PHASE RESOLVED PD PATTERNS IN ELECTRIC TREEING

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Abstract: One of the important aspects of insulation condition monitoring through partial discharge (pd) detection is the need to establish a trend in the discharge pattern for a given insulating system over its lifetime. Treeing is one of the principal routes to failure in insulating materials, and its growth is accompanied by pd activity. In this work, a study of the evolution of the phase resolved pd patterns during the various stages of tree growth is undertaken. Electrical pd detection is performed simultaneously with online visual observation of tree growth with a high resolution high speed camera. Epoxy resin specimens with needle-plate electrode geometry are used. A correlation of pd patterns to the tree morphology is established.

Key words: Treeing, PRPD patterns, back discharge, partial discharge activity, pulseless glow.

1. Introduction

When a polymeric dielectric is subjected to high local electric stresses, electric trees may develop in the volume of the material by formation of filamentary channels through material erosion and degradation. The channels continue to grow, eventually initiating a failure through dielectric breakdown. Tree growth is accompanied by partial discharges (pd) taking place within the tree tubules. PD monitoring might therefore constitute an important indicator of tree growth and thereby of the health of the insulation. In this work, we monitor the partial discharge activity during the various stages of treeing.

PD activity is characterized and quantized using phase-resolved partial discharge (PRPD) patterns. As the tree grows, the nature of pd activity changes. Tree growth may be monitored using an electrical pd detector, in which individual pd pulses are measured. The phase resolved pd pattern, also called the ϕ-q-n plot, is based on real-time recording of consecutive pd pulses quantified by their apparent charge q_i (usually in pC) occurring at phase angle ϕ_i (0^o-360^o) within a voltage cycle of the test voltage. Also n_i, the number of identical or similar pd magnitudes recorded within short time- or phase- intervals. The pd pulses are summed for a large number of consecutive cycles to construct the plot. Since the occurrence of pd pulses is a statistical phenomenon, the plot effectively represents a probability distribution. The pd pattern must be relatively stable over the sampling period.

The interpretation of a discharge pattern, and its correlation with the nature and site of discharge is far from straightforward 1. However, some useful pointers are available from the plots. Larger the discharge magnitude, larger the site of degradation with which it is associated; greater the repetition rate or the number of discharges per cycle, greater the number of discharging sites. If the discharge magnitude increases with voltage, it would indicate the presence of cavities of different magnitudes; with increase in voltage, larger cavities also begin to discharge. Nattrass 1 illustrates several examples of how the nature and site of discharge shows up as differences in pd patterns.

One of the important aspects of insulation condition monitoring through pd detection is the need to establish a trend in the discharge pattern for a given insulating system over its lifetime 3. This is especially true where treeing is considered: it is well-known that treeing is characterized by bursts of pd activity followed by relatively quiet periods 4. Guastovino et al 4 demonstrated that in XLPE specimens it was possible to monitor the tree growth morphology through non-visual methods, extracting information from pd pattern analysis. The correlation of pd patterns to the tree morphology, should be useful in predicting residual lifetime from digital pd measurements. This would be particularly useful in situations where tree growth cannot be monitored by means of optical methods.

2. Experiments

Epoxy (CY230) and Hardener (HY951) are used for formulation of the dielectric material. The specimens used are $40mm \times 40mm \times 40mm$ sized cubes. A non-uniform field is established by adopting a needle-plate geometry, with a gap-distance of 2-3 mm. A stainless steel needle typically with tip-radius of about 7 µm is inserted into the epoxy sample, which is then placed on a metallic plate that is grounded. Aluminum foils with adhesive are used on the grounded surface to ensure proper dielectric-metallic contact. The sample is placed inside an oil-bath to avoid corona and surface flashovers. The growth of the electrical tree is monitored on-line with a high-resolution high-speed camera. Simultaneously, partial discharge activity within the tree channels is monitored using a partial discharge detector. A digital storage oscilloscope is used for acquiring the pd pulses. Camera images and pd detector output are transferred online to a PC using a data acquisition module, for online monitoring and further data-processing.

3. Results and Discussion

3.1 Tree Initiation

The electrical pd detector registered pulses before any tree was observed visually on the camera. These may be assumed to be due to pre-tree discharges 6. In this work, tree initiation is considered to have occurred when the first branch is visible on camera. It is observed that the initiating pulses (before appearance of a tree) always occur in the first quarter of the positive cycle. Mammeri et al 7 reported that the first micro-discharges recorded during tree growth were of a typical magnitude of 0.04 pC, and these occurred in the positive half cycle of the sine wave. Similarly, Hozumi et al 8 reported that positive pulses (0.05 - 0.1 pC) were first observed at tree initiation.

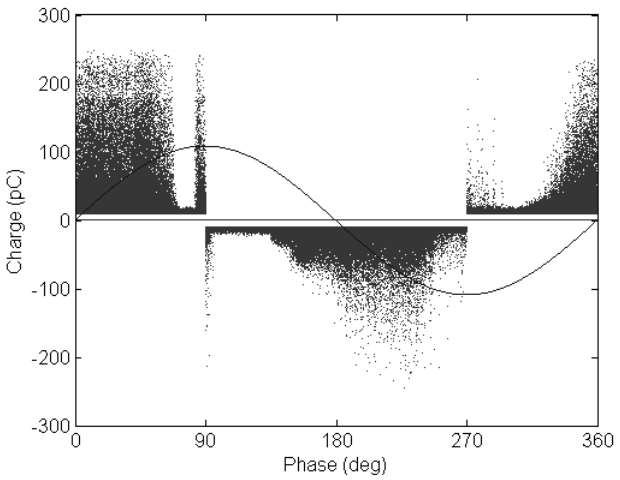
A mechanism that explains the reason for appearance of positive pulses at tree inception was put forward by Tanaka 9. It was postulated that in the positive half cycle of the applied ac voltage, the trapped electrons would move back to the electrode, causing a back discharge. This is what causes the occurrence of a positive current pulse. With higher applied voltages, initiating pulses are seen to have a higher magnitude e.g. the average pulse magnitude is 19 pC when 10 kV is applied, while an identical sample stressed at 16 kV registers initiating pulses of 30 pC. This is to be expected, since higher amounts of charge are injected and deployed in a discharge at higher voltages.

Thus to summarize, tree initiation is characterized by the appearance of positive pulses, with bigger pulses appearing at higher voltages.

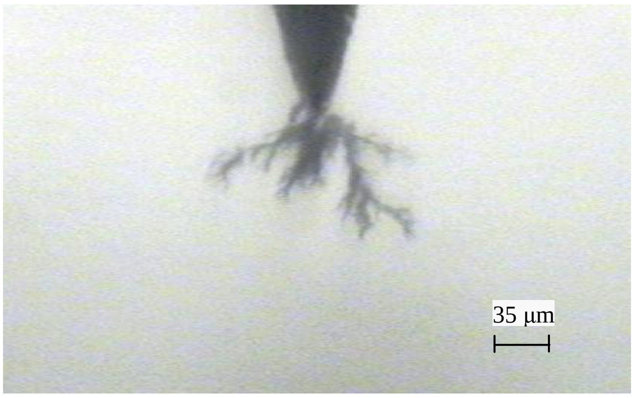
3.2 Tree Growth

After tree initiation, pd monitoring is continued over the subsequent phases of tree growth. A large number of experiments were performed; here we present a few representative trees and the associated observations.

Figure 1(a) shows the pd pattern in a sample stressed at 10 kV, 25 minutes after tree initiation. The positive pulses are concentrated along the rising portion of the sine wave (positive slope) rather than at the peak, and the negative pulses along the negative-going slope. While the maximum magnitudes of the positive and negative pd pulses are about the same (~240 pC), the number of high magnitude positive pulses is higher. The presence of pd pulses over a range of magnitudes from about 20- 250 pC, indicates that the discharges are concentrated along tree segments of varying lengths. The discharge magnitudes are a rough indicator of the discharging segment lengths. Obviously, there are a larger number of low magnitude pulses (as indicated by the heavy concentration of points for lower values of q). Negative pulses appear to be mostly of smaller magnitudes (< 100 pC), with fewer large magnitude pulses, concentrated mostly between 200^o - 240^o. The camera image of the corresponding tree structure is shown in Fig. 1(b). The tree growth was observed to be rapid and extensive at this point.



(a)



(b)

Figure 1: (a) PD pattern and (b) photograph of tree in a sample stressed at 10kV, 25 minutes after tree initiation.

As the tree grows, both positive and negative pulses increase in magnitude. The maximum discharge magnitude increases to about 550 pC, obviously indicating increase in the maximum length of the discharging channel segments. At this point, the number of high magnitude negative pulses is considerably increased, though they still occur in a lower proportion than high magnitude positive pulses. Visual observation of tree growth at this point shows that the tree continues to extend by production of newer branches or extensions of existing branches.

In contrast, Fig. 2 shows pd data for a second sample stressed at 6 kV, in which tree has stopped extending 90 minutes after tree initiation. The pd signature is completely different; the positive and negative pulse distributions are almost identical.

Similar observations from a large number of cases bring out two important points. Firstly, the tree growth (extension of branches) is characterized by a significantly larger number of high magnitude positive

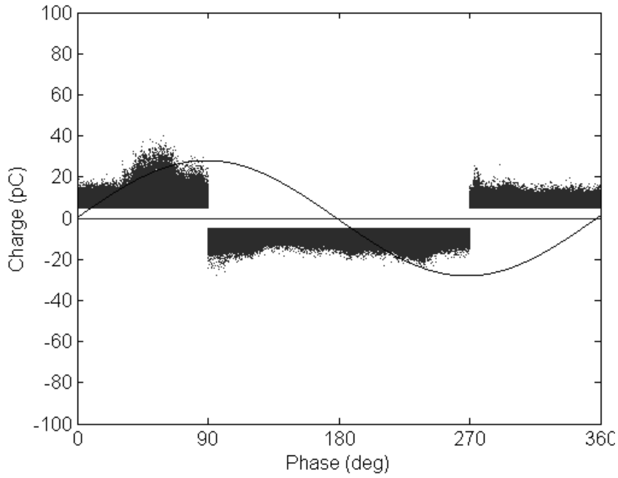


Figure 2: PD pattern at 6 kV, 90 min after the tree initiation

pd pulses compared to negative pulses. Discharges continue to occur on both cycles even after the tree has stopped growing significantly; however the distributions of the positive and negative pulses are almost similar during this stage of treeing. Secondly, pd magnitude on both cycles increases as the tree grows in size.

A close examination of Fig. 2(b) in 10 showing the pd pattern obtained by Suwarno et al for tree-like tree growth, is similar to our findings: in fact, the pulses in the positive half-cycle show the presence of a larger number of high magnitude pulses. Tree extension may be assumed to occur by a similar mechanism of back discharges from negative charge trap centers as in the initiation mechanism postulated by Tanaka 9. A pd in an existing tree tubule itself acts as a source of charge injection into the dielectric. Part of the charge involved in the discharge process is trapped on the tubule surface and part of the charge migrates deeper into the dielectric 11. Thus, a process of negative charge injection 9, followed by subsequent charge extraction from near the channel-end, in a manner similar to the one described for tree-initiation, results in the formation of negative space charge sites ahead of, but a little distance away, from the ends of existing tree-tubules. The formation of such negative charge centers ahead of each tree-tip is shown in Fig 3.

Back-discharge from these negative charge sites results in extension of the tree branch, and is accompanied by positive pulses just as during tree initiation 12. Thus, the presence of comparatively higher magnitudes positive pd pulses are an indicator that the tree is continuing to grow new filaments. It may be noted that tree extension is also accompanied

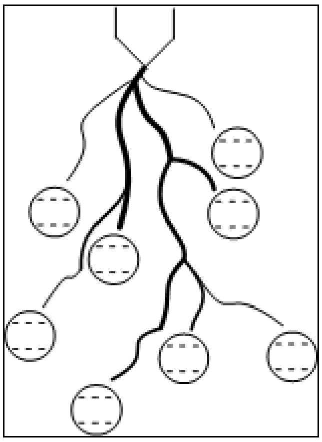


Figure 3. Formation of such negative charge centers ahead of each tree-tip (from thesis)

by increase in pd magnitudes in general.

During voltage rise of the ac cycle, potential builds up across the existing tree tubules, both during the positive and negative cycles. In the initial growth phase, larger number of positive pd pulses of high magnitude indicate the formation of longer channels by extension of existing branches. The first extension from the tip of any existing tree tubule occurs by the production of a very narrow filamentary channel linking the existing channel tip to a new point; the new segment thus added may be too constricted to support a long discharge along the entire length of the branch very easily. At this point, discharges of small magnitude occur in the small tree segments added, leading to the widening of the new tubule. With the needle tip at positive polarity, electrons at and near the tubule end are more energetic and less massive, and are possibly capable of movement in the added constricted segment. This allows pd pulses to build up along the entire length of the elongating channel including the added segment. With the needle at negative polarity, the tree tip behaves like the anode and can inject only positive ions, which may not have sufficient mobility in the constricted portion. Thus, the negative pulses are only supported in the original branch. Once a long continuous and extended channel is produced, discharges of equal magnitudes in both half-cycles occur. Tree extension is accompanied by a large number of tree channels discharging simultaneously; therefore a large number of extensions might occur at any point of time to the existing tree structure. The cumulative effect is therefore seen as an increase in the magnitude of the average positive pulses compared to negative pulses. Once a particular tree segment stops extending, it supports equal magnitude discharges at both polarities. These discharges are accompanied not by further tree extensions, but widening of the existing tree tubules.

3.3 Back Discharge from Plate Electrode

The pd pattern changes completely when one or more tree tubules reach close to the ground electrode; at this point of time, we see a preponderance of high magnitude negative pulses. This is seen in Fig. 4 that shows the pd pattern for a sample stressed at 10 kV, 45 minutes after tree initiation. The maximum pd magnitudes lie between 160-190 pC.

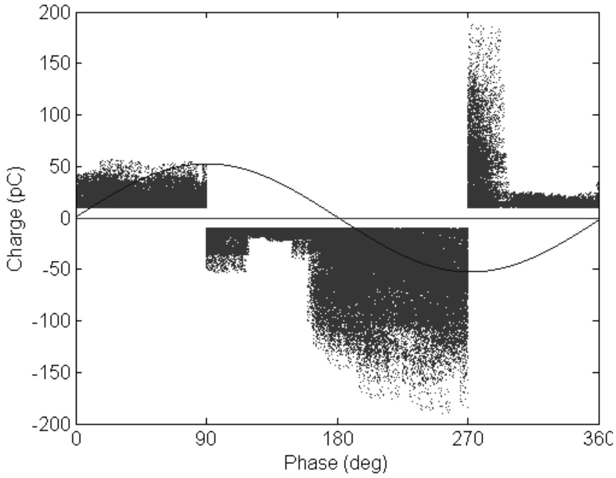


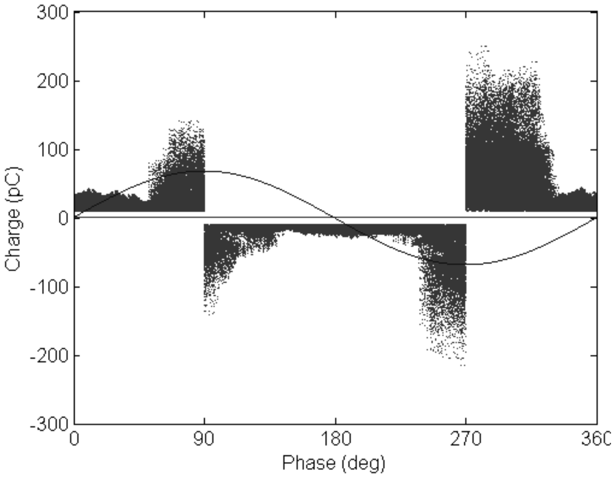
Figure 4: PD pattern in a 10kV sample 45 minutes after tree initiation.

Soon after this, the pd pattern is again seen to change drastically. The pd pulses appear to be concentrated at the positive and negative peaks, instead of the rising edges of the half-cycles. This is shown in Fig. 5(a). Visual inspection of the tree at this point shows that multiple channels have reached the ground electrode; further these channels have selectively increased in diameter. The tree at this point of time is shown in Fig. 5(b). The maximum values are between 200-250 pC.

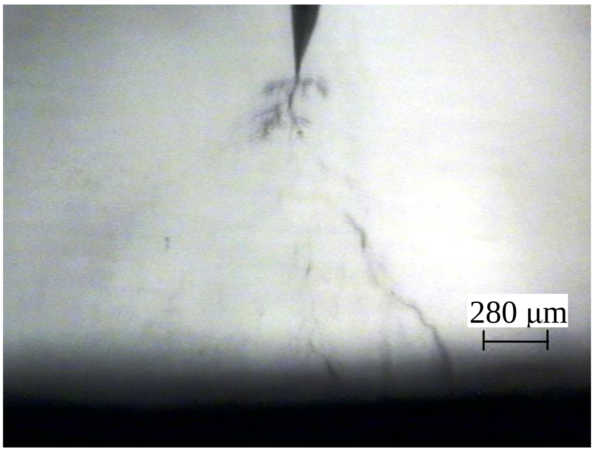
As discussed earlier, tree extension occurs by production of negative charge sites ahead of the tree tubules, and field enhancement in the intervening region. As the tubules approach the plate electrode, it is possible that the enhanced field becomes higher in the small gap distance between the negative charge site and the plate electrode, rather than between negative charge site and tree tubule. This would result in discharges ensuing between the plate electrode and the negative charge site, when the plate electrode is positively charged i.e. during the negative half-cycle. This would explain the occurrence of high magnitude negative pulses. Repeated discharges would cause breakdown of this intervening region, and the gap between the tree and the ground electrode would be breached. At this point, discharges would take place along the long tree channels breaching the two electrodes.

This understanding is supported by the discussion of Mammeri et al on grounding trees. They describe the formation of a negative space charge region ahead of the needle tip during voltage application, and before treeing occur. Subsequently, the sample is short circuited and grounded. While the applied field goes down to zero, the space charge field due to the above-mentioned charge centre causes a local field reversal, allowing some of the charges to detrap. When the charge density is high enough, charges drift back to the needle electrode and a local breakdown follows. In their estimation, a charge density of the order of 10^{16} electrons per cm^3 in a spherical region of 10 μm in diameter is required to reverse the field at the needle tip when the sample is grounded. As a result of this effect, a local breakdown trace of about 5 μm in length is formed.

Once the tree tubules reach the ground electrode, positive and negative pulses in the tree channels help in their widening. As the tubules touching the grounded electrode grow wider by damage due to both positive and negative pulses, they create long continuous gas channels. Large field enhancement is required for breakdown of these long channels, and this is possible only at and around the peak magnitudes of the voltage applied. The large number of pulses at the peaks, as seen in Fig. 5(a), is probably due to multiple discharges in the multiple tubules that have reached the ground plate. Intense discharge activity is observed during this period, before catastrophic failure occurs. Obviously, the discharges perform the function of widening of the tree tubules so that they become capable of supporting high current discharges leading to breakdown.



(a)



(b)

Figure 5: (a) PD pattern when channels reaching ground electrode. (b) Image of tree with multiple channels having reached the ground electrode.

Thus, we summarize the findings:

1. Tree extension, especially in tree-like trees which have at least one long trunk, is characterized by high magnitude of pulses in the positive half-cycle.
2. Arrested tree growth is characterized by equal magnitudes of pulses in the positive and negative half-cycles.
3. When tree nears the opposite (grounded) electrode, negative pd pulses have higher magnitudes.

3.4 Pulseless Tree Growth

There are instances when treeing proceeds either without any perceptible pd pulses, or very fleeting high pulses that are only instantaneously registered. For example, in a sample stressed at 18 kV, no more than 3-4 pC were recorded throughout the growth. A long tree-like tree was seen to have been produced immediately after initiation. The tree tubules were very fine.

Unfortunately, it is well known that often treeing proceeds by micro-discharges which are not picked up be conventional pd detecting equipment. This is related to the establishment of stable discharge conditions, at higher applied voltages, so that steady glow discharge is produced 13]. The changes in the patterns were attributed to the increased surface conductivity. Champion et al 15 reported that in epoxy resin, tree propagation takes place below its glass transition temperature, without observable partial discharges. Hudon, Bartnikas and Wertheimer 16 observed that long exposure of epoxy resin surfaces to partial discharges under ac field stress permitted the establishment of a definite transition from spark to glow discharges. There is no way of detecting such pulses through the technique under discussion. It is important to remember though that pulseless glow discharges are nevertheless demonstrated to cause extensive damage to dielectric materials.

4. Conclusion

In this paper, the evolution of the phase resolved pd patterns during the various stages of tree growth has been traced. It was seen that tree growth is accompanied by pd activity. As long as the tree tubules extend in length, the pd pattern is dominated by a larger number of high magnitude positive pulses. The pd magnitudes depend on the lengths of the discharge paths, as well as the applied voltage across the dielectric specimen. The diameters of the channels also play a role in allowing discharges to build up along large fractions of the long tubules. When the tree stops growing in length, the positive and negative pulses show a similar distribution. When the tree reaches the opposite plate electrode, the pd pattern is seen to change drastically; negative pulses are seen to be predominant, and occur at a different phase angles.

Thus, the stages of tree growth indeed show a significant effect on the pd patterns, However, as well known, sometimes pulseless pd evolves within the tree channels; there is no way to detect such discharges, not even just prior to breakdown.

5. References

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