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The Influence of Space Charge and Gas Pressure during Electrical Tree Initiation and Growth

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Abstract

The analysis of the **sequence of partial discharges** that occur during the growth of electrical trees shows that **local space charges** play an important role, especially at the early stage. In the space charge build-up, that occurs within the polymer as a consequence of the partial discharges a marked **polarity dependence** can be found. At the late stage of the tree growth this difference diminishes and the gas pressure in the tree channels is the decisive parameter.

Introduction

Over the past few years attempts have been made to use polymer insulated cables up to 400 or 500 kV. As a consequence there is a need to increase the working stress and thus the electrical treeing phenomenon has become a matter of interest again.

The **Pulse Sequence Analysis**, a new method to evaluate partial discharge signals [1-4], can be used to get a better insight into the physics of the treeing phenomena especially with regard to the influence of local space charges and their build-up and decrease over time. In this paper partial discharge signals from different stages of the electrical tree growth will be analyzed and their meaning with regard to the local microscopic phenomena inside the tree or in the vicinity of the tree tips will be discussed.

Experimental procedure

The experiments discussed in this paper were performed with low density polyethylene, in which needles of about **5 μm** tip-radius were molded in. The distance to the plane electrode was **2 mm**. The partial discharges were recorded with a digital storage oszilloscope and transferred to a PC for further analysis.

To initiate a tree the voltage was first increased without the data collecting system until the first discharges occurred and then switched off quickly. The tree inception voltage was about **20** and **28 kV$_{rms}$** for dry and wet polyethylene respectively.

For the acquisition of the data, the voltage was slowly increased, and the partial discharges during the first **100 cycles** after discharge inception were recorded. This procedure was repeated after different periods of constant voltage load, during which the tree increased in size. Typical values for the start of the discharges were about **8 kV**.

Occurrence of discharges

During the beginning of the electrical tree growth the discharges seem to occur at random if one only considers the voltages or the phase angles at which discharges occur. Looking at the data in more detail especially analyzing the **pulse sequences** and the **voltage changes** which occur before the next discharge, there is no erratic behaviour but a nearly predictable behaviour as shown in **Fig. 1**. In contrast to the apparently erratic voltage heights at which discharges occur, the corresponding voltage changes concentrate around two distinct values, and the positive voltage changes seem to be slightly higher than the corresponding negative ones. This characteristic sequence occurs in dry polyethylene as well as in wet polyethylene.

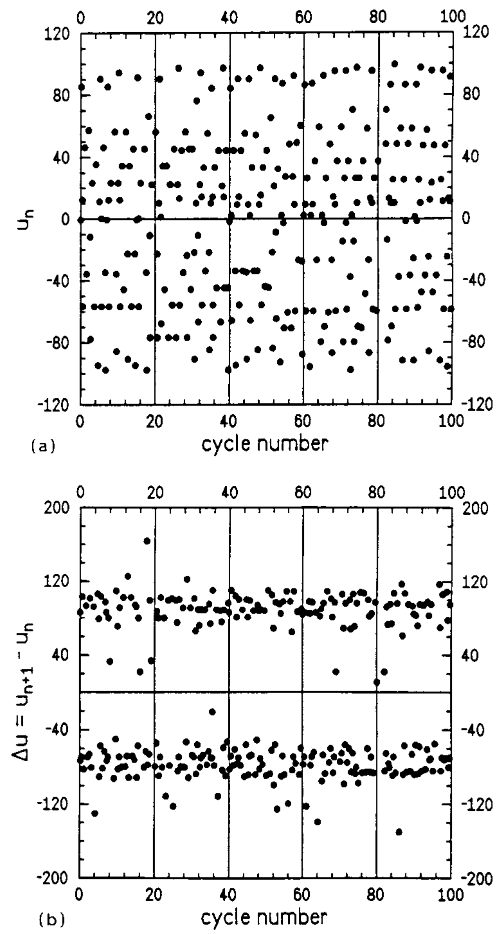

Fig. 1: Voltages (a) at which discharges occur and voltage changes (b) between consecutive discharges for 100 cycles (wet polyethylene, early stage of electrical tree growth)

In most cases there is only one discharge event per half cycle, and looking at the direct sequence in more detail (**Fig. 2**), the positive voltages at which the discharges occur increase from cycle to cycle, whereas the negative voltage levels decrease in a corresponding way. After four or five cycles the positive discharge occurs near the positive crest voltage followed by a discharge at nearly zero voltage or a small negative voltage, followed by a discharge near the negative crest voltage. After this, the **step by step increase of the positive voltages** and the step by step decrease of the negative voltages occurs again, until after another four or five cycles there is a reset again. This behaviour is characteristic of the early stage of the electrical tree growth, which is mainly determined by **solid state phenomena** within the polymer around the needle tip.

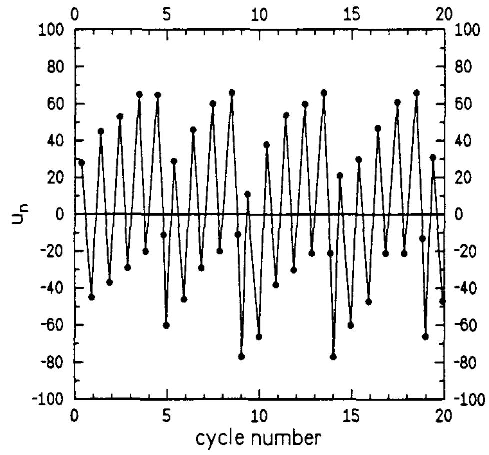

Fig. 2: Sequence of voltages at which discharges occur for 20 consecutive cycles (dry polyethylene, early stage of electrical tree growth)

Effect of space charges

A partial discharge, which is a locally confined electrical breakdown, occurs if the **local electric field** exceeds a critical value that depends on the polymer material. The externally measurable partial discharge signal is a result of an **avalanche of charge carriers** that starts in the critical field region and stops as it reaches regions with a lower electrical stress. In addition to this, the charge carriers of the avalanche in turn influence the local electric field.

According to the **Poisson equation** space charges influence the local electric field by superimposing an internal **DC**-field onto the externally applied **AC**-field. Thus the actual value of the **local electric field** within the specimen is determined by the external voltage, the geometric dimensions of the electrodes and **local space charges** within the electrode gap. As a consequence of these space charges, the highest local electric stresses in general will not occur at the highest values of the externally applied voltage. A unipolar space charge will reduce the local electric field for one polarity of the applied voltage and increase it for the other polarity. Hence a change in the voltages at which partial discharges occur provides some information on changes of the local space charges with time.

Space charge development

A positive space charge situated within the polymer near the needle tip reduces the local electric field during the positive half cycle.

As shown in **Fig. 2**, at the initial stage of the tree growth there is a characteristic **step by step increase of the positive voltages** at which discharges occur and a corresponding **decrease of the negative voltages**. This indicates a **step by step build-up of positive space charges** within the polymer or at the walls of the tree channels. The voltage changes between two discharges are approximately constant. Each discharge seems to compensate the local electric field that initiated the discharge, and the next discharge occurs due to the local electric field generated by the **external voltage change**.
The positive space charge is a result of positive discharge events by which electrons are extracted from the polymer by the needle tip.

After a certain number of cycles - and actually after a discharge at the positive crest voltage - the internal **DC**-field generated by the **positive space charges** is high enough to compensate the **AC**-field at the positive crest voltage. After the following decrease of the **AC**-field, the **DC**-field is unchanged and leads to a negative partial discharge at nearly no external voltage, by which electrons are injected from the needle tip into the polymer that compensate the positive space charge. In the following negative half cycle another negative discharge pulse follows, that produces a **negative space charge** and causes the next discharge in the positive half cycle to occur at a low external voltage.

If there were no space charges as a consequence of the partial discharges, the electric field due to the externally applied voltage would be the only decisive parameter and the voltages at which discharges occur should only vary, if - as a consequence of degradation processes within the polymer - the local electric field has changed, which is necessary for the ignition of a discharge.

In the case of a wet specimen at an intermediate stage of the tree growth the space charge build-up may also occur in the opposite direction. As can be seen from **Fig. 3(a)**, during the cycles 50 to 85 of the recorded data, the voltages at which the discharges occur show a tendency to lower magnitudes of the negative voltages as well as some periods later a tendency to higher negative voltages. Around cycle 50 there must be a **negative space charge** that is first compensated or overcompensated by a positive space charge (until cycle 70) and then restored again. Even in this complex situation the discharges occur exclusively after **characteristic voltage differences**. As shown in **Fig. 3(b)** there is a **grouping of the voltage changes** around three distinct values.

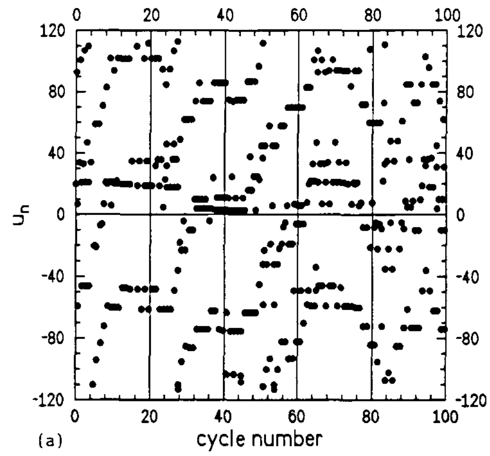

Fig. 3(a): Voltages at which discharges occur (wet polyethylene, intermediate stage of electrical tree growth)

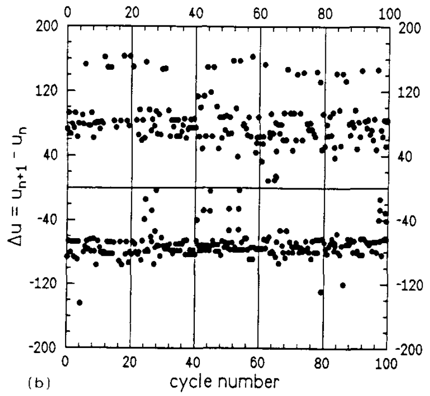

Fig. 3(b): Voltage changes between consecutive discharges (wet polyethylene, intermediate stage of electrical tree growth)

The analysis of the sequence of the voltages at which partial discharges occur shows that during tree growth there are periods of a few ten cycles of the applied voltage, in which a **'continuous' change of the space charges** within the polymer or at the walls of the tree channels occurs. From time to time **'pseudo stochastic' discharges** occur, which indicate a further step in the tree growth.

At the late stage of the tree growth the prevailing influence of space charges seems to disappear, at least there is no obvious drift of the external voltages at which discharges occur. Nevertheless the voltage changes tend to concentrate at three values with a comparatively small scatter (**Fig. 4**). At this stage the **gas pressure** determines the discharge activity, an equilibrium pressure may exist that does not suppress the discharges as discussed later.

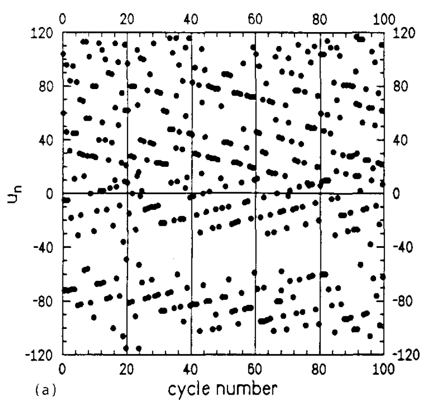

Fig. 4(a): Voltages at which discharges occur (wet polyethylene, late stage of electrical tree growth)

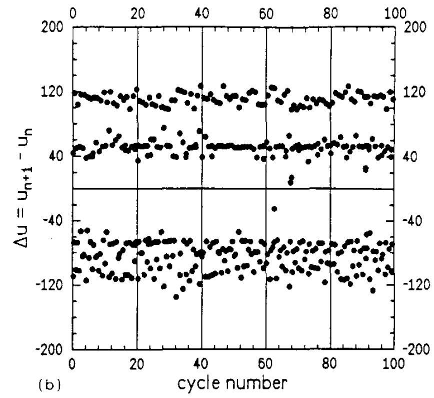

Fig. 4(b): Voltage changes between consecutive discharges (wet polyethylene, late stage of electrical tree growth)

Discharge frequency

At the initial stage of the electrical tree growth in general there is only **one discharge per half cycle** whereas at the later stage approximately **two discharges per half cycle** occur. The number of dis-charges per cycle at a discharge site depends on the relation of the magnitude of the voltage change, which is necessary to start a discharge, to the crest voltage of the externally applied voltage. At the beginning of the tree growth the voltage change before the next discharge nearly seems to be constant and approximately equals the crest voltage. When examining the sequence of the voltage changes in more detail, often a small decrease can be found, which usually ends in the aforementioned reset with two consecutive discharges after voltage changes of the same polarity.

In some cases the phenomenon switches to a situation in which two discharges per half cycle occur. Two discharges per half cycle are typical of a late stage of electrical tree growth. In this case the second voltage change of the same polarity is usually significantly smaller than the first one and this holds for both polarities.

Influence of gas pressure in the tree channels

When comparing the sequence of discharges immediately after tree initiation, after 30 min voltage load and after additional 30 min of voltage load, with continuing tree growth there is an increased probability of **discharge free time intervals** of increasing length up to the region of seconds. After an hour of voltage load the discharges even cease to appear totally; after a slight increase of the applied voltage they restart again.

This phenomenon is a consequence of the deteriorating influence of the partial discharges on the polymer material. They lead to a **molecular degradation** of the polymer and low molecular weight degradation products and cavities (tree channels) are formed within the polymer. At this stage the **gas pressure** in these cavities is the decisive parameter whether there is a discharge or not. If the gas pressure is higher than a critical value, there will be no discharges, until some of the discharge products have diffused into the surrounding polymer. The experimental finding that tree growth is quicker at higher temperatures results from the higher diffusion constant of the degradation products at higher temperatures.

Polarity dependence

The analysis of the **sequence of the voltages** at which consecutive discharge pulses occur reveals important information too. **Fig. 5(a)** shows such a plot at an early stage of the electrical tree growth. At the late stage of the tree growth this pattern looks totally different (**Fig. 5(b)**).

The finding, that at the initial stage of the tree growth the absolute value of the voltage change, which is necessary before a positive discharge, is slightly but significantly higher than before a negative discharge (**Fig. 1(b)**), may be an indication of the fact that negative charges diffuse away easier or quicker than positive space charges and thus their field modifying influence is smaller a few milliseconds after the discharge event.

The influence of the magnitude and polarity of a discharge on the voltage change necessary for the ignition of the next discharge is shown in **Fig. 6**. At the initial stage of the tree growth (**Fig. 6(a)**) a polarity dependent behaviour can be observed. At the late stage of the tree growth the polarity dependence is less pronounced (**Fig.6(b)**).

Influence of the polymer

When comparing dry and wet polyethylene the basic behaviour is the same, but minor differences exist. The influence of the space charge at the initial stage of the tree growth is more pronounced with dry polyethylene. In most cases a step by step build-up of positive space charges occurs with a negative 'reset'. In the case of wet polyethylene there is more scatter, and there may be a step by step build-up of negative space charges too.

Conclusions

The evaluation of the **pulse sequences** of the **partial discharges** during electrical treeing shows that local **space charges** play an important role at the early stage of the tree growth in polyethylene. The **magnitude** and the **polarity** of the space charges change with time. Consequently the externally measurable voltage heights or the corresponding phase angles at which the discharges occur scatter at 'random' if taken without mutual correlation. A more meaningful parameter is the **voltage change between consecutive discharge pulses**. The **Pulse Sequence Analysis** can be used to clarify the local space charge phenomena and their influence on the degradation processes in polymers.

At the late stage of the tree growth the **gas pressure** within the tree channels is the important parameter and the influence of space charges is less pronounced.

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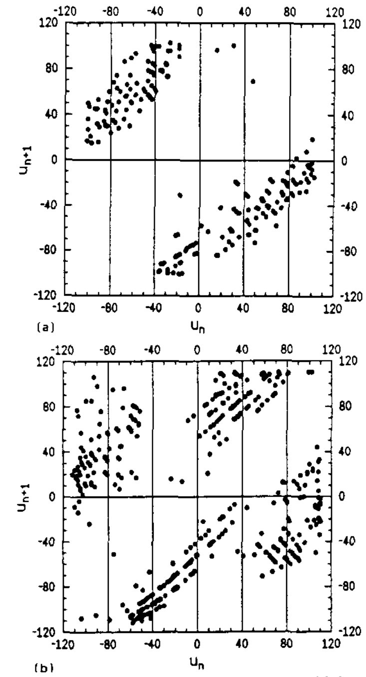

Fig. 5: Correlation between the voltages at which consecutive discharges occur at an early (a) and a late (b) stage of the electrical tree growth (dry polyethylene)

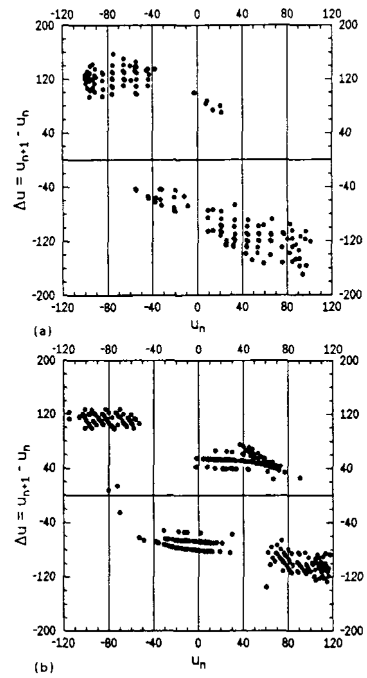

Fig. 6: Voltage change before the next discharge against voltage of the preceding discharge at an early (a) and a late (b) stage of the electrical tree growth (wet polyethylene)