Investigation into Partial Discharge Dependence in Air Gaps between High Density Polyethylene Tapes

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Abstract: The amount of literature on partial discharge (PD) and partial discharge induced degradation is vast. It has been shown that in the past 10 – 20 years significant progress has been made on aging of dielectrics due to internal partial discharges. The combined effect of temperature and PD has been shown to lead to synergistic effects in some cases but there still are contradictory opinions on the nature of this interaction. The complex relation between space charge and partial discharge has been the topic of very few studies. Focusing on internal partial discharge in solid polymeric insulation we try to contribute in these topics. Partial discharges occurring in an air-filled gap between two adjacent high density polyethylene slabs are experimentally investigated. Measurements are performed at different temperatures ranging from 10°C to 85°C and for different relative humidity level ranging from 20 to 70%. The influence of environmental parameters on PDIV, PD phase distribution and numbers is studied. Regarding the relation between space charge and stress conditions, partial discharges phenomena due to this factor are investigated, showing both simulation and experimental evidences of relation between voltage thresholds of partial discharges and electrical stress conditions associated with charge accumulation.

Keywords: high density polyethylene, cavity, space charge, temperature, relative humidity, partial discharge.

1. INTRODUCTION

By controlling processing techniques, void size and quantity in dielectric materials may be minimized but not suppressed. On the other hand, if a cavity does not exist it may be induced due to thermal, mechanical or electrical stresses. The latter case may correspond to a local field enhancement due to accumulation of space charges. Further more such microvoids grow in size and quantity at temperatures approaching the material's maximum service temperature. These microvoids give rise to a large variety of physical phenomena responsible of lower partial discharge inception voltage and lower breakdown strength. Further more, electrical overstressing caused by these defects is, to a large degree, controlled by similar physical processes and contributes to the degradation of the insulation and else lead to breakdown.

PDs process depends on many factors such as the size and the shape of the void, its surface properties, the nature and the pressure of the gas trapped in, the amount of charges on the cavity walls, the statistical time lag and of course the dielectric constant of the surrounding. Numerous paper deal with PDs phenomena and their corresponding patterns [1,2].

In this paper experimental results about PD activity in an embedded void in polyethylene samples are presented. The influence of environmental parameters (temperature and relative humidity) on PDs will be analyzed. In the other hand, in order to better understand the influence of space charge on PDs inception voltage a space
charge has been created on one side of the cavity realized in HDPE model samples. A quantitative analysis of the electric field distribution in the material and within cavity has been realized and PD-activity study has been experimentally investigated.

2. INSULATING MATERIALS CONTAINING CAVITIES

Important efforts were made to manufacture insulation with a minimum of defects. However, in 1975 Kageyama et al. [3] counted $10^6$ cavities/mm$^3$ ranging from 1 to 5 µm, about ten years later Ball et al. [4] published that the normal manufacturing cooling process for dry-cured XLPE cables led to a density of $10^3$ to $10^7$ cavities/mm$^3$ in the same size range.

Previous research results have allowed successful cavity detection and imaging. Electric insulation cavity size and density information may be established via optical microscope, conventional ultrasound (200 kHz to 10 MHz), Scanning Acoustic Microscopy (SAM) (10 MHz to 1 GHz) or scanning electron microscope (SEM) [5, 6].

Cavities in insulator will grow in size and the cavity density will increase as a function of energy absorption (heat, radiation dose, electrical field induced stress, temperature, etc...). The result is that the net or equivalent amount of insulation between the separated conductors decreases. [7]

3. SPACE CHARGE IN INSULATING MATERIAL

Dielectrics are rarely homogeneous at microscopic level. They may be considered as a composite of amorphous and crystalline regions. Ieda [8] has shown that the interface between amorphous and crystalline regions is host to hopping sites of the order of 0.3 to 0.4eV. In general, the conductivity of amorphous and crystalline regions will differ, as will that of the interface region between them. Of course the electric field distribution will be moderated by the field-dependent conductivity of all the regions in series. Thus, the microscopic inhomogeneity of the conductivity should give rise to substantial space charge at microscopic level. The other issue is that space charge on a nanoscopic scale is distributed around inhomogeneities, which are usually distributed randomly in three dimensions in such a way that the effects of nanoscopic space charge are likely to average out to a large degree in determining the local electric field [9].

Space charge formation is a major issue for DC systems, but most high voltage systems in electrical engineering operate under AC, not DC. However recent works [10-14] demonstrated the presence of space charges in polymeric cable insulation materials under ac conditions. Under AC excitation, space charge tends to be less an issue, except around microscopic stress enhancements where space charge oscillates during each half AC cycle, resulting in hot electrons and photon emission from carrier recombination, both of which degrade the dielectric. Such phenomena can only occur within microscopic geometries, as the power density would cause thermal runaway in a macroscopic volume. In [15] space charge in PE after ac ageing at 50 Hz has been investigated.

![Fig. 1. Relationship between the total charge and ageing time at 50 kV/mm [15].](image)

4. PARTIAL DISCHARGE

The electric potential for which a partial discharge initiates corresponds, by definition, to the threshold voltage of gas breakdown.
According to the law of Paschen, two factors are dominating, the first is the density of the particles in gas volume; it is expressed overall by the pressure \( p \). The second factor is the channels length in which the avalanche must traverse; it corresponds to the distance between electrodes \( d \) (mm).

Discharges within cavities (voids) in solid insulating systems have long been associated with gradual degradation and eventual dielectric failure. Studies by the C. Laurent and C. Mayoux [16, 17] among others have shown that gas-filled cavities can originate in a wide range of solid dielectric systems through many mechanisms including differential thermal expansion, incomplete impregnation or excessive mechanical stress, or improper process control. Progressive deterioration caused by discharges in gas filled cavities has long been known to be a major factor limiting the life of insulators. [18]

4.1. **Space charge and partial discharge**

Partial discharge and space charge are closely related; one affects the other. Charges trapped in shallow trapping sites at the boundary between dielectric and cavity serve as initiatory electrons. These charges may have been deposited by earlier PD events but they can also be the result of charge transport from the electrodes towards the cavity. The nature of these trapping sites is not quite clear; i.e. the trap depth and trap density can be estimated [8, 19, 20] but to the authors’ knowledge estimations have never been verified by experiment. In order to understand and describe why and how the PD mechanism changes as a result of the cavity aging. Measuring the trap distribution is a challenging task. Moreover, the properties of the cavity surface change as a result of PD activity. Last but not least, the PDs also act as a source of charge injection into the dielectric. Part of the charge involved in the discharge process is trapped at the cavity surface and part of the charge migrates deeper into the dielectric. Very little literature [20] is available on measurements of space charge injected by discharging cavities. It would therefore be of great interest to study simultaneously the PD activity in a cavity and the space charge profile in the dielectric. The results of such a study could give some idea on the relation between PD and breakdown.

4.2. **Temperature and partial discharges**

The temperature has a direct impact on partial discharges or more precisely on the induced aging which may be associated to the acceleration of chemical processes. Gmez-Garcia et al [21] studied the modification of XLPE exposed to PD at temperatures up to 160°C using an air gap of 50 µm. A change in the nature of the reaction products at the gap surface was observed but more importantly, enhanced bulk and surface oxidation increased with the temperature. Infrared spectroscopy was used to monitor the carbonyl band at 1715 cm\(^{-1}\). The carbonyl concentration increases monotonically with temperature, with a sharp rise between 80 and 100°C. Figure 2 shows a plot corresponding to 12 h of PD exposure in which three different temperature regimes can be identified.

![Fig. 2. Carbonyl band (1715 cm\(^{-1}\)) absorbance vs. temperature (A and B) after 12 h of PD exposure. The dashed curve represents the volume expansion of XLPE [21].](image)

Hence, one of the main effects of temperature is the permeation of oxidizing species into the bulk of the polyethylene. Gjærde [22-23] studied the combined effect
of PD and temperature up to 80°C in a 0.125 mm air gap in epoxy. A change in the nature of the PD by-products was found as a function of temperature as it was observed in PE [21]. At 80°C (the glass transition temperature) the effect of PD was strongly reduced. It was attributed to the softening of epoxy: a part of the energy being dissipated by segmental movements of the polymer chains [24].

5. EXPERIMENTAL PROCEDURES

5.1. Sample under study

The geometrical characteristics of the studied sample are given in Figure 3.

![Fig. 3. Structure of the samples.](image)

The sample is composed of a 1mm-thick air gap dividing two 1 mm-thick slabs. These dimensions are calculated from Paschen's curves in order to reach the PDIV for an applied voltage of some kV. External removable grips ensure the attachment of the three slabs. Gold electrodes (thickness: 0.9µm and diameter: 30 mm) are deposited by sputtering on the opposite external sides.

5.2. Experimental Setup

Partial discharges activity is measured thanks to the experimental set up reported in figure 4.

![Fig. 4. Experimental set up for PD measurements under different climatic conditions.](image)

It is composed of a 30kV RMS transformer, a measuring cell equipped with cylindrical electrodes and a detection system (Power Diagnostics System). The pulses associated to the discharges are plotted in a three dimensions map. A special care was taken to reduce external noise, corona effects and flashover. A filter was used to reduce the noise originated from the HV transformer. Screened cell was used to avoid any electromagnetic interference. HV connections were made by using corona-free HV cables.

A climatic chamber (model VÖTSCH - VC 7018 range of temperature and moisture: -70 to 180 °C/20 to 98 %RH) was used to modify the climatic conditions.

In order to study the relation between partial discharge activities electrical stress conditions associated with charge accumulation, the same sample shown in figure 3 is used. Except in this time the air gap is 1mm-thick and a metallized layer is deposited inside sample higher part. As shown in figure 5, this configuration enables us to introduce a controlled charge quantity in

![Fig. 5. Configuration of the sample used to study the effect of space charge.](image)
the volume of the sample by applying a DC voltage through the metallized wall of the cavity. Then AC voltage of increasing magnitude is applied until PD is initiated.

In this case, partial discharges activity is measured using the experimental set up reported in Figure 6.

![Experimental set up including sample and PD detection system.](image)

**Fig. 6.** Experimental set up including sample and PD detection system.

**6. RESULTS AND DISCUSSION**

**6.1. Environmental conditions and PD**

Experimental results of PDIV and PDEV versus temperature and relative humidity are given in Figures 7 and 8. For a fixed relative humidity (RH) of 50% and for temperatures ranging from 10°C to 85°C, a decrease of both PDIV and PDEV is observed. Such behaviour may be associated to the gas density which increases with the temperature, leading to a decrease of the PDIV [2, 22].

If the temperature is fixed (T=25°C), and for a value of the relative humidity lower than around 35%, PDIV increases and then decreases beyond this value. As previously mentioned, the formation of water droplets on the walls of the cavity has to be taken into account to explain these results.

![PDIV and PDEV vs temperature](image)

**Fig. 7.** PDIV and PDEV vs temperature (RH=50%).

![PDIV and PDEV vs RH](image)

**Fig. 8.** PDIV and PDEV vs RH (T= 25°C.).

The increase in both DIV and DEV caused for the low RH values may be explained by an increase of the moisture content of the gas. Water vapour at this low level of RH could act like an electro-negative gas and thus could increase the dielectric strength of the atmospheric air. For higher RH values, the condensation of water and the formation of droplets on insulating surfaces could change the electrical field distribution thus leading to a DIV decrease.

**PD phase distribution, PD magnitude**

Partial discharges patterns (pulse shape, phase distribution, magnitude and number) are recorded for two different temperatures at
a constant RH (50%). Whatever the temperature, the signature is slightly dissymmetrical in the phase of the applied voltage. This dissymmetry may be due to space charge. The space charge produced by an earlier partial discharge reduced the local electric field. Under an alternating voltage, the polarity of the local field changes periodically.

The reduction of the local field for a polarity of the tension leads to an increase in the field on the opposite polarity. The next discharge, on the half wave of opposite polarity, appears with a weaker tension. The effect of the space charges will be the modification of the discharges amplitude and in addition the modification of phase angle.

Figure 9-a (T= 10°C) shows shape of the discharge distribution is relatively wide, with a high repetition rate and a high PD number.

Figure 9-b (T= 85 °C) shows the decrease of the PD repetition rate and the increase of the PD magnitude. A decreasing repetition rate with temperature may be explained by the increasing conductivity of the cavity wall, may be the result of the higher temperature and the PD deposited by-products. An increasing surface conductivity will lead to a reduced field in the air gap and consequently a reduced PD repetition rate. The increase of the PD magnitude with temperature could be explained by the larger area that is discharged [25].

6.2. Space charge and PD

Space charge and electric field distortion

Knowing that space charges in the material are usually distributed randomly in three dimensions. These charges may have been deposited by earlier PD events but they can also be the result of charge transport from the electrodes towards the cavity. For this reasons a bulk, containing a constant space charge amount, is introduced in different positions as it shown in the next figure.

Fig. 9. Influence of the temperature on the PD phase pattern and PD magnitude.

Fig. 10. Position of the charge density compared to the cavity position.

The effect of the distance, separating space charge and cavity, on the electric field distortion and using Comsol Multiphysics software is investigated; the numerical resolution of electric potential and electric filed distribution in material insulation and within the artificial cavity is achieved. Indeed figure 11 shows that distance has an important effect on electric field distortion. The electric field increase with the distance decreasing, a maximum of field is obviously reached for a charge density deposited directly on cavity side (distance equal to
zero); it increases by 70% compared to the case where there is no space charge.

Likewise, the next figure shows well that more and more the distance decreases more and more electric field is reinforced in the cavity, so partial discharges are more probable. It is the same for electric potential.

This result leads us to consider the case when a space charge of variable density is distributed on cavity surfaces. In the first time a controled DC voltage is applied to a part of the sample under study as it indicates in figure 5.

The higher metallized face of the cavity is connected to the ground, this enables us to polarize the sample and thereafter a surface density of charges electric is formed on the cavity walls. Figure 13 shows the results obtained per simulation proving that the deposited charge density increases when the applied DC voltage increases.

A quantitative analysis of electric field and electric potential distribution in the material and within the cavity is calculated. For increasing charge density, figure 14 shows well that electric potential is infected and reinforced within the cavity, so the potential difference in the cavity increases.
The electric field and electric potential within the cavity are calculated. Figure 15 is the proof that electric field magnitude is affected. It is the same for electric potential. These two electrical sizes increasing if space charge density increases.

**Partial discharge measurement**

PDs activity is investigated experimentally in order to show how the main PD characteristics are influenced by the field and potential distortion. For both case, presence and absence of charge density, the pulse shape, pulse phase distribution, PDs magnitude and PDs number are recorded. Discharges inception voltages are measured (voltage rising rate about 0.5kV/s). A sufficient number of measurements are realized in order to verify the reproducibility and to find an average value.

Preliminary measurements are made on virgin sample, free from any electrical treatment. In this case, partial discharges are detected for applied voltage equal approximately 5.5 kV, which corresponds well to a potential difference in the cavity about 2 kV. This value is in correspondence, according to Paschen curve, with the breakdown voltage of a 0.5 mm air interval.

Immediately after space charge creation, PD activity is recorded during the first 10s of polarization. Under such conditions, it may be considered that a part of the introduced space charge (which has been deposited on metallized cavity side) may affect the PD activity. In fact, as the next figure shows the space charge effect is undoubtedly to modify the pulse-height and pulse phase distributions, since they are no symmetrical, more there is no discharge in the opposite polarity. These changes are attributed to the surface cavity.

![Fig. 15. Electric filed distribution within the cavity as a function of charge density.](image1)

![Fig. 16. Partial discharge pattern with space charge.](image2)

When the polarity of the AC voltage is positive, space charge creates an additive field, thus the number of pulses becomes higher. On the contrary, during the negative polarity of the applied voltage, the charges create an opposite field so partial discharge appears with higher applied voltage. This charge effect can only be observed in the very first seconds of polarization. But when this space disappears, PD activity during the two polarity of the voltage must become symmetrical.

In order to validate experimental results, it is important to calculate by simulation PD threshold voltage by introducing the charge density values already calculated (figure 13). It was shown that in the charge density absence case and for our sample dimensions the potential difference in the cavity which will produce PD is about 2 kV. This value corresponds to an applied voltage equal to 5.5 kV. So taking account of this value which is maintained constant, and for various values of charge density, we calculated PD threshold voltage. Indeed figure 17 and 18 show that potential...
difference and electric field in the cavity are constant for different values from tensions applied and different charge density.

For increasing values of charge density and to have a potential difference equal to 2.1 kV and constant electric field equal to 4.2 kV/mm, it is necessary to apply a voltage more in more reduced. Further more, as shown in figure 19, the discharges inception voltage decreases from a value close to the one of a virgin sample when charge density increases.

The simulation results are in good agreement with the experimental one. The larger the space charges on the cavity the lower the PDIV. PD is strongly influenced by field modification due to space charge. However, space charges modify the field in the cavity; space charge field in the dielectric could be created and the field was reinforced, so partial discharges are more probable. In fact more and more the charge density increases more and more threshold voltage of PD ignition decreases.

7. CONCLUSION

PD which can occur in embedded voids in solid dielectrics depends upon many factors among them environmental conditions such as temperature and relative humidity. These parameters affect PD activity, especially the partial discharge inception voltage and the partial discharge extinction voltage. PDIV and PDEV decrease when the temperature increases. Such behaviour may be associated to the gas density which increases with the temperature, leading to a decrease of the PDIV; the statistical time lag it is expected to be larger for lower gas pressures and colder temperatures.

There are a proportional relationship between DIV and relative humidity respectively. One mechanism relates to the increase in DIV observed at lower humidity. We speculate that the increase in DIV is caused by an increase in the electric
breakdown strength. The other mechanism may relate to field enhancement effects occurring on the insulation surface as a result of moisture condensation. The most evident effect was reported to be the decrease of the PD repetition rate and the increase of the PD magnitude with temperature.

Space charges modify the field in the cavity; space charge field in the dielectric could be created and the field was consequently reinforced. Maximum of field is obviously reached for a charge density closer to the cavity, so partial discharges are more probable. Furthermore electric field is more reinforced for important values of charge density. According charge sign, charge creates an additive field, and contrary during the opposite polarity of the applied voltage, the charges create an opposite field. It was shown that the larger the space charge amount, the larger PDIV decreases. Both the numerical analysis and the experimental results show that PD is strongly influenced by field modification. Computation results by simulation are in good agreement with the experimental one.

Acknowledments

The present work was released in Laplace laboratory, Paul Sabatier University. The authors are particularly grateful to researchers and personal who have gone part of the way with him.

REFERENCES


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