \frac{R_c q}{2\varepsilon}$$

But

$$V = \frac{R_c^2 q}{2\varepsilon} log_e\left(\frac{R_c}{R_i}\right)$$

And hence

$$V = R_c E_{Rc} log_e\left(\frac{R_c}{R_i}\right)$$

Re-arranging, gives

$$E_{Rc} = \frac{V}{R_c log_e\left(\frac{R_c}{R_i}\right)}$$

It is possible to minimise the worst case electric field by appropriate setting of R_c. This can be achieved by using:

$$\frac{dE_{Rc}}{dR_c} = 0$$

Which yields a solution for the ratio R_i/R_c of 2.718.

Cables for high voltages, e.g. 3.3kV and above are sophisticated electrical components which use high performance material and use many ingenious design features to manage the electric field very precisely to enhance reliability and lifetime. One

Figure 5 Examples of typical high voltage cables with polymer insulation

<u>Useful general articles and data sheets on cables available at:</u>

http://www.kpa.co.ke/InfoCenter/Tenders/Documents/Archives/Appendix%20ii%20typical%20cable%20specs%20A%2003_web_xlpe_guide_en.pdf

http://www.eepublishers.co.za/images/upload/Trans%20-%20High%20voltage.pdf

http://www.neetrac.gatech.edu/publications/jicable07_C_5_1_5.pdf

http://www.bruggcables.com/domains/bruggcables_com/data/free_docs/Ageing%20of%20XLPE%20and%20SiR%20for%20HV%20cables%20and%20accessories_Paper%20CIGRE_Vogelsang_Brugg%20Cables_2.pdf