Lecture # 5

Long-term Breakdown in Solids

Partial Discharges

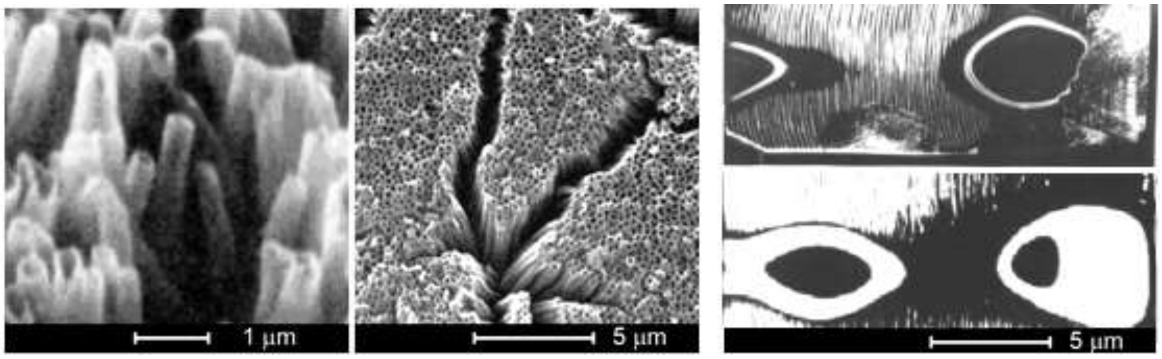
Discharges that are only confined to voids in the bulk of material are thus considered as a localized dielectric breakdown of a small portion of a solid or fluid under high voltage stress, which does not bridge the space between two conductors and are therefore termed as Partial Discharges (PD). PD within solid insulation system may not be visible and can occur in a gaseous or liquid medium filling the defects. In contrast a corona discharge is usually revealed by a relatively steady glow or brush discharge in air. PDs are localized tiny breakdowns occurring in voids or cavities present in the bulk solid dielectric, when the applied voltage exceeds a critical value. Partial discharges are responsible for the long-term breakdown of solid dielectrics.

Defects in Solid Dielectrics

Solid dielectrics contain some free electrons that are inherited to the material and are responsible for very small conduction current when voltage is applied. Besides solids contain discontinuities in the form of defects, which are:

1. Structural defects (due to non-homogeneous and anisotropic nature)
2. Manufacturing defects (lack of quality control)
3. Voids and cavities (due to trapped air during processing from molten state to room temperature)

Solid dielectrics, such as thermo-setting plastics are processed from molten state during manufacturing. During curing to room temperature, internal defects in the form of micro-cracks may develop. These micro-cracks are the consequences of differential thermal stresses at the interface of crystals or boundary between amorphous and crystalline regions in a semi-crystalline solid. Voids or cavities are one of the most common manufacturing induced defects; they indicate the presence of air. Fig (1) shows defects; structural, micro-cracks and voids in polymer. Although voids can originate from different sources, air entrapment is believed to be the primary cause of void formation. Voids are defects that form the potential locations for failure and cause discontinuity in the material properties. Voids are classified as harmful and harmless. Harmful voids are those, which can sustain electrical activity in the form of tiny or micro-discharges on the application of normal power frequency voltage that can be checked in the testing laboratory with a discharge detector. On the contrary those voids, which do not sustain any such discharges on the application of normal power frequency voltage, are referred to as harmless voids. Most testing laboratories rely on discharge magnitudes between 0.1 to about 1pC. But figure of 0.1pC is more reliable.



(a) (b) (c)

Figure 1: Material Defects: (a) Structural (b) Micro-cracks (c) Voids

Breakdown by Partial Discharges

PD activity often starts within gas or air-filled voids. Partial discharge activity is also initiated in mechanical defects such as micro-cracks, or inclusions within a solid dielectric. Cumulative PDs results in the slow "eating away" of the inside of a material, producing gradual erosion that can develop to a stage, eventually lead to breakdown of insulation.

The mechanism can be understood, if we start at a micro level by considering a void/cavity in a bulk dielectric subjected to voltage applied across a pair of electrodes as shown in Fig (2). When the electric field attains a critical value, PD activity starts within gas-filled voids. Because the dielectric constant of the gas, usually air present in a void is considerably less than the surrounding dielectric, the electric field across the void is significantly higher than within the solid dielectric. PD activity in voids transfer charges into the dielectric material thereby increasing conduction current and are accompanied by high temperatures, sufficient to cause localized heating or hot spots within the solid. The heat flow due to temperature gradient is slow because bulk dielectric surrounding the cavity is not a good heat conductor and therefore, the temperature inside the void or cavity does not subside quickly. This results in melting and vaporization of the material surrounding the discharge activity that is the walls of the cavity. The partial discharge activity is intermittent (occurs then cease and then re-occur).

The intermittent activity of PD can be explained as when the gas pressure inside the cavity increases due to high temperature according to the kinetic molecular theory. According to Paschen’s law, the discharges may cease due to high pressure built-up, since at high pressure higher voltages are required to cause breakdown. The gases formed as the by-product of discharges gradually escapes to the surroundings by diffusion through bulk solid.

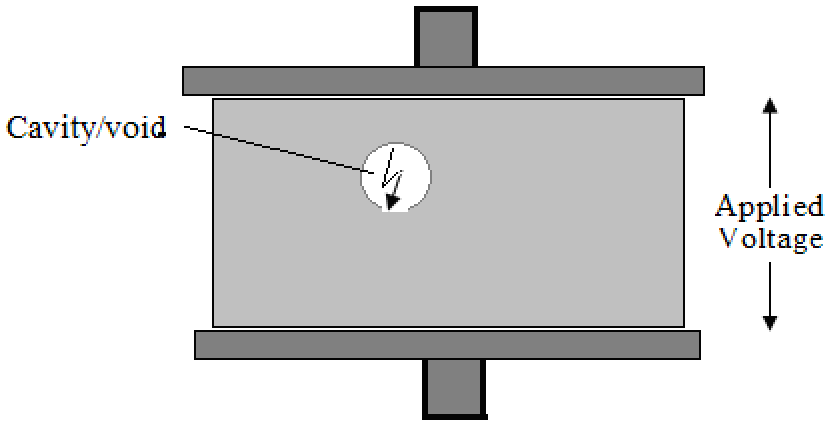


Figure 2: Partial Discharge in Void inside Bulk Dielectric

When the gas pressure gradually drops to a stage, the partial discharge activity is re-established. The PD activity is cyclic over the time of application of voltage. The PD activity in voids normally occurs at the peaks of applied AC voltage as illustrated in Fig (3). Once initiated, PD causes progressive erosion of cavity walls from inside, resulting in the enlargement of cavity thereby causing deterioration of insulating materials, ultimately leading to dielectric breakdown. This breakdown mechanism in majority of cases is slow, extending from few hours, days even to years. This type of breakdown mechanism is mainly responsible for insulation failure of cables, transmission line insulators, and transformer insulators etc. in which the electric stresses are much lower than the intrinsic strength of the solid. Since the process is slow, there may not be any notable difference on the performance of insulation during service.

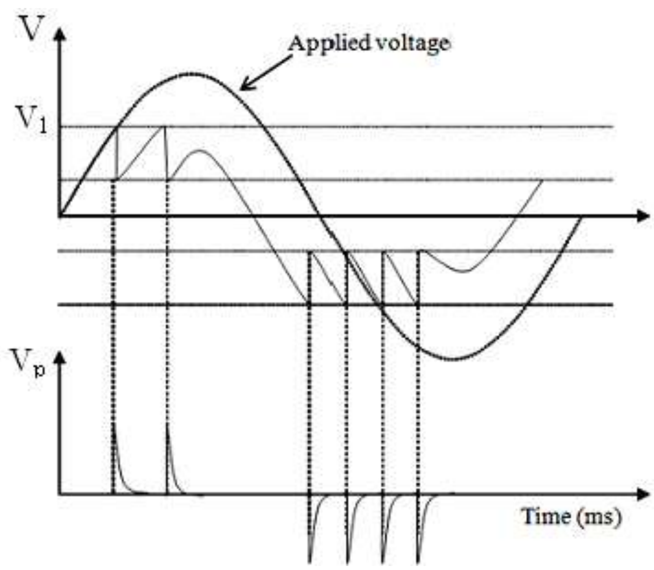


Figure 3: Illustration of Partial Discharge Activity

The effect of PD within high-voltage cables and other equipment can have very serious repercussions on the life of solid insulation. The cumulative effect of PD within solid dielectrics degrades its properties and the dielectric becomes weaker to withstand much of the electric field and the conductivity gradually increases. Repetitive discharge events cause irreversible mechanical and chemical deterioration of the insulating material. As PD activity progresses, the recurrent discharges eventually cause permanent changes within the dielectric. Over the time, partially conducting carbonized channels are formed. This places greater stress on the remaining insulation, leading to further growth of the damaged region, resistive heating along the channels, and results in further carbonization (sometimes called tracking). This eventually culminates in the complete dielectric failure of the cable and, typically, an “electrical explosion”.

PD can be prevented through careful design and material selection. In critical high voltage equipment, the reliability of the insulation is confirmed using PD detection equipment as a quality assurance test at the manufacturing industry as well as periodically through the equipment's useful life. PD in high-voltage electrical equipment should be monitored closely with early warning signals for inspection and maintenance in order to avoid inconvenience due to long power outages caused by breakdown.

Electrical Treeing

Treeing is an electrical pre-breakdown phenomenon. The name is given to the type of damage caused to the solid dielectrics by PDs, which progresses in the form of "microcrack-like" fissures or tubules structure to form network of random channels through certain regions of dielectric under electric stress in extremely non-uniform fields (typically point-plane electrode configuration in the laboratory). An image of an electrical tree completely bridging the gap between electrodes is shown in Fig (4).

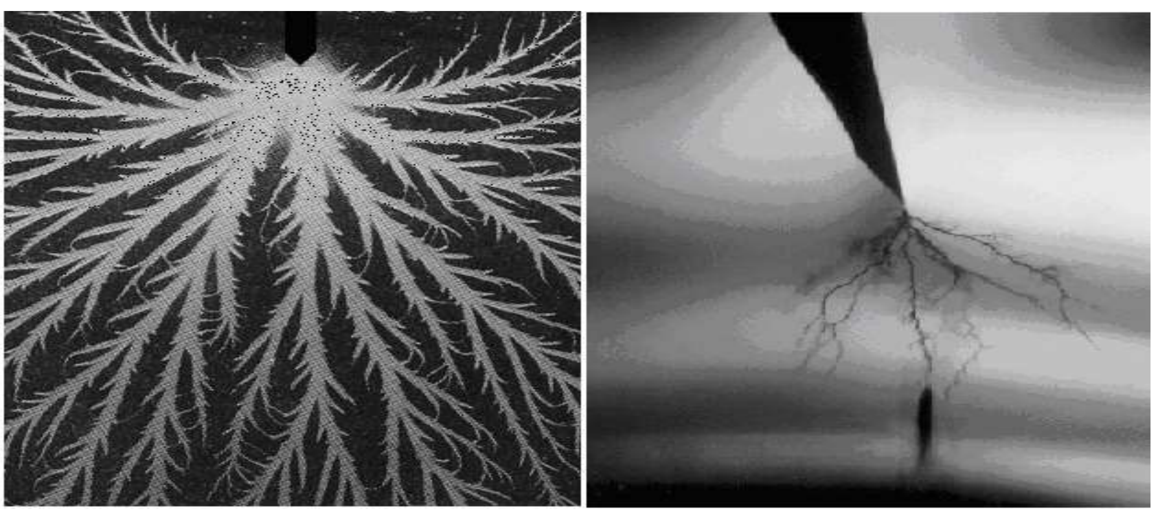


Figure 4: (a) Positive Lichtenberg Figure (b) Electrical Tree

The path of its growth appears like a miniaturized botanical tree originating from sharp electrodes, hence the name electrical tree is given and the phenomenon is referred to as electrical treeing or simply treeing. Electrical treeing is a major cause of failure in underground power cables. Treeing is responsible for long-term failure in buried polymer-insulated high-voltage cables. Following these tree-like figures in the insulation during investigation of the failed or broken down insulation can be most useful in finding the cause of breakdown. An experienced High-voltage engineer can see from the direction and the type of trees and their branches where the primary cause of the breakdown was situated and possibly find the cause. Broken-down transformers, high-voltage cables, bushings and other equipment can usefully be investigated in this way; the insulation is unrolled (in the case of paper insulation) or sliced in thin slices (in the case of solid insulations), the results are sketched and photographed and form a useful archive of the breakdown process.

The mechanism of electrical treeing that leads to breakdown, in simple manner can be explained as follows: Partial discharges in void inject charges which are trapped at various sites around the channel walls. The discharge is due to the ionization process which contains liberated electrons and positive ions. Due to their relatively larger size and being bulky, the positive charged ions remain but the electrons penetrate through the material and get trapped in the micro-defects such as cracks and voids. Thus there are strong forces of attraction along the very minute length between the source void containing the positive charge and the traps sites containing negatively charged electrons. The miniaturized breakdown resulting from forces of attraction between these trapped charges and those already deposited on the walls of the source cavity to cause the existing cavity to elongate or to form additional branches or side channels. The cumulative discharge activity enhances the electrical stress, and speeds up the discharge process leading to progressive propagation of miniature breakdown paths in the form of tree. Over a period of time, a partially carbonized, tree-like figure is formed within the dielectric. The formation of Townsend-type discharges during tree inception and propagation alters the shape of the tree formed. Finally the tree can grow to the point that it eventually causes complete electrical failure of the dielectric.

Types of Electrical Trees

Types of electrical tree can be identified on the basis of different pattern or structure they possess. A variety of tree structures can form from a potential site depending on the type of discontinuity and applied voltage in cable insulation that is: bush-type trees, branch-type, strings, fibular type, spike, dendrite type, fan, plume, delta, broccoli and bow-tie type. Electrical trees are also categorized depending on either vented or non-vented and depending, whether the type of gas is present. Typically, the tree which starts at the surface of the dielectric exposed to air are vented trees, whereas, those that initiates inside the dielectric, not exposed to ambient air are non-vented trees as shown in Fig (5). These trees have discontinuous growth, which is why the non-vented trees usually do not grow long enough to fully bridge the entire insulation between the electrodes, therefore causing less chances of failure of the insulation. Vented trees initiate at electrode insulation interface and grow towards the opposite electrode. Having access to free-air, these trees are able to grow continuously until they are long enough to bridge the electrodes, therefore causing failure of the insulation. Bow-tie trees are those, which start to grow from within the dielectric insulation and grow symmetrically outwards from the electrodes and are mostly non-vented.

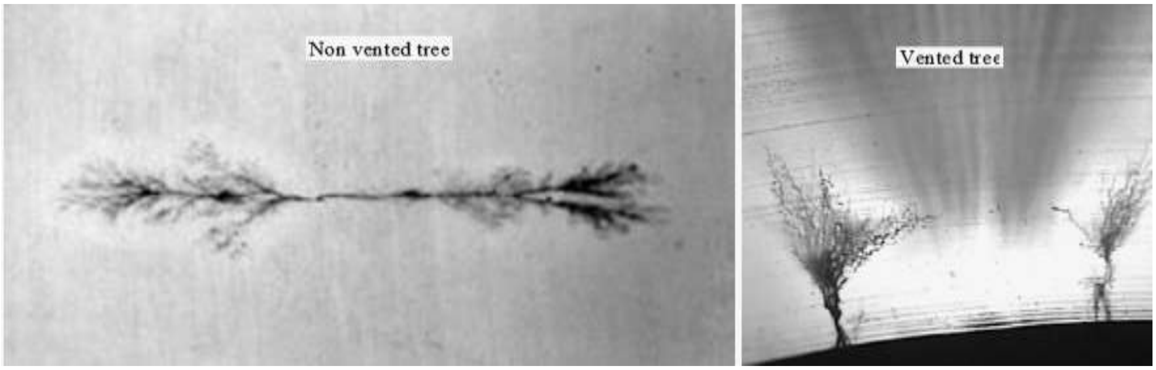


Figure 5: Non-vented and Vented Trees

Furthermore, cables are buried in different soil environment which may contain certain chemicals; constituting of sulphur, chromium, ferrous compounds, salts and minerals etc. Thus trees may be referred to as sulphide trees due to the presence of sulphur compounds and chromium trees in the presence of chromium compounds. In a transparent dielectric, these can also be identified by their distinct color, for example, orange-yellow color of sulphide trees and blue-green for chromium trees.

While treeing is generally associated with AC and impulse voltages, it also takes place under high DC stresses. The whole process may or may not take long time since it strongly depends upon the local conditions. Treeing develops rapidly when an impulse voltage is applied.