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# Investigation of PRPD during electrical tree initiation and growth in a needle-free void geometry

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***Abstract*- A needle-free geometry has been developed to produce electrical tree initiation and growth using an engineered void and interface between epoxy resin and silicone rubber. A rod electrode of 4 mm diameter is embedded in the silicone rubber, with a controlled void at its flat end, and 12 kV is applied. Treeing and tracking activities are observed along the epoxy silicone interface and within the epoxy bulk. The dependence of partial discharge (PD) measurements on track development is also studied. Phase-resolved PD patterns are used to compare and understand PD behavior during testing. The geometry used is capable of generating electrical tree growth without the recourse to needle electrodes, and is therefore more representative of damage in high voltage equipment than most laboratory grown trees.**

## I. INTRODUCTION

Needles are commonly used as electrodes in the study of electrical treeing. Due to their reproducibility and the field enhancement created they are a very reliable way to observe treeing. However, the sharp steel tips (3 µm radius) typically used are not representative of defects in power cables. An engineered void might better reflect the causes of field enhancement in high voltage plant, especially in cable joints and terminations where faults can lead to localized partial discharges (PD) which, with time, can lead to material degradation and causing breakdown of the insulation.

The name treeing is designated to a type of damage that develops through a dielectric under electrical stress. The branching path of degradation resembles a botanical tree. Electrical trees are gaseous channels within the solid dielectric formed under a divergent electric field. Electrical tracking is the formation of damage at interfaces or along the surface of an electrically insulating material. Both of these phenomena can be precursors to breakdown in a cable system [1] [2].

PD are associated with electrical tree growth, accompanying tree propagation [2]. The tree growth is seen to be greatly influenced by the PD properties [3]. PD measurements capture the phase, frequency and amplitude of the discharges allowing correlation with typical patterns associated with known void geometries. PRPD (Phase Resolved Partial Discharge) analysis can be used as a tool to compare such signals, allowing an understanding of changes leading to and following events such as when an electrical tree is forming.

This paper discusses the formation of electrical trees from a void cavity and the accompanying discharge patterns. This can provide an understanding of the generation of PD from a defect in the insulation of a cable which with time may lead to tracking, treeing and a failure in the high voltage system.

## II. EXPERIMENTAL

The sample was prepared using two different types of insulation material. The first material in the top layer was made of silicone rubber (SiR) AS40 Addition Cure supplied by Easy Composites. It was mixed with their addition cure Catalyst at a ratio of 100 parts of silicone to 10 parts Catalyst. In this first part, an electrode rod is embedded as the high voltage electrode. The second material was epoxy resin provided by Huntsman (LY 5052 Araldite/Aradur 5052 CH). It is a low viscosity resin with a mixing ratio of 100:38 parts by weight. Samples are mixed, vacuumed, cured, and post cured following manufacturer recommendations.

A void was fabricated by using a Nylon tool which could be adjusted to the desired thickness. Here, this was chosen as 120 µm to produce high energy discharges within the void [4]. For discussion, the bottom of the surface of silicone rubber, which is level with the flat surface of the metallic electrode, is designated as Surface A. The top surface of epoxy resin in which the void was created is designated as Surface B. Surface A and Surface B are pressed together so the electrode surface encloses the void. Fig. 1 illustrates the fabricated sample.

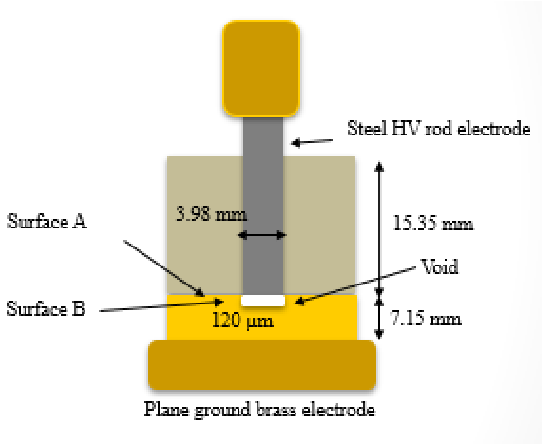


Fig. 1. Void cavity of 120 µm depth and 4 mm diameter in epoxy resin, colored yellow, adjacent to the interface of Surfaces A and B. The steel electrode is embedded in silicone rubber.

## III. EXPERIMENTAL ARRANGEMENT

The experimental arrangement can be observed in Fig. 2. It includes a test sample (with the void) and a dummy sample (without the void). An HVAC amplifier provides the high voltage in series with a 500 kΩ limiting resistor to protect the equipment in case of breakdown. A balanced circuit is implemented to mitigate background noise and it is connected to the sample via Omicron MPD600 software to monitor PD during the test. This circuit gave a background noise level of 500 fC. External illumination and a CCD Camera provided optical images of the sample.

In [5] a “wing-like” PRPD pattern, typical of electrical tree growth, was observed after 20 h of testing yielding strong evidence of electrical tree growth in the sample under test [11]. Hence, in this investigation, the sample was observed after each 20 h of ageing. Samples were taken apart (the two molded blocks were separated) to inspect the surfaces which made up the void and the interface after every 20 h of ageing. In this investigation 20 h of testing is approximately a lapsed week of time.

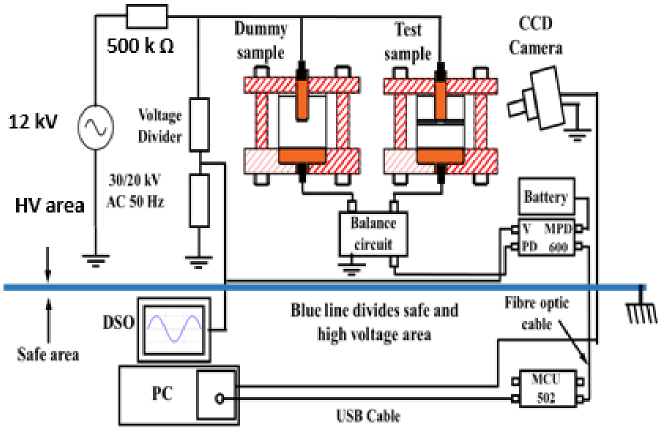


Fig. 2. HVAC experimental circuit. Taken from [4].

## IV. METHODOLOGY

With a higher thickness of void, the magnitude of the discharges would not cause localized damage in the sample. However, with the void thickness of 120 µm and with 4 mm diameter, it was calculated that with 12 kV peak AC applied, an electric field across the void of 6.14 kV/mm would result and yield a maximum charge stored of 632 pC. The measured partial discharge inception voltage (PDIV) was 4 kV peak which corresponds to an internal field and voltage in the void of 2.04 kV/mm and 245 V, respectively. These values were determined using the equivalent capacitance of a void enclosed in an insulation system [6].

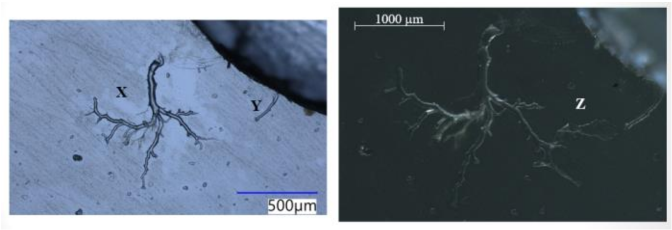
As the electric field generated within the cavity was higher than the breakdown strength of air, internal discharges activities were expected from this arrangement, with a maximum value of 632 pC.

The sample was aged for 110 h at 12 kV peak AC. Every 20 hours the layers were separated so the interface Surface A and B could be studied under an optical microscope. It is acknowledged that this inspection process may influence the tracking process.

## V. EXPERIMENTAL RESULTS

### *A. Electrical tracking*

After 20 h of test at 12 kV peak AC an electrical track had formed in the epoxy. The track labelled X in Fig. 3, was generated adjacent to the edge of the void, and a smaller branch can be seen at location Y. After 40 h of test, the small branch Y was directly connected to the track X by extension marked Z in Fig. 3 (b). It was observed under an optical microscope that some branches are at the surface and others are within the bulk of the epoxy. None were found in the bulk of the SiR.



(a) (b)

Fig. 3. Images of electrical tracking forming from a cylindrical void: (a) shows the branches formed in epoxy at locations X and Y at the edge of the void after 20 hours.
(b): shows channel Z connected X and Y after 40 hours.

The observations suggests that the first branch was created with a main, thicker channel of 36 µm diameter leading to the formation of other branches.

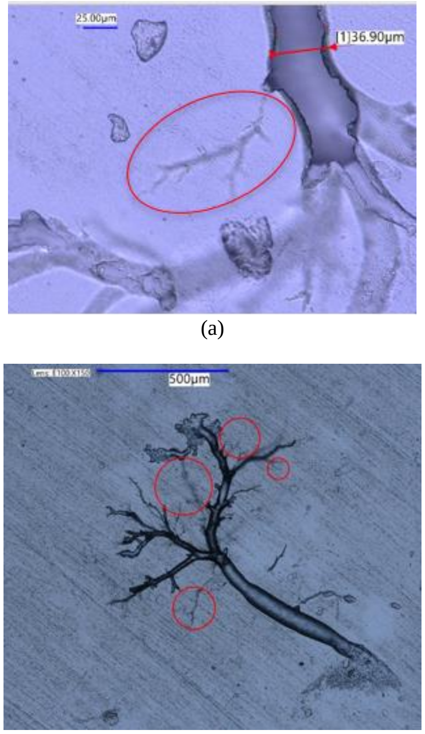
Between the 60th and 85th hours of the test, a new track formed at a different location in the epoxy. The main channel diameter varied between 36 µm to 84 µm. This second track had smaller channels developing from it below the surface within the epoxy bulk, and are more akin to trees grown from needles. Fig. 4 illustrates the form of the second electrical track. This second track comprised wider channels than the first one formed in the sample.

Fig. 4. Electrical track within epoxy resin formed between 60 and 85 hours.

### B. *Electrical trees*

Interfacial tracking with track widths of tens of microns formed in the sample after tens of hours, and this subsequently led to more traditional to trees forming in the epoxy channels of a few microns diameter as seen in red circles in Fig.5 (a) and (b) after 20 hours and 60 hours, respectively.

This behavior is similar to that reported by Bastidas in rather different geometry which also featured an interface between epoxy and high temperature vulcanized SiR [7].



(a)

(b)

Fig. 5. Electrical tree formed in epoxy from the wider tracking channels.

### C. *Partial discharges magnitude variation*

PD activity was monitored during testing to understand the correlation between the discharge measurements and the track/tree morphology. It is known that PD activity usually accompanies the growth of an electrical tree so it is helpful to observe the discharges during a test and correlate these with the geometry studied [1]. The predominant behavior of PD was used to identify the moment electrical tree or track branches started to form at the interface.

Fig. 6 (a) to Fig. 6 (d) shows the PD magnitude during 21 h of test. It can be seen in Fig. 6 (a), Fig. 6 (b) and Fig. 6 (c) where the test durations were 2 h, a further 6.5 h and 7.5 h, respectively, that during the first 16 hours of testing, the average magnitude of PD was 300 pC.

However, after 16 hours of test, PD became higher in magnitude (up to ~1 nC) during all 5 h of test, as observed in Fig.6. (d), suggesting that the charge carriers produced by each PD were trapped along the wall channel becoming longer and higher in magnitude and this might identify the development of a tracking channel at in this period [8].

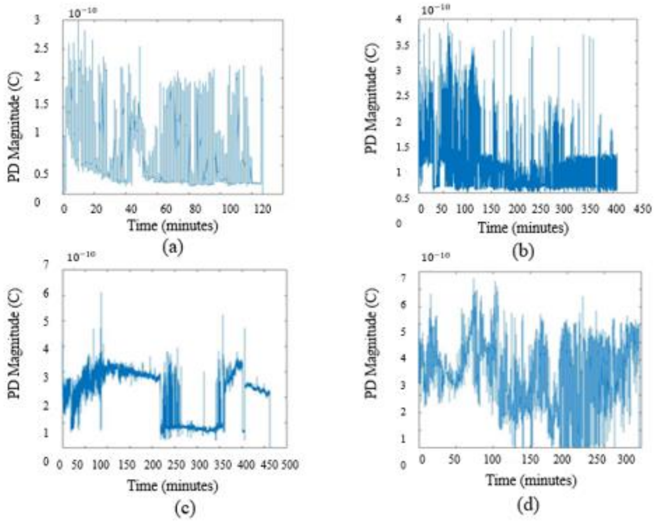


Fig. 6. PD magnitude during 21 hours of testing. a) The first 2 hours of testing, b) Testing from 2 to 8.5 h, c) Testing from 8.5 h to 16 h, d) Testing from 16 to 21 h.

Between 48 and 51 hours of testing, PD magnitude was observed to be around 1.5 nC as seen in Fig.7 (a) and (b). However, during the subsequent 7.5 hours of test, it dropped to ~400 pC and remained around this level of PD. This can be observed in Fig. 7 (c) and Fig.7 (d). These PD trends are seen to correlate with the time formation of the second branches in epoxy as it was seen that these new branches formed between 60 h and 85 h of testing. It shows that these branches have formed channels in different depths within epoxy.

PD magnitude of 632 pC was previously calculated from this arrangement. However, lower value initially observed is likely because the discharge is occurring at an instantaneous voltage lower than the peak (a reasonable assumption – so a measured 300 pC is sensible). The higher values seen later, may be because a larger surface is getting charged because of tree/track formation, or a gap forming at the interface, essentially increasing the size of the capacitor formed by the void.

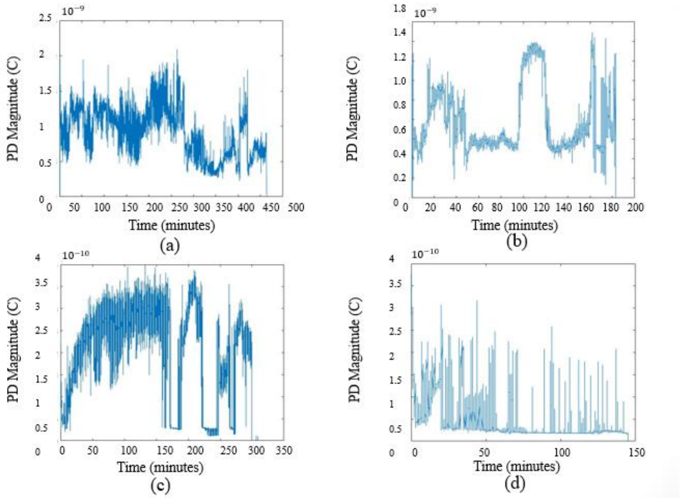


Fig. 7. PD magnitude between 40 and 58 hours of testing a) 40 and 47.5 h , b) 47.5 and 50.5 h, c) 50.5 and 55.55 h and d) 55.5 and 58 h.

### D. Phase resolved partial discharge analysis

PD activity and behavior in a void can be characterized and quantified by the PRPD pattern. Relating PD patterns to the sample geometry may allow predictions of insulation lifetime [9]. Here the shape of PRPD patterns are used to identify and understand tree and track growth [10].

In Fig.8 (a), discharges of 30 pC over a 10 minute period after 1 h of testing are observed from the PD trend of Fig.6 (a). The PD magnitude distribution is more independent of the phase which can because it is more related to the void geometry in this test.

However, a “wing-like’’ or “triangle-like” pattern started to form after 11 hours of testing, with large discharges in the positive cycle tending to grow with the point on wave voltage as seen in Fig.8 (b) and (c). This is a strong evidence that electrical trees were developed in the sample where charges carriers were trapped to form a long and narrow channel [11].

These types of pattern were most predominant during the first 21 h of test. Thereafter, PD developed into a stronger “rabbit-like” pattern with a greater proportion of PD magnitude being dependent on the point on wave voltage in the positive cycle, in Fig. 8 (d). This can be related to the propagation of the pulse depending on the instantaneous voltage rather than the void geometry [11].

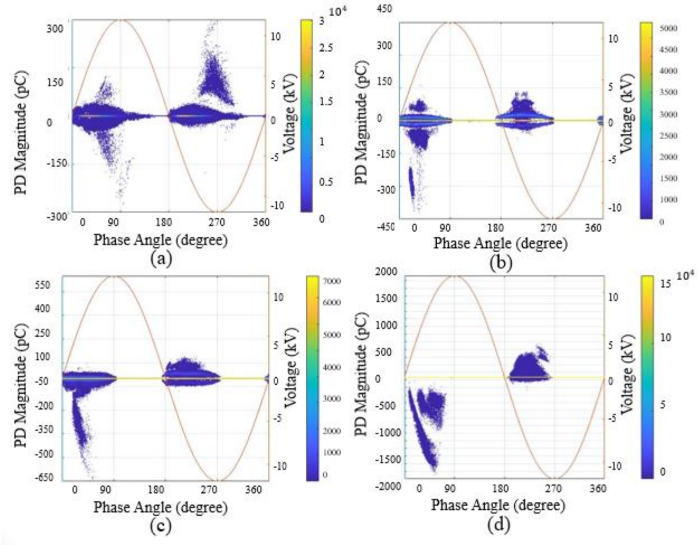


Fig. 8. PRPD pattern after a) 1 hour, b) 10 hours, c) 11 hours, d) 60 hours.

## VII. CONCLUSION

A new sample geometry has been developed and shown to produce electrical tracking from a void without the need for a significant geometric voltage enhancement point such as a metallic needle. Trees were identified as forming from those tracks. The track and tree growth have been correlated with PD amplitude trends against time and PRPD patterns, showing PD magnitude and phase distribution changes as the tracks and trees developed.

The void fabricated may be more representative of an imperfection or defect in a cable, joint or termination and present an alternative to a needle-plane geometry in laboratory tests. More samples including such voids need to be tested to understand the reproducibility of the system.

## ACKNOWLEDGMENT

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