Lecture # 4

Short-term Breakdown in Solids

Solid Dielectrics

Solids find extensive use as dielectric and insulation in numerous power system and high-voltage apparatus, such as electrical machines, transmission lines, transformers, cables, capacitors etc. Commonly used inorganic materials are ceramics and glass. The most widely used organic materials are the thermosetting epoxy resins such as Polyvinyl Chloride (PVC), Polyethylene (PE) or Cross-linked Polyethylene (XLPE), Kraft paper, natural rubber, silicon rubber and polypropylene rubber. Solid insulation, when homogeneous and almost free from imperfections, will have a dielectric strength of the order of 10 MV/cm, referred to as the intrinsic breakdown strength, and can be obtained only under carefully controlled laboratory conditions. The intrinsic electric strength or simply intrinsic strength of a material is the measure of the highest voltage it can sustain without causing breakdown and is therefore measure of its ultimate electric strength. The maximum electrical strength recorder is 15MV/cm for polyvinyl-alcohol at cryogenic temperature (liquid nitrogen temperature; –196°C). The maximum strength usually obtainable for most solids ranges from 5MV/cm to 10MV/cm. While measuring the intrinsic strength, if there exists a cause that leads to other than electronic instability, the value of electric strength measured may be anywhere below intrinsic strength.

However, in practice, such high fields are seldom achieved and the breakdown fields are very much lower than intrinsic value. There are several different mechanisms of breakdown in solids, but in majority of cases, the breakdown occurs over the surface due to flashover and deterioration by tracking rather than in the solid itself. Followings are some important characteristics of solid insulation for most applications.

1. High dielectric strength.
2. Adequate mechanical strength.
3. Non-degradable during exposure to a particular environment.
4. Temperature resistant.
5. Chemically stable.
6. Fire resistant.

Breakdown in Solids

The mechanism of failure of solid dielectrics is time dependent. The breakdown of solid dielectrics not only depends upon the magnitude of voltage applied but also it is a function of time for which the voltage is applied. It is therefore convenient to divide the time-scale of voltage application into regions in which different mechanisms may are believed to be operative as in Fig (1). Roughly, the product of the breakdown voltage and the log of the time required for breakdown is almost constant, represented by:

$$V_b = \ln(t_b) = \text{Constant} \qquad 1$$

The breakdown mechanisms in solids are different under different laboratory and service conditions. Under certain controlled laboratory conditions the breakdown in solids is thought to be accomplished by the same process as breakdown of gases as mentioned earlier. The experimentally observed breakdown values are, however, dependent on the method and conditions of the measurements and the actual values will depend on the breakdown processes, which is dominant under the particular conditions. Unlike gases and dielectric liquids, the dielectric strength of solid dielectric is not recoverable after a breakdown.

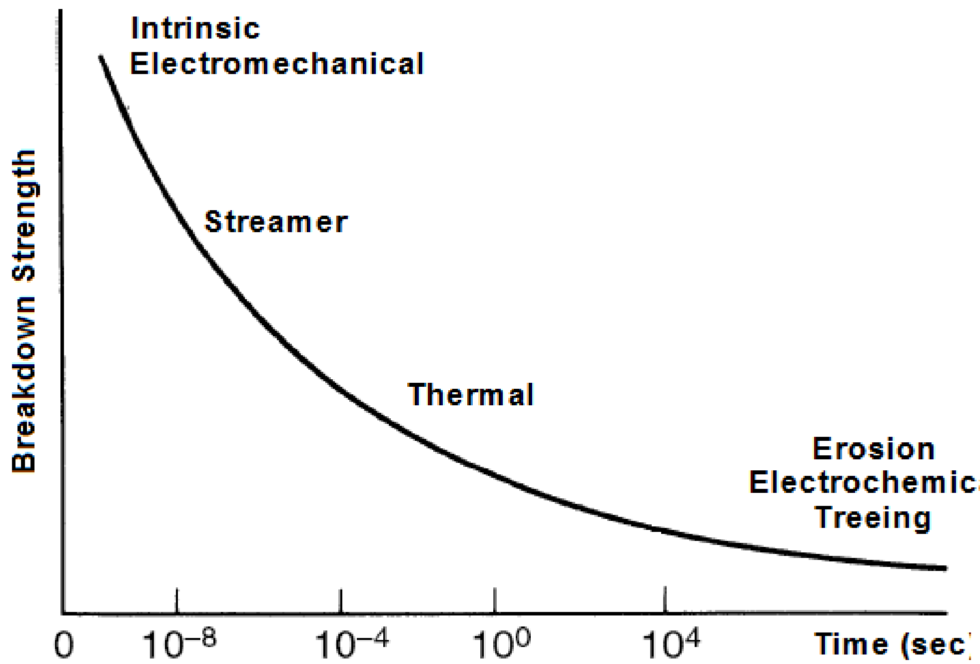

Figure 1: Breakdown Strength and Mechanisms with Time

Electronic Breakdown Mechanism

Experimentally, the highest dielectric strength can be obtained only under uniform fields and carefully controlled laboratory conditions when all extraneous influences have been isolated and the value depends only on the structure of the material and the temperature. Very high voltages applied to almost homogenous and pure solids, the upper limit of its dielectric strength may be reached (called the intrinsic electric strength), intrinsic breakdown takes place. Since the process of intrinsic breakdown develops very rapidly, in times of the order of 10^{-8} seconds, it is assumed to be electronic in nature and follow Townsend mechanism as discussed for gases.

In solids free electrons are always present at room temperature. For superior quality dielectric these electrons are, however, smaller in numbers and therefore insufficient to result in any significant measurable current. In the case of an inferior dielectric material, the electrons present due to anisotropy may contribute significant current in the presence of external field thus accounting for appreciable leakage current. The simplest theoretical approach for intrinsic breakdown has been to derive a theory for an electronic instability in the dielectric subjected to a uniform field.

When high electric field is applied, electrons in the valence band will gain sufficient energy to cross the forbidden energy gap and will move to conduction band where already some free electrons are present. In addition, the high electric field may release electrons from cathode by overcoming its work function, and the trapped electrons from deep and shallow traps (defects). Besides, the temperature of the lattice will result into increase in the number of trapped electrons release from defects and taking them to the conduction band. These electrons, together with the already present free electrons are imparted with very high energy, sufficient to produce collision-ionization of the neighboring atoms that are fixed in lattice, thereby resulting in electrons multiplication.

The breakdown criterion is derived from the energy balance between the energy gained by conduction electrons from the applied electric field and that portion of the energy, which is being lost to the lattice on collision and any surplus energy is taken by the removed electron as its kinetic energy. The process continues and finally may lead to formation of an electron avalanche similar to gases and will lead finally to breakdown if the avalanche exceeds a certain critical size. It must be remembered in case of solid dielectric the short circuit will leave a permanently conducting path via carbonization as a consequence of burning of the path along the trail of positive ions. This makes the dielectric unfit for future use for insulating purpose.

Electromechanical Breakdown Mechanism

The electromechanical breakdown mechanism is applicable to those materials that are visco-elastic in nature and are compressible, such as some thermo-setting polymers. Thermo-setting plastics are extensively used as insulation in low voltage to extra high voltage cables. Such insulation may fail when the applied electric stress exceeds its mechanical strength. This breakdown mechanism takes into account both electrical strength and mechanical strength of the dielectric material. The mechanical strength of a solid material is governed by a constant, referred to as modulus of elasticity or Young's modulus denoted by *Y* and is equal to ratio of stress to strain. The strain produced during application of stress in solid insulator is highly non-linear and follows a logarithmic law. If d_o is the original thickness of solid held between two identical plate electrodes and d is the final thickness to which it is compressed by an application of force as shown in Fig (2), then:

$$Strain = \ln\left(\frac{d_0}{d}\right) \qquad 2$$

The Coulomb force (electrostatic force) F resulting from the applied voltage V and electric field E between two parallel plate electrodes in Fig (2) is:

$$F = \frac{1}{2}\, q\, E \qquad 3$$

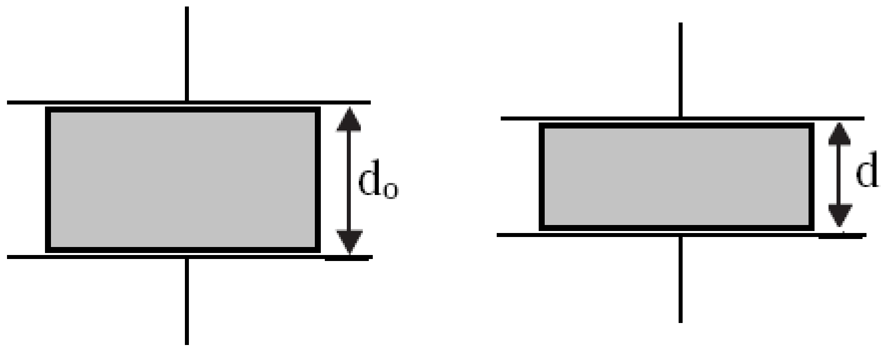

Figure 2: Solid dielectric between parallel plates on voltage application

The Coulomb force will produce a compressive force and hence compress the solid dielectric held between the plates, thereby inducing mechanical strain that can be determined from Eq (2). Since the ratio of stress to strain is the Young's modulus *Y* of the material, the compressive mechanical stress acting on the solid between plates is:

$$(Stress)_{\mathrm{M}} = Y \ln\left(\frac{d_0}{d}\right) \qquad 4$$

Dividing both sides of Eq (3) by area A and using the definition of pressure and stress (force per unit area), [remember this force per unit area will be electric stress $(\mathrm{Stress})_{\mathrm{E}}$ as it results from electrostatic forces due to charges that appear on the plates when voltage is applied between them]. Thus:

$$(Stress)_{\mathrm{E}} = \frac{qV}{2Ad} \qquad 5$$

The solid dielectric sandwiched between the two electrodes in Fig (2) appears as a system of parallel plate capacitor with capacitance *C*. Using the definition of capacitance, the expression for stress due to electric field becomes:

$$(Stress)_{\mathrm{E}} = \frac{CV^2}{2Ad} \qquad 6$$

Since the capacitance of a parallel plate arrangement is $C = \varepsilon A/d$. Where: $\varepsilon = \varepsilon_0 \varepsilon_r$, which when substituted in Eq (6) and simplified will result in:

$$(Stress)_{\mathrm{E}} = \frac{\varepsilon V^2}{2d^2} \qquad 7$$

The critical condition to cause electromechanical breakdown of the solid can be obtained under equilibrium state where the applied electrical stress overcomes the mechanical compressive stress (compressive strength). Comparing Eq (4) and Eq (7), we have:

$$\frac{\varepsilon V^2}{2d^2} = Y \ln\left(\frac{d_0}{d}\right) \qquad 8$$

The voltage required to commence electromechanical breakdown of solid under compressive forces will then be given by:

$$V = d\sqrt{\frac{2Y}{\varepsilon}\ln\left(\frac{d_0}{d}\right)} \qquad 9$$

From Eq (9) the electric field E within the dielectric in Fig (2) is:

$$E = \sqrt{\frac{2Y}{\varepsilon}\ln\left(\frac{d_0}{d}\right)} \qquad 10$$

Breakdown will commence under the condition when the solid compresses to a critical thickness. This condition can be obtained by squaring both sides of Eq (9) and then taking the derivative of voltage with respect to the thickness d of the solid and then equating the derivative to zero. That is:

$$\frac{d}{d(d)}[V^2] = \frac{d}{d(d)}\left[\frac{2d^2Y}{\varepsilon}\ln\left(\frac{d_0}{d}\right)\right]$$

Or $$2V\frac{dV}{d(d)} = \left(\frac{2Y}{\varepsilon}\right)\left[d^2\frac{d}{d(d)}\ln\left(\frac{d_0}{d}\right) + \ln\left(\frac{d_0}{d}\right)\frac{d}{d(d)}(d^2)\right]$$

Or $$2V\frac{dV}{d(d)} = \left(\frac{2Y}{\varepsilon}\right)\left[d^2\left(\frac{d}{d_0}\right)\left(-\frac{d_0}{d^2}\right) + \ln\left(\frac{d_0}{d}\right)2d\right]$$

Putting the derivative to zero we have:

Or $$\frac{dV}{d(d)} = -d + 2d\ln\left(\frac{d_0}{d}\right) = 0$$

Or $$\left(\frac{d}{d_o}\right) = \exp\left(-\frac{1}{2}\right)$$

Or $$d = d_0 \exp(-0.5)$$

Or $$d = 0.6 d_0 \qquad 11$$

Substituting the condition obtained in Eq (11) in the expression of electric field in Eq (10) and simplifying, the expression for critical field will be:

$$E_{crit} = 33.83 \times 10^4 \sqrt{\frac{Y}{\varepsilon_r}} \text{ V/m} \qquad 12$$

Under applied electric stress through application of voltage, the solid dielectric compresses to 0.6 of its original thickness for the breakdown to occur. It must be remembered that electromechanical breakdown can take place in those materials that can be compressed by Coulomb forces experienced by application of electric field that are sufficient to cause deformation. In the case of stiff or un-compressible materials, the electromechanical mechanism may be superheated by other mechanisms.

Example 1: A sample of Polymethyl-Metha-Acryl (PMMA), 1cm thick having dielectric constant of 3.6 and modulus of elasticity of 3.2GPa is introduced in a uniform field created between two plate electrodes with steady voltage applied. Calculate the critical field for electromechanical breakdown of PMMA.

Solution:

Given that: $\varepsilon_r = 3.6$ and $Y = 3.2$ GPa or 3.2×10^9 N/m^2

And $d_0 = 1$cm

Using:

$$E_{crit} = 33.83 \times 10^4 \sqrt{\frac{Y}{\varepsilon_r}} \text{ Volts/m}$$

Or $$E_{crit} = 33.83 \times 10^4 \sqrt{\frac{3.2 \times 10^9}{3.6}} = \mathbf{100.81 MV/cm}$$

The critical field exceeds the intrinsic breakdown strength of PMMA which is about 0.3MV/cm. In other words to compress the given sample of PMMA (a stiff material) to 0.6 of its original thickness, an electric field of 100.81MV/cm is required. Thus the possibility of electromechanical breakdown does not exist, and PMMA may breakdown following the electronic breakdown mechanism.

Example 2: Find the value of critical electric field for the possibility of electromechanical breakdown under uniform field conditions in insulating rubber, having dielectric constant of 6 and modulus of elasticity 0.01MPa. The thickness of the sample is 2cm between plate electrodes.

Solution:

Given that: $\varepsilon_r = 6$ and $Y = 0.01$MPa or 0.01×10^6 N/m^2

And $d_0 = 2$cm

Using:

$$E_{crit} = 33.83 \times 10^4 \sqrt{\frac{Y}{\varepsilon_r}} \text{ Volts/m}$$

Or $$E_{crit} = 33.83\times10^4\sqrt{\frac{0.01\times10^6}{6}} = \mathbf{0.13MV/cm}$$

The calculated critical field value seems reasonable so far as this value lie within the range of the dielectric strength of rubber insulation. Rubber is soft and can be compressible by Coulomb forces in electric field so that a possibility of electromechanical breakdown exits.

Example 3: Find the electric field and voltage for a laboratory test uniform field conditions on a given specimen of 2cm thick neoprene rubber, having dielectric constant of 6.7 and modulus of elasticity 0.01GPa. The specimen is held between two spring loaded electrodes that compresses it to a thickness of 1.85 cm.

Solution:

Given that: $\varepsilon_r = 6$ and $Y = 0.01\text{MPa}$ or $0.01\times10^6\ \text{N/m}^2$

And $d_0 = 2\text{cm}$

Using:

$$E = \sqrt{\frac{2Y}{\varepsilon}\ln\left(\frac{d_0}{d}\right)}$$

Or $$E = \sqrt{\frac{2\times0.01\times10^9}{6.7\times8.85\times10^{-12}}\ln\left(\frac{2}{1.85}\right)} = \mathbf{1.62MV/cm}$$

The voltage required is:

$$V = \frac{E}{d} = \frac{1.62\times10^6}{1.85} = \mathbf{875.67kV}$$

Thermal Breakdown Mechanism

Thermal breakdown proceed from the onset of thermal instability. The thermal instability is caused due to the self-heating of the dielectric due to power losses. The power loss is the consequence of flow of electrons that constitutes the current when voltage is applied across the solid dielectric. It must be remembered that in solids there are already electrons in conduction band (free electrons) Because of power loss due to conductivity and polarization or other forms of dielectric loss, heat is produced continuously in electrically stressed dielectrics. In general, the conductivity increases with temperature, since all dielectric materials have negative thermal-resistance coefficient. Depending upon the magnitude of the applied voltage, its period of application and the conduction of heat, the dielectric temperature rises. If the heat generated within a dielectric system equals the dissipation of heat to the surroundings by thermal conduction, the temperature rises to an equilibrium value, and a thermally balanced and stable operation of the insulation system takes place. Since the conductivity increases with increasing temperature, the power losses increase with temperature. If the dissipation of heat by natural or forced cooling process is not adequate, it is possible that an unstable state may arise in which the temperature increases without limit and thus cause breakdown. Consider a finite unit volume element in the form of a unit cube inside a dielectric material as shown in Fig (3), stressed by voltage that produces an electric field *E*.

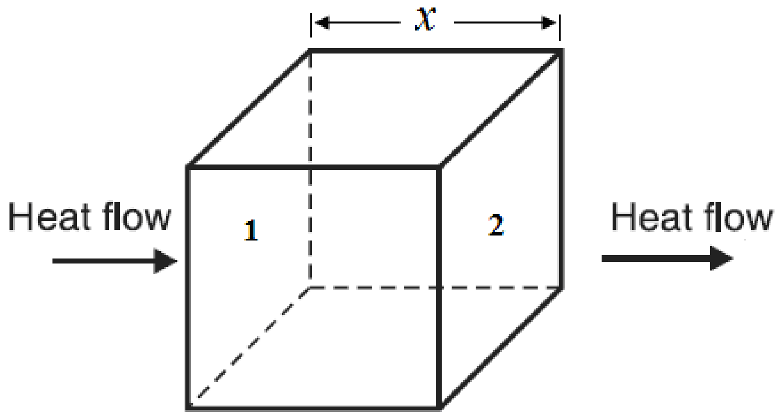

Figure 3: A Unit Cube Element of a Dielectric

The power loss P_L resulting in the production of heat by a flow of conduction current *I* through a dielectric with insulation resistance *R* is $I^2 R$. If the average electric field is $E = Vx$ acting over a length *x* of the unit volume element, then it can be expressed as:

$$P_L = \frac{V^2}{R} = \frac{E^2 x^2}{R}$$

Since the facial area of the unit volume through which heat flows is $A = x^2$, then:

$$P_L = \frac{E^2 A}{R} \qquad 13$$

Using the definition of resistance, which relates the conductivity σ with the geometry of the material; in the case of a unit volume element shown in Fig (3), we have:

$$R = \frac{x}{\sigma A}$$

Substituting the above expression for *R* in the expression for P_L in Eq (13), and knowing that: $A = x^2$, we have:

$$P_L = \sigma E^2 (A \times x)$$

The term in the brackets of the above expression is the volume ΔV of the unit volume element over which the power loss in the form of heat takes place, therefore:

$$P_L = \sigma E^2 (\Delta V)$$

Or

$$\frac{P_L}{\Delta V} = \sigma E^2$$

The power loss P_L that produces heating of the unit volume element of the dielectric can be more conveniently expressed as the power loss per unit volume (power density) W_L of dielectric, which is responsible for the total heat flux. Therefore it can be expressed as:

$$W_L = \sigma E^2 \quad 14$$

Part of the heat produced due to the power loss will be absorbed (H_{abs}) and will raise the temperature of the material, while part of the heat will be conducted away or dissipated (H_{diss}) to the surrounding. The heat flow across the unit volume element to the surrounding can be obtained by considering the heat flux into face-1 and heat flux out of face-2, knowing the thermal conductivity K and the temperature gradient (difference of temperature between face 1 and face 2), the heat flux flowing out through the dielectric to the surrounding is given as:

$$H_{diss} = K\frac{d}{dx}\left(\frac{dT}{dx}\right) = div(KgradT) \quad 15$$

The component of the total heat which is absorbed by the material is dependent on C_v (the specific heat of the dielectric material at constant volume). The portion of heat absorbed by unit volume element of the dielectric is thus given by:

$$H_{abs} = C_v\frac{dT}{dt} \quad 16$$

According to the law of heat exchange, the thermodynamic equilibrium: *Heat produced = Heat absorbed + Heat flux dissipated*. Therefore:

$$\sigma E^2 = C_v\frac{dT}{dt} + div(KgradT) \quad 17$$

The onset of thermal instability results in an unbalance of thermodynamic equilibrium; that is: $C_v\frac{dT}{dt} > div(KgradT)$.

Example 4: Calculate the critical electric field for the onset of thermal instability in polystyrene when the constant rate of rise of temperature is 0.6ºC/sec along a unit length resulting in conductivity of 10^{-10} S/cm. The thermal conductivity of polystyrene is 0.13W/mºK and specific heat at constant volume is 1.3kJ/kgºK. Assume steady voltage applied with the heat losses to the ambient negligible and that the heat flow is uniform.

Solution:

Given that: K = 0.13W/mºK and C_v = 1.3kJ/kgºK

$$\frac{dT}{dt} = 0.6 + 273 = 273.6 \text{ and } \sigma = 10^{-10} \text{ S/m}$$

Using: $$\sigma E^2 = C_v \frac{dT}{dt} + K \frac{d}{dx}\left(\frac{dT}{dx}\right)$$

The term $+K \frac{d}{dx}\left(\frac{dT}{dx}\right)$ in the above expression is $(K grad T)$. When the heat losses to the ambient is negligible then $div(K grad T)$ is zero and all the heat produced rises the temperature of dielectric. Thus

$$\sigma E^2 = C_v \frac{dT}{dt}$$

Or $$E^2 = \frac{1}{\sigma} C_v \frac{dT}{dt}$$

Or $$E^2 = \frac{1}{10^{-8}} \times 1.3 \times 10^3 \times 273.6 = 35.56 \times 10^{12}$$

Or

E = **5.96 MV/m or 59.6 kV/cm**

Example 5: Find the power loss per meter cube in polystyrene between two uniform field electrodes separated by a distance of 4cm when an AC voltage of 100kV at 50Hz is applied. The relative permittivity of polystyrene is 2.6 and assume loss angle of 5 degrees.

Solution:

Given that: electrode separation: d = 4cm or 0.04m, frequency f = 50Hz

Applied AC voltage V = 100kV, ε_r = 2.6. and δ = 5º. The electric field value under uniform field condition is calculated as:

$$E = \frac{V}{d} = \frac{100}{0.04} = 2500 \text{ kV/m or } 25 \times 10^5 \text{ V/m}$$

Using: $$W_L = \varepsilon E^2 \omega \tan\delta$$

Or $$W_L = 8.85 \times 10^{-12} \times 2.6 \times (25 \times 10^5)^2 (2\pi \times 50) \tan(5) = \mathbf{3950.73 W/m^3}$$

The magnitude of the product $\varepsilon \tan\delta$ which represents the loss is a very essential parameter for the application of insulation material and that under AC the losses are much greater than under DC.