Chapter 3

Insulators & Dielectrics

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High voltage engineering is an important sub set of advanced Electrical Engineering. It has very specific applications in the field of Electrical Engineering. The most common application of high voltage is long distance power transmission. Use of high voltage for power transmission reduces copper loss thus allows efficient transmission. However, high voltage got extreme prominence with advancement of particle physics studies and experiments. As research on particle physics advanced, requirement for high energy particle increased. High energy particles are generated using high voltage accelerators. Thus High Voltage Engineering became a prominent subject of expertise in modern day science research and technological applications.

The single most important component in high voltage engineering is insulators. Many a times they are referred as dielectrics too. However, they are little different from the perspective of applications. If we consider any insulating material it has two independent properties (a) relative permittivity, (b) High voltage withstand capability i.e. breakdown strength (defined as kV/cm). Every insulating material has different values of relative permittivity and breakdown strength. A material, with high breakdown strength is often used to insulate high voltage from other components of the system and known more as an insulator. Whereas a material with high relative permittivity is often used to store energy between high voltage and ground, and mostly known as dielectric. As for example, De-ionized water is having $\varepsilon_r = 80$ compared to Teflon whose $\varepsilon_r = 2.3$. So DI water is better known as good dielectric. However DI water on application of high voltage fails to withstand it because of low insulation resistance, whereas Teflon can handle high voltage up to 100-200 kV/mm thus can be called a good insulator compared to DI water.

Mylor (V_{bd} = 100-200 kV/mm, $\varepsilon_r = 3.5$), Mineral oil (V_{bd} = 100 kV/cm, $\varepsilon_r = 2.1$) and gases (V_{bd}= 25-90 kV/cm, $\varepsilon_r = 1$) are the list of a few insulators and dielectrics. These are examples of good insulators. DI water ($\varepsilon_r = 80$) and Ceramic materials (ε_r = 1000-2000) are known as good dielectrics.

Insulators or dielectrics can be classified into following categories,

- Solid insulators [Example: Paper, Ceramic (porcelain, glass etc.), Polymers (Mylar, Polypropylene etc.)]
- Liquid insulators [Oils, DI water, Alcohol]
- Gases [SF_6, N_2, He, Ar, H_2]

3.1. Breakdown in Gases

High voltage based instruments i.e. accelerators, pulsed power sources etc. consist of complex combination of metallic structures and insulators. Selection, coordination and compatibility of the insulating materials are critical factors in design and performance of such equipment. As requirement of realizable voltages and powers of the equipments increased over the years, physical and electrical properties of insulating materials have greatly improved following extensive research by scientists and engineers across the world. In this chapter we will discuss about different types of dielectric materials, their voltage withstanding capabilities and mechanisms of failure.

3.1.1. Gases as Insulating Media

Among the insulators, gaseous insulators are widely used for certain advantages. Among them most important is ease of availability and maintainability. Gaseous insulators can be used easily in any shape or size as it takes the shape of its container. Breakdown strength of gaseous materials changes with pressure variation, this gives flexibility during initial design and development stages. Most commonly used gaseous insulator is dry air (breakdown strength 28 kV/cm). However for advanced technological applications, IOLAR Grade (99.99% pure) nitrogen (breakdown strength 30 kV/cm), carbon-di-oxide, Argon (breakdown strength 22 kV/cm), Helium etc. are used based on applications and design requirements. Freon (CCl_2F_2) and Sulphur-hexafluoride (breakdown strength 89 kV/cm) has very high breakdown strength compared to air. This is due to presence of electronegative atom like fluorine in the compound. Details of breakdown strength of electro-negative gases will be discussed in following sections. Use of these gases are prevalent in circuit breaker, high voltage switches etc. as gaseous insulators have inherent capability to self-heal and recover itself within very small time. Thus most suitable for use in places where breakdown is expected for multiple times. Gases under high voltage experience different phenomena i.e. dark discharge, glow discharge, Corona discharge and arc discharge. These distinctions are based on current flowing through the gaseous insulator while applied with high voltages of different level. Details of these processes are explained below in following sections.

3.1.2. Ionization Process

Townsend discharge is named after John Sealy Edward Townsend, a theoretical physicist from Oxford University. He had given the hypothesis for explaining breakdown of gases under application of high voltage.

Consider two parallel plate electrodes (representing uniform field geometry) separated by a distance d and kept in a gas medium at pressure p. A uniform electric field E appears between two electrodes while subjected to voltage V. Certain free electrons are always available in the gas medium at natural temperature or pressure. Along with them there are electrons produced due to cosmic radiations and field emission from cathode. These electrons while subjected to E field, they accelerate along the field line and gather energy.

$$\text{Energy} = eE.x = 0.5mv^2 \tag{3.1}$$

Where x is the distance traveled by the electron from the cathode, m is the mass and v is the velocity of the electron.

On its path towards anode, these electrons collide with neutral gas molecules. If the energy of these electrons are sufficiently high, it dissociates gas molecules and creates positive ions and electrons. Newly generated electrons further accelerate and the same process repeats creating multiplication of electrons and ions in a chain of reaction. Ultimately multiplied number of electrons reach anode forming a conducting plasma channel connecting anode and cathode. This hypothesis is experimentally verified by Townsend and the theory proposed thereafter is commonly known as Townsend Breakdown Phenomena.

3.1.3. Townsend's primary Ionization

Assuming n_0 electrons are emitted from the cathode and when one electron collides with a neutral particle, a positive atom and an electron is formed. This is called an ionization collision. Let α be the average number of ionizing collisions made by an electron per unit length of travel in the direction of the field. α is called **Townsend's first ionization coefficient or primary ionization coefficient**. Hence, we can write,

$$\frac{dn}{dx} = \alpha n \qquad (3.2)$$

[i.e. number of electrons produced due to ionizing collisions is proportional to number of already accelerating electrons],

$$\text{Or, } n = n_0 e^{\alpha x} \qquad (3.3)$$

Therefore the average current in the gap, which is equal to the charge traveling per unit time, will be,

$$I = I_0 e^{\alpha x} \qquad (3.4)$$

However, this theory implies that any electric field however small is capable of creating an avalanche current or breakdown. But in practice it is not true. To explain this paradox Townsend's second coefficient is required.

3.1.4. Townsend's Secondary Ionization

Townsend further proposed that, the assumption that initial electrons at cathode may not be all from natural sources of from field emission. It is suggested that positive ions being created during chain reaction will accelerate towards cathode and will further generate electrons by bombarding cathode surface. These electrons are mainly of three types.

i) Positive ions will impinge on the cathode surface to liberate electrons from cathode surface.

ii) Photons emitted during primary collisions will reach cathode surface and ionize neutral molecules near cathode and emit electrons

iii) The metastable particles may initiate electron emission.

- Number of electron released from cathode due to natural radiation = n_0
- Number of electron released from cathode due to secondary ionization = n+
- Number of electrons at x distance from cathode $n = (n_0 + n_+)\, e^{\alpha x}$
- Number of positive ion generated ion the gas medium = $n - (n_0 + n_+)$
- Number of electron produced by positive ion bombardment = $n_+ = \gamma[n - (n_0 + n_+)]$

  γ = Townsends second ionization coefficient

$$n_+ = \gamma(n-n_0)/(1+\gamma) \tag{3.5}$$

Hence, we can write

$$n = (n_0 + n_+)\, e^{\alpha x} = [n_0 + \gamma(n-n_0)/(1+\gamma)]\, e^{\alpha x} \tag{3.6}$$

$$n = n_0\, e^{\alpha x}/[1-\gamma(e^{\alpha x}-1)] \tag{3.7}$$

$$I = I_0\, e^{\alpha d}/[1-\gamma(e^{\alpha d}-1)] \tag{3.8}$$

- d = gap between anode and cathode

$$\gamma = \gamma_1 + \gamma_2 + \gamma_3$$

γ_1 = secondary electron produced by ions

γ_2 = secondary electron produced by photon

γ_3= secondary electron produced by ions

Townsend's Criterion for Breakdown

- $I = I_0 e^{\alpha d}/[1-\gamma(e^{\alpha d}-1)]$
- If $\gamma(e^{\alpha d}-1) = 1$, we get infinite current or avalanche.

$$\gamma e^{\alpha d} \approx 1 \tag{3.9}$$

3.1.5. Breakdown in Electronegative Gases

Electronegative gases, if used as insulating medium, show some special behavior of extremely high voltage withstanding capability. This is attributed to the electronegative nature of the gas molecule. Gases like Freon, Sulphar-hexafloride etc. contain Fluorine atoms. Fluorine is an extremely high electronegative element and has high affinity for electrons. As a result of which, whenever free electrons are created in the gas medium, they are adhered to the gas molecules. Gas molecules are much heavier compared to electron and have less mobility. As a result of which collisions with neutral molecule is less frequent and probability of multiplication of electrons by chain reaction is pretty low. This results in very high voltage withstand capability in electronegative gases.

3.1.6. Paschen's Law

Paschen's law explains the relationship between the Break Down voltage and the product of pressure (p) and gap (d), in the case of Breakdown in gas. If the process of Breakdown is keenly observed, it can be noticed that, energy of the accelerated electrons while colliding with a neutral atom, plays a very crucial role. Energy of an accelerated electron depends on the distance it has travelled before facing a neutral atom in its path, under the influence of externally applied electric field. The statistical probability of finding a neutral atom for collision is function of gas pressure and usually represented as mean free path. With increase in gas pressure mean free path length reduces and so reduces the energy of accelerating electrons before they collide with a neutral atom. So, in high pressure gas medium, at the moment of collision, electrons have lesser energy than required to ionize the neutral atom and hence sustaining chain ionization and electron multiplication becomes difficult. Again, in a medium with very low pressure, presences of neutral molecules are so sparse, that events of collision are rare. Thus chain ionization and electron multiplication becomes difficult even if electrons have sufficient energy to ionize neutral molecules. Probability of collision ionization, which is represented by α, therefore is a nonlinear function of gas pressure and represented by Eq. (3.10). Coefficient A & B depends on multiple factors and usually determined experimentally.

$$\alpha/p = Ae^{-Bp/E} \quad \text{or,} \quad \alpha = Ape^{-Bp/E} \tag{3.10}$$

if, $\gamma(e^{\alpha d}-1) = 1$ [Townsends criteria for breakdown]

$$e^{\alpha d} = 1+1/\gamma \tag{3.11}$$

$$\text{or, } \alpha d = \ln(1+1/\gamma) = K$$

$$\text{or, } Apde^{-Bp/E} = K \tag{3.12}$$

$$\text{or, } Apde^{-Bpd/V} = K \tag{3.13}$$

$$\text{or, } e^{-Bpd/V} = K/Apd \tag{3.14}$$

$$\text{or, } V/Bpd = \ln(Apd/K) \quad \text{or, } V = Bpd/\ln(Apd/K) \tag{3.15}$$

While plotted, this V vs pd curve is called Paschen curve.

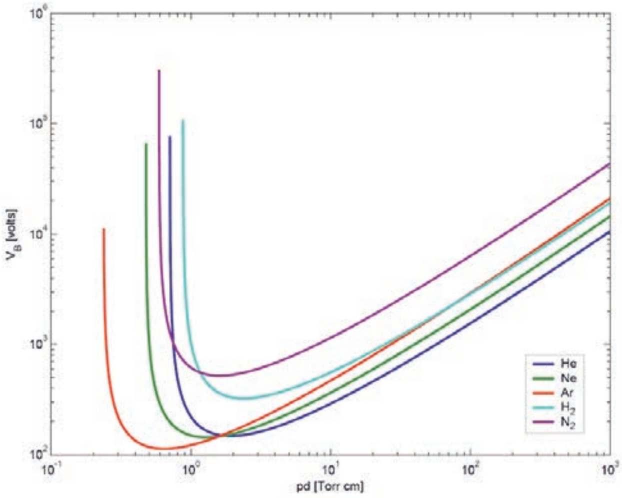

Figure 3.1. Paschen curve of different gas dielectrics.

3.1.7. Time Lags for Breakdown

As Townsend breakdown phenomena suggests, breakdown process is involved with two main physical phenomenons. First one is availability of free electron to initiate chain multiplication and the second one is the chain multiplication process itself. Once high voltage, sufficient to create breakdown, is applied across two electrodes, these two phenomena starts occurring before actual breakdown takes place. Availability of initiating free electron depends on multiple ambiance parameters and probability of finding it in the most convenient position is a statistical phenomenon. This time lag varies from experiment to experiment statistically and popularly known as Statistical Time Lag (T_s). Once initiating free electron is available at suitable position, it starts acceleration, collision followed by multiplication of electrons and ions. This process of multiplication of electrons and formation of plasma channel across anode and cathode takes some finite time. This time is known as Formative Time Lag (T_f). Total delay between application of high voltage and breakdown between electrodes is summation of statistical time lag and formative time lag, known as Time lag ($T = T_s + T_f$).

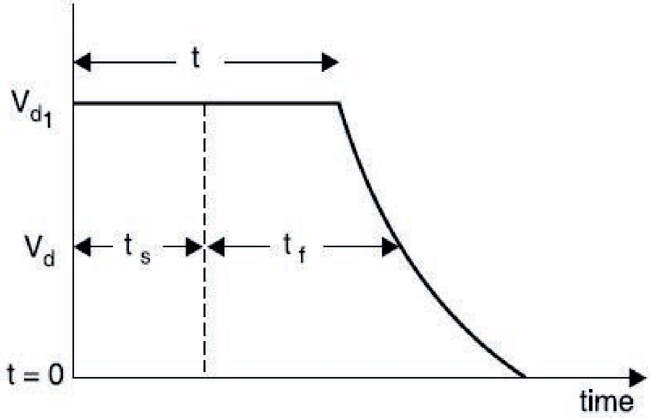

Figure 3.2. Picture depicting Statistical time lag & Formative time lag.

3.1.8. Limitations of Townsend Theory

(i) Fails to explain the formative time lag of breakdown. Analytically calculated time of sequential collisions and chain ionization process is much higher than experimentally obtained breakdown time.

(ii) Fails to explain the effect of space charge. Due to presence of high electric field, localized space charges are formed inside the gas volume. However, Townsend model doesn't consider effects of space charge in its estimation.

3.1.9. Streamer Theory of Breakdown in Gases

This theory predicts the development of a spark discharge directly from a single avalanche in which the space charge developed by the avalanche itself is said to transform the avalanche into a plasma steamer. Due to presence of high electric field in the gas medium, localized polarization of gas molecules takes place. This creates distortion in the uniform electric field and localized enhancement of the electric field. Such field enhancement further initiates localized ionization. Such formation of localized conglomeration of ions electrons and neutral particles are known as avalanche. It is possible to form multiple avalanches in a medium while high electric field is applied with. Lights emitted from one avalanche, initiates ionization at little far off position in the medium much faster. This is because of the fact that light travels much faster than electrons in gas medium. Formation of multiple avalanches within very short span of time and progression of avalanches towards anode and cathode forms channels of plasma in the gas medium known as streamer or kanal. As soon as a single kanal connects anode and cathode whole energy is discharged through it creating breakdown of the gas medium.

3.1.10. Corona

In non-uniform geometry, the increase in voltage will cause low current discharge with the production of hissing noise at points with high electric field intensity. This is caused due to localized field intensification and associated ionization. Due to ionization of neighboring gas medium, a sheath of plasma is formed over the metallic part and commonly known as corona discharge. Usually such ionization process emits blue lights with a hissing sound. Nascent oxygen is produced due to corona often reacts with atmospheric oxygen to generate ozone.

An important point in connection with corona is that, it is accompanied by a loss of power. The current waveform is non-sinusoidal and contains high frequency harmonics. These high frequency current harmonics causes radio interference in the nearby communication systems. The power loss during corona discharge leads to deterioration of insulation due to combined action of the bombardment of ions and of the chemical compounds formed during discharges.

3.2. Breakdown in Liquid Dielectrics

Liquid dielectrics are most commonly used for multipurpose design requirements in High Voltage systems. As for example, in transformer mineral oils are used as insulating mediums. This mineral oil also acts as a cooling agent and carries the heat from thermal hot spots (mainly windings of the transformer) to fins of heat exchanger. Thus it helps in cooling the transformer during operation along with providing sufficient insulation to it. In energy storage capacitors, use of oil impregnated paper is prevalent worldwide. In this case solid paper is used as main insulator, but impregnation of oil ensures no cavity is left inside the layers of paper. Thus insulation coordination is well maintained and high voltage performances of the capacitors improve drastically. Among other liquid dielectrics there are Ethylene, DI water etc. which have very high relative permittivity of 37 & 80. They are commonly used to develop compact pulse forming lines for high voltage pulsed power applications.

Though very useful, liquid dielectrics are extremely sensitive to impurities and its behavior under high voltage is predominantly decided by impurities present. Among these impurities moisture, dust particles etc. are predominant. Presence of even 0.01% of moisture in mineral oil reduces its breakdown strength drastically. This much moisture oil absorbs from atmosphere itself. Hence, mineral oil for high voltage application must be stored in sealed container and preferably needs to be heated and degassed while employed in applications. Dust particles present in air get settled in liquid dielectric very easily. These dust particles are mostly silica fragments and having relative permittivity extremely high compared to that of oil. As a result of which, if dust present in oil, they have tendency to create localized high field zones and initiate high voltage breakdown. Most of the mineral oils are different types of hydrocarbons and while subjected to high voltage discharges, they generate carbon particles as well as dissolved gases. These gas bubbles play significant role in initiating high voltage breakdown in oil or other similar liquid dielectrics. Carbon particles produced due to arcing impure the liquid, form sludges and deteriorate high voltage performance of liquid dielectrics. From analysis point of view, it is extremely difficult to estimate purity of liquid dielectrics and effect of very small quantity of impurities. Hence, no credible mathematical model of liquid dielectric breakdown is available. However certain hypotheses are proposed for explaining breakdown phenomena of liquid dielectrics. In practice, either one of them or more than one of them simultaneously play role in high voltage breakdown of liquid dielectric. Following are the most important mechanisms of liquid dielectric breakdown.

a) Electronic breakdown

b) Suspended solid particle mechanism

c) Cavity breakdown

d) Electro-convection breakdown

3.2.1. Electronic breakdown

This process is similar to breakdown in gaseous dielectric. Free electrons present inside the liquid volume gets accelerated upon application of electric field and gathers energy. These accelerated electrons collide with neutral molecules. If energy of the accelerated electrons is sufficiently high, neutral molecules dissociate in positive ions and electrons. This process repeats and multiplies the number of electrons and ions in a chain of reactions. These newly produced electrons and ions form plasma channel connecting anode and cathode initiating total breakdown.

3.2.2. Suspended Particle Theory

Suspended particle theory suggests solid impurities present in the form of dust particles etc. initiate breakdown in the liquid. These solid impurities usually have relative permittivity higher than that of liquid. Hence these particles experience a Coulombic force as per following equation.

$$F = r^3 E(dE/dx) \tag{3.16}$$

As the equation suggests force, will be zero where E is maximum i.e. along the central line of the electrodes. This means, solid particles suspended in liquid dielectric will move towards maximum filed position and align so as to connect cathode to anode bit by bit. This chain of dust particles connecting electrodes become the weakest link in the high voltage and initiates breakdown along it.

3.2.3. Cavitations and the Bubble Theory

Cavitations and bubble theory explains breakdown in liquid dielectrics due to presence of gaseous bubble or cavity inside liquid volume. Usually most of the gaseous medium exhibits relative permittivity of 1. Liquid dielectrics have relative permittivity of more than one. As a result of which electric field intensifies inside the small volume of gaseous cavities or bubbles. If the field inside the bubble is so high that it breaches the breakdown strength of the particular gas inside, breakdown takes place inside the bubble. This breakdown gives rise to ion, electron and charged particle inside the liquid volume and thereby triggers breakdown across the liquid volume. This phenomenon is prevalent in case the liquid has tendency to adsorb gases or dissolve gases. As for example, water naturally dissolves lot of gases from atmosphere, hence while being used as insulator in high voltage applications, it is mandatory to use bubble remover system to avoid presence of bubbles inside the liquid volume.

3.2.4. Electro-convection Theory

Insulating liquid dielectrics, when subjected to high field stress conducts current through charge carrying particles. These charge carriers are injected usually from cathode and form space charge volumes inside the liquid. These localized charge centers attracts each other due to columbic forces and creates convection current in the liquid medium. As the voltage increases, convection movements become turbulent and create instability. Upon application of voltage beyond a limit, current across the electrodes increase drastically with onset of a breakdown. However, the amplitude of the critical voltage limit varies with multiple physical and chemical parameters and extremely difficult to mathematically model or estimate analytically. This mechanism of breakdown in liquid dielectric is known as stressed liquid theory or Electro-convection theory.

3.3. Breakdown in Solid Dielectrics

Solid dielectrics are excellent insulators compared to its gaseous and liquid counter parts. Voltage withstand capability of solid dielectrics are way more compared to others. This is fundamentally due to the fact that electrons in a solid insulator lattice are strongly bonded and very difficult to dissociate or break free to form a conduction path. However, when subjected to extreme high electric field of about 15 MV/cm accelerating electrons do get sufficiently energetic to break free lattice structures and multiply electrons. So, beyond such high field catastrophic break down of solid dielectrics do take place. However, rather than such intrinsic breakdown, surfaces of solid is of more concern from high voltage point of view. Surface of solid insulators contains lot of impurities like dust particles, moisture etc. On application of certain high electric field, electrons jump along the surface and reach anode from cathode forming a conducting path. Impurities on the surface assist the process by helping in electron multiplication phenomena. Roughness of the insulator surface also helps the cause by adhering more impurities. So, it is always advisable to use solid dielectrics with extremely smooth surface finish and the surfaces must be cleaned with best possible engineering practices to avoid unwanted surface breakdown.

A rare but catastrophic solid insulation failure takes place while they are subjected to extremely high electric field is due to Columbic force. When a solid insulator is subjected to high electric stress, electrodes across the dielectric experience very high electrostatic Columbic attractive force. This force reflects on the insulator as a compressive stress. Certain solid insulators i.e. Perspex, ceramic etc. have very low elasticity limits. While subjected to extreme compressive stress, crack is generated through and through in these insulators and these crack becomes weakest link between electrodes. Current path is developed along the crack creating breakdown and failure of the insulating material.

Intrinsic and electromechanical failure of solid dielectrics is extremely short term phenomena in time scale and requires very high voltage to cause failure. Whereas on application of comparatively lower voltage for longer time, treeing and tracking structures are formed on the solid dielectrics. These are due to motion of free electrons from cathode to anode finding small weaker section in the crystal structure. However these free electrons do not reach anode very first time, but further weak portion is created in the solid lattice. On occurrence of such phenomena over longer period of time, finally a complete weak path is formed from cathode to anode causing failure of the solid dielectric. Tree formation structure or tracking marks in solid dielectric material is very common observation. This is signature of high voltage stress and indicates probability of failure in near future.

When an electric field is applied to a dielectric a small conduction current flows through the material. Due to this current dielectric gets heated up through Joule heating and temperature of the dielectric material increases locally. Here it must be noted that most of the solid dielectrics are bad conductor of heat, hence temperature increase in local volume will not be reflected at other parts of the material Most of the dielectric materials are having negative thermal coefficient of resistance. Hence, resistance of the insulator reduces with time increasing the leakage current. If this process continues for longer enough period of time, insulator deteriorates and at certain point of time breakdown takes place.

Chemical or electrochemical induced failures of solid dielectrics are slowest and occur over very long period of time i.e. few years. In these process atmospheric gases like oxygen, hydrogen sulphide, ammonia, carbon-di-oxide etc. along with moisture deteriorates solid dielectrics and its surface over the period of time. Deterioration of dielectrics is usually accelerated by application of electric field and formation of localized chemical cell inside or on the surface of the solid dielectric material. Such erosion over the period of time reaches its limit to initiate catastrophic failure.

In the following figure different types of breakdown of solid dielectrics are plotted against voltage and time of application. It can be observed that certain mechanism do require extreme high voltage but causes breakdown in a very small span of time, whereas some can occur on application of comparatively lesser field stress but needs persistent application of the same for very long period. It is the discretion of the designer to prioritize importance of failure modes in particular high voltage equipment based on its application and product life to select particular solid dielectric in its design.

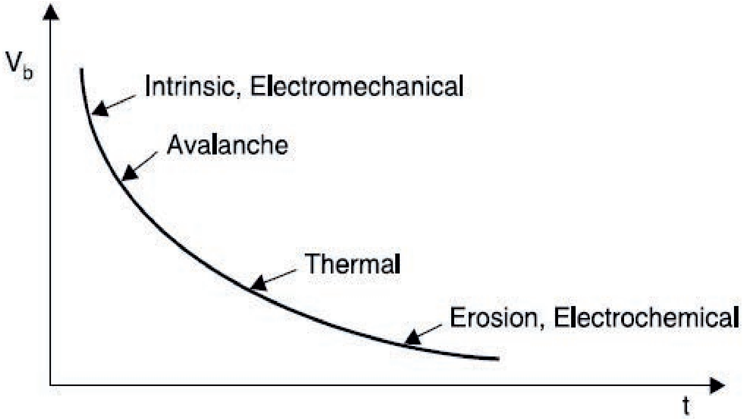

Figure 3.3. Voltage and time dependent breakdown characteristics of solid dielectrics.

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