Electrical Treeing and Reverse Tree Growth in an Epoxy Resin

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ABSTRACT

An electrical treeing process is presented which consists of two types of electrical tree structures that coexist in the same epoxy resin: these have been termed as 'filamentary trees' and 'reverse trees'. In samples with needle-plane electrode geometries, a filamentary tree that consists of fine tree channels propagates from the needle electrode to the plane ground electrode under an applied AC voltage. It is observed that once the filamentary tree has crossed the insulation, trees then grow from the planar electrode towards the needle electrode as reverse trees, eventually leading to dielectric breakdown. The characteristics of the treeing processes have been obtained for a range of samples through optical observations. In addition, partial discharge (PD) activity associated with the growth of a reverse tree is thoroughly characterized. The prior existence of a filamentary tree is a prerequisite for the development of a reverse tree. PD does not appear to be a driving force for the growth of the filamentary trees, whereas high levels of PD are associated with the growth of a reverse tree. This distinction shows that aging can occur undetected by PD, but asset management of the more aggressive treeing stages can use PD analytics.

Index Terms — **Electrical tree, epoxy resins, filamentary tree, reverse tree, partial discharge, PD, prognostics.**

1 INTRODUCTION

ELECTRICAL treeing is an important degradation mechanism in AC high voltage polymer insulation. In the laboratory, trees are commonly grown in needle-plane electrode geometries [1, 2]. The literature widely reports that after inception, a tree-like structure consisting of hollow tubes grows from the needle towards the counter electrode/ground electrode in the form of a branched, bushy or bush-branch form [2-4]. Once the tree channels approach the ground electrode, their growth accelerates and dielectric breakdown typically occurs shortly after the insulator has been fully traversed [5]. This is widely described as a 3-stage process: inception, growth, and runaway [2]. Some exceptions have been reported, for example in [6] and [7] in which trees stopped growing when approaching the ground electrode, resulting in long times to breakdown.

The authors have previously reported that electrical trees have been observed to grow from the plane electrode and propagate towards the needle electrode, within an existing tree structure that originally grew from the needle electrode [8-10]. For the sake of convenience, this process is hereafter called 'reverse tree' growth. Only a few similar phenomena can be found in the literature. Budenstein [11] introduced a 'return streamer' as a part of the breakdown process during which the tree channels bridging the needle and plane electrode did not lead to immediate breakdown. Electrical trees are also found to grow from a planar electrode when water trees are formed from a wet needle electrode [12]. Tree growth towards the needle originating from an interface in a layered system has also been reported [13].

Most electrical tree models, as reviewed in [14] for example, focus on the algorithms controlling the extension of the tree and assume breakdown occurs directly after a branch bridges the two electrodes. However, dielectric integrity can remain for a considerable time after fine tree channels fully traverse the insulation [11, 15-16]. Subsequent breakdown may occur as a consequence of either the erosion and broadening of fine tree channels by partial discharges [16] or the growth of reverse tree bridging two electrodes. The latter is considered here in detail.

Two key issues arising from the process of reverse tree growth are: firstly, that they are initiated in what was originally the low electrical field region; and secondly that no clear mechanism (or geometry) is present to create a high divergent electric field, as has been found necessary to initiate trees traditionally.

Given that the initial forward-growing tree does not necessarily result in breakdown, the study of the reverse tree formation may contribute to an understanding of high voltage

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insulation failure, as well as the development of asset management techniques. This paper describes reverse tree growth in the context of insulation failure in the laboratory and provides evidence which can support further explanation and modeling of the phenomenon.

Before discussing the formation of reverse trees, features of the entire treeing process will be reviewed, based on experimental observations of a range of epoxy samples.

2 EXPERIMENTAL

The general process of reverse tree growth has been found to be reproducible over many years' experience. Results presented here are from tests on 20 samples of Araldite LY5052 / Aradur 5052 (Huntsman) which has a glass transition temperature of between 120 °C and 134 °C. A needle-plane electrode configuration was adopted, casting needles into a 22 mm × 22 mm × 20 mm epoxy resin cuboid. The needles (Ogura Jewel Industry) have a shank diameter of 1 mm, a tip taper angle of 30° and a tip radius of 3 µm. There is a 2 mm (± 5%) gap between the needle tip and the bottom surface of the sample. After casting, samples were cured at room temperature for 24-48 hours. Before post-curing, some samples (labelled T1 and T2) were released from the PMMA mould and the surfaces exposed to ambient conditions (18-24°C, 50% RH). These samples are identified as 'exposed to air' in Table 1. The rest of the samples (T3 and T4) were kept in their moulds until they were coated or tested. Post-cure was at 100°C for 4 hours. For some of the samples, the planar surface of the moulding opposite the needle electrode was coated by vacuum evaporated aluminium. The sample preparation conditions can be found in Table 1.

During testing, samples were clamped onto a metallic plate acting as a plane ground electrode. The sample and test cell were either immersed in a silicone oil bath or exposed to ambient air (referred to as Oil and Air in Table 1). 15 kV_p (peak), 50 Hz AC voltage was applied to the needle electrode. The test was stopped when a sample had broken down or intensive damage was observed within the sample. The visible aspect of treeing was recorded by a CCD camera (Manta G-504, resolution: 2452 × 2056). The partial discharge (PD) measurements were conducted using an Omicron MPD 600 with a balanced circuit. A schematic of the experimental setup is shown in Figure 1.

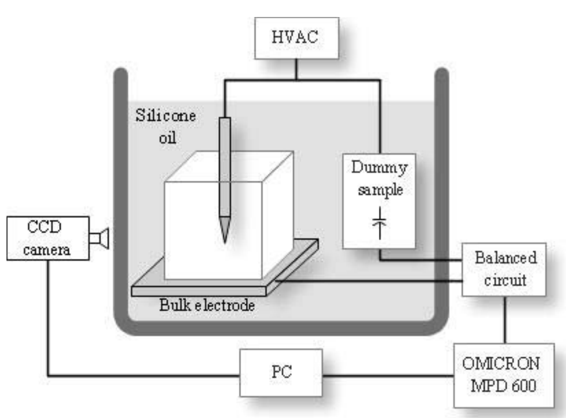

Figure 1. Experimental set-up enabling real-time microscopy and PD measurements. The needle-plane electrode gap is 2mm.

Table 1. Summary of Experimental Conditions and Resulting Tree Types.

Test	Bottom surface	Exposed to air	TE[a]	Initial dark tree	Partially extended tree	RT[b]	RT BD[c]
T1-1	Al	√	Oil		√		
T1-2	Al	√	Oil	√	√	√	
T1-3	No	√	Oil	√	√	√	
T1-4	Al	√	Oil	√	√		
T1-5	No	√	Oil	√	√	√	
T1-6	No	√	Oil		√		
T2-1	Al	√	Air	√		√	√
T2-2	No	√	Air	√	√	√	√
T2-3	No	√	Air	√	√	√	√
T2-4	No	√	Air	√	√	√	√
T2-5	No	√	Air	√	√	√	
T3-1	No		Oil	√			
T3-2	No		Oil	√			
T3-3	No		Oil				
T3-4	Al		Oil			√	
T3-5	Al		Oil				
T4-1	No		Air	√		√	√
T4-2	Al		Air	√		√	√
T4-3	Al		Air			√	√
T4-4	Al		Air	√			

[a]TE = Test Environment (in silicone oil bath or in air)
[b]RT = Reverse Tree formation
[c]RTBD = Reverse Tree followed by breakdown

3 ELECTRICAL TREEING PROCESS

3.1 OVERVIEW

The distinct tree structures generated during the complete process are introduced in the schematic drawing of Figure 2a. The 'initial dark trees' are initiated at the needle tip and consist of thicker channels than the subsequent trees as can be observed for example in Figure 2b. The initial dark tree propagates a limited distance in the shape of a bush or branch tree and partial discharges can be detected during its formation. 14 of the 20 samples listed in Table 1 developed a distinguishable initial dark tree, six did not.

Subsequent to the growth of the initial dark tree, or directly if no such tree initiated, a finer tree develops which appears to be less interconnected and less branched, and is hereafter called a 'filamentary tree'. Filamentary trees can be initiated either from the tips of an initial dark tree or directly from a needle tip as shown in Figure 2b and 2c respectively. Filamentary trees can be divided into two types: those which grow until they have extended fully across the dielectric, which we term 'bridging' and those which appear to stop growing before reaching the planar electrode, which we call 'partially extended'. Before partially extended trees reach the planar electrode, their growth slows. Consequently the tree tips darken and local dark breakdown channels form between the darkened tree tips and the plane electrode, as shown in Figure 2c (5). The bridging filamentary trees traverse the insulation without major changes in the tree morphology, as seen in Figure 2b.

The final stage of tree growth is that reverse trees originate from the planar electrode and grow 'backwards' through the existing filamentary tree towards the needle electrode as shown in Figures 2b (4-6).

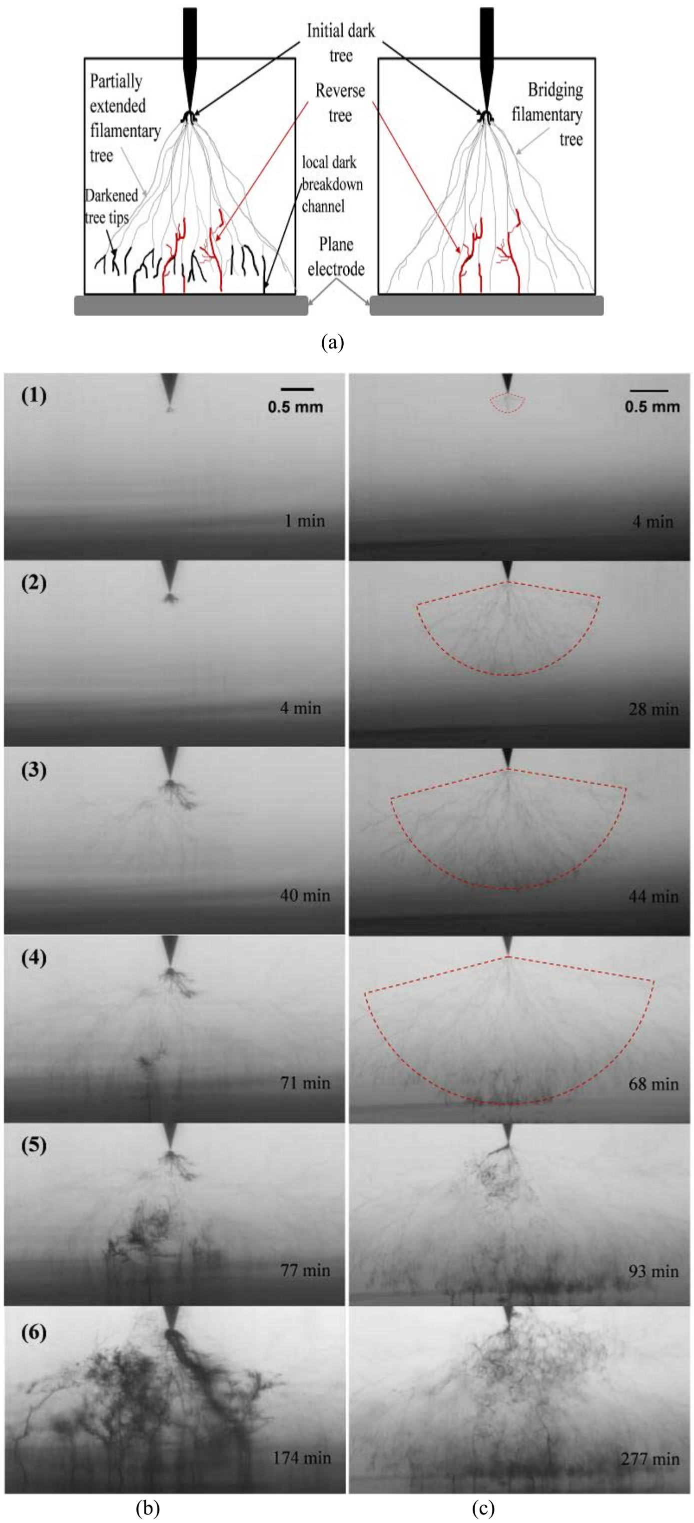

Figure 2. (a) Schematic drawing of different tree structures. The red lines

3.2 FILAMENTARY TREE GROWTH

Observation of filamentary trees is more difficult than traditional trees which comprise thicker and darker channels of several microns diameter. Nano-XCT imaging [3] shows that the diameter of a filamentary tree channel is about 0.6 µm. Even assuming a filamentary tree channel to be 1 µm diameter, it requires a CCD camera of at least 4000×4000 pixels to image a 2 mm × 2 mm area. Consequently, the camera of 2452×2056 pixels can only provide blurred images for the filamentary tree channels, as shown in Figure 2b and 2c.

Although the image quality limits the analysis of the filamentary tree morphology, macroscopic tree growth can be determined. Figure 3 plots the growth of trees (normalized to 2 mm) along the needle axis for four samples, each of which represents a combination of the forward-treeing features. Specifically, as seen in Table 1, filamentary trees in T1-1 and T1-3 were partially extended, whereas bridging filamentary trees formed in T3-1 and T3-5. Filamentary trees initiated directly from the metallic needle tip in T1-1 and T3-5, whereas in T1-3 and T3-1, dark trees developed initially, and filamentary trees subsequently grew from these. As shown in Figure 3, those samples which grew dark trees from the needle tip have a period of relatively slow initial tree propagation, i.e. the first 10 and 20 minutes for T1-3 and T3-1 respectively. The filamentary trees in T1-1 and T1-3 feature decelerated propagation as the trees approach the planar surface. This stage is illustrated in Figure 2c. In Figure 2c (1) and (2), the extended tree channels fall within circular envelopes which are outlined by red dashed lines. In Figure 2c (3) and (4), tree channels on the sides exceed the fan-shaped area as a consequence of the deceleration of the forward tree growth and continued sideways growth.

In summary, there are up to 3 stages during forward tree growth as illustrated in Figure 3 for T1-3. The relatively slow growth of an initial dark tree is followed by the growth of a filamentary tree which is fairly linear with time, and is then followed by a period in which it extends as a dark tree.

3.3 REVERSE TREE GROWTH AND ACCUMULATED DAMAGE

12 of the 20 samples developed reverse trees, as listed in

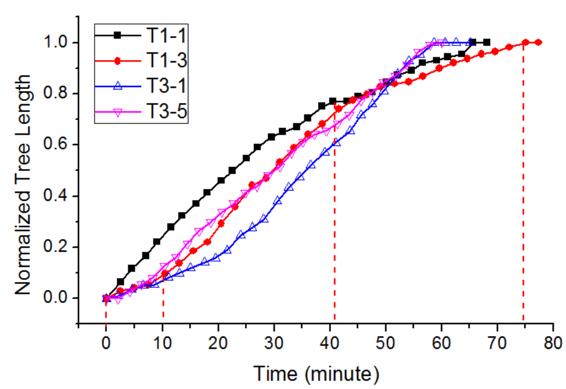

Figure 3. Tree length growth after inception, normalized for the needle-plane distance (~2 mm). Four samples are shown, each of which represents a different combination of the filamentary treeing features.

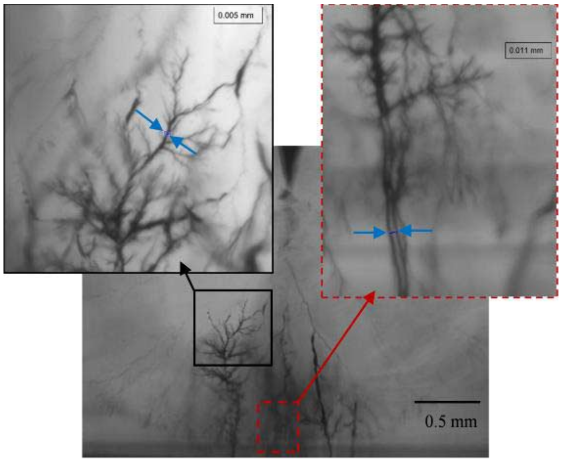

Figure 4. Reverse trees in T2-4. Trees in the two frames above were at different distances from the camera lens. As a result the dashed area on the right cannot be clearly seen as the bottom image was focused to show the tree branches on the left.

Table 1, column ‘RT’. These vented channels appear to either originate from the vented branches of a filamentary tree which has crossed the insulation, or from thick local breakdown tunnels between the ends of a partially developed filamentary tree and the planar electrode. Magnified images of the reverse trees, such as those shown in Figure 4, appear to show two mechanisms for the reverse tree extension: firstly sprouting out from a main reverse tree trunk (in the ‘traditional tree growth manner); and secondly, growing back through existing filamentary tree channels. The diameter of a reverse tree trunk is about 11 μm and a limb is about 5 μm. This compares to the fine forward tree channel diameter of 0.6 μm.

In some cases (c.f. Table 1, column ‘RTBD’) the growth of a reverse tree eventually led to breakdown as shown in Figure 2b (6). In other cases, the reverse tree ceased to grow. For samples that did not develop reverse trees or for which the reverse tree did not result in breakdown, damage would generally accumulate in the filamentary trees due to continued local breakdowns, for example in Figure 2c (6). In this situation, even with what visually appeared to be massive damage, a sample might still withstand the applied voltage for a considerable time (even days).

4 PARTIAL DISCHARGE BEHAVIOR

4.1 OVERVIEW

Previously the authors have distinguished 5 stages of the treeing process, based on the partial discharge level [10]. Stage 1 is pre-initiation, prior to a visible tree. Stage 2 is the growth of the initial dark tree. Stage 3 is propagation of the filamentary tree. Stage 4 and Stage 5 are the darkening of the tip of a partially extended filamentary tree, and reverse tree growth respectively. Generally, no discharges can be detected during the filamentary tree growth (Stage 3), probably as a result of insufficient measurement sensitivity (~0.5 pC). In these experiments measurable discharges are only associated with the growth of ‘dark’ trees, i.e. the initial dark tree, darkening of the partially extended filamentary tree tips, and the reverse tree.

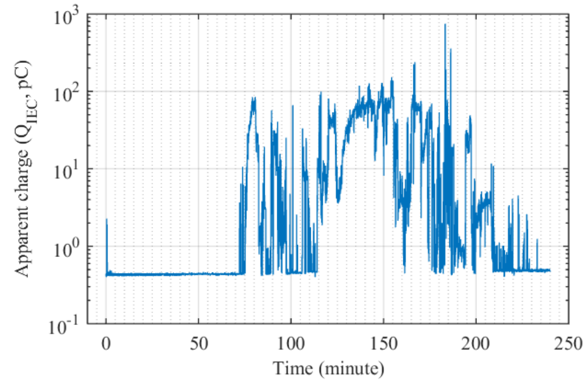

Figure 5. Apparent charge, Q_{IEC}, measured during the electrical treeing of T3-4. Images of the tree are shown in Figure 6.

For samples which did not feature an initial dark tree and a partially extended filamentary tree, not all the five stages can be observed. One example of such a case is shown in Figures 5 and 6. During that test, a tree was quickly initiated after voltage application with small discharge magnitudes of a few pC lasting for about 10 seconds. Afterwards, no discharge was detected above the noise level (~0.5 pC) during the growth of the filamentary tree which eventually bridged the insulation. Consequently no PD was measured until the first filamentary tree channel reached the ground electrode at 72 minutes. The first reverse tree started to grow at 75 minutes as shown in Figure 6a (from which the time-zero background image has been subtracted for clarity). After 200 minutes, localised

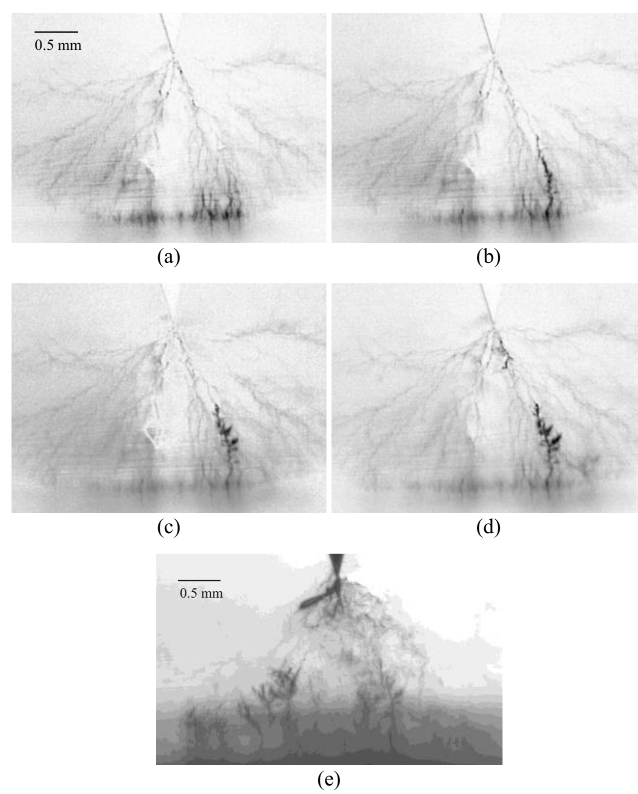

Figure 6. Images of tree growth in T3-4 at (a) 75.5 minutes, (b) 76.5 minutes, (c) 78.5 minutes, (d) 80.5 minutes and (e) 240 minutes. The background image at time 0 was subtracted from (a) – (d). The scale bar in (a) applies to (b) – (d).

breakdown occurred near the needle tip resulting in a large dark cavity, shown in Figure 6e, whereupon the magnitude of PDs reduced. The sample was stressed for another 17 hours before breakdown occurred.

4.2 PARTIAL DISCHARGE IN REVERSE TREES

Partial discharge measurements for the reverse tree growth in sample T3-4 are further analysed in Figures 7 and 8. This example is presented because there was no initial dark tree and the filamentary tree bridged the insulation, meaning that the PD signals can be clearly associated with the reverse tree only. The discharge magnitude, Q_{IEC}, and the number of discharges per 20 ms cycle during the first reverse tree formation are plotted. The phase-resolved PD activity (ϕ-|q|-n plots) and the Pulse Sequence Analysis (PSA) [17, 18] at six times (each with duration of 1 second) representing different stages of growth are presented in Figure 8.

Figure 6a shows that a few filamentary tree channels had reached the ground electrode at 75min 30s and some of the channels near the ground electrode had been darkened. The PD activity associated with the original darkening of channels can be found in Figures 7 and 8 at Time 1. At this stage, the discharges were small in magnitude and few in quantity, and the occurrences were concentrated in phase angles between 30°-90° and 210°-270°.

Between 75min 42s and 76min there was a burst in the number of discharges per cycle. The discharges were of small magnitude and distributed relatively evenly over a wide range of phase angles as shown in Figure 8 (Time 2). After this burst, the trunk of a reverse tree formed as shown in Figure 6b.

At 78min 30s, branches had grown out of the reverse tree trunk as shown in Figure 6c. A period of stable repetition of PD can be identified from the 77th to 79th minute. During this period the magnitude of discharges increased. The PD pattern and PSA plot of Time 4 (77min 44s) represent the PD activity in this reverse-tree branching stage. Time 3 is shortly after the PD burst, and the shapes of PD pattern and PSA plot lie between that of Times 2 and 4. This indicates a transition from the formation of the reverse-tree trunk to the subsequent reverse-tree branching.

Q_{IEC} reached peak levels between the 79th and 81st minutes.

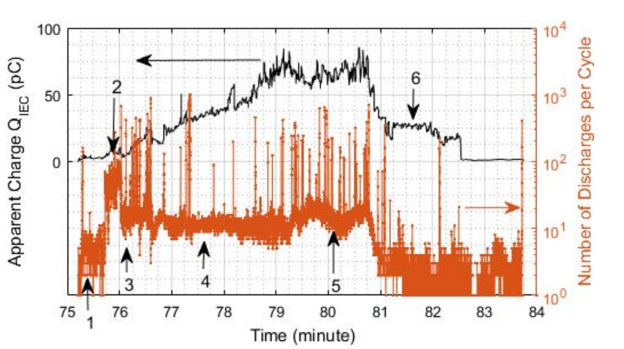

Figure 7. Apparent charge and the number of discharges per 20 ms cycle measured in T3-4 from 75th – 84th minutes. Six one-second periods are identified for discussion. Time periods are from: 75min 22s, 75min 51s, 76min 9s, 77 min 44s, 80min 10s, and 81min 30s.

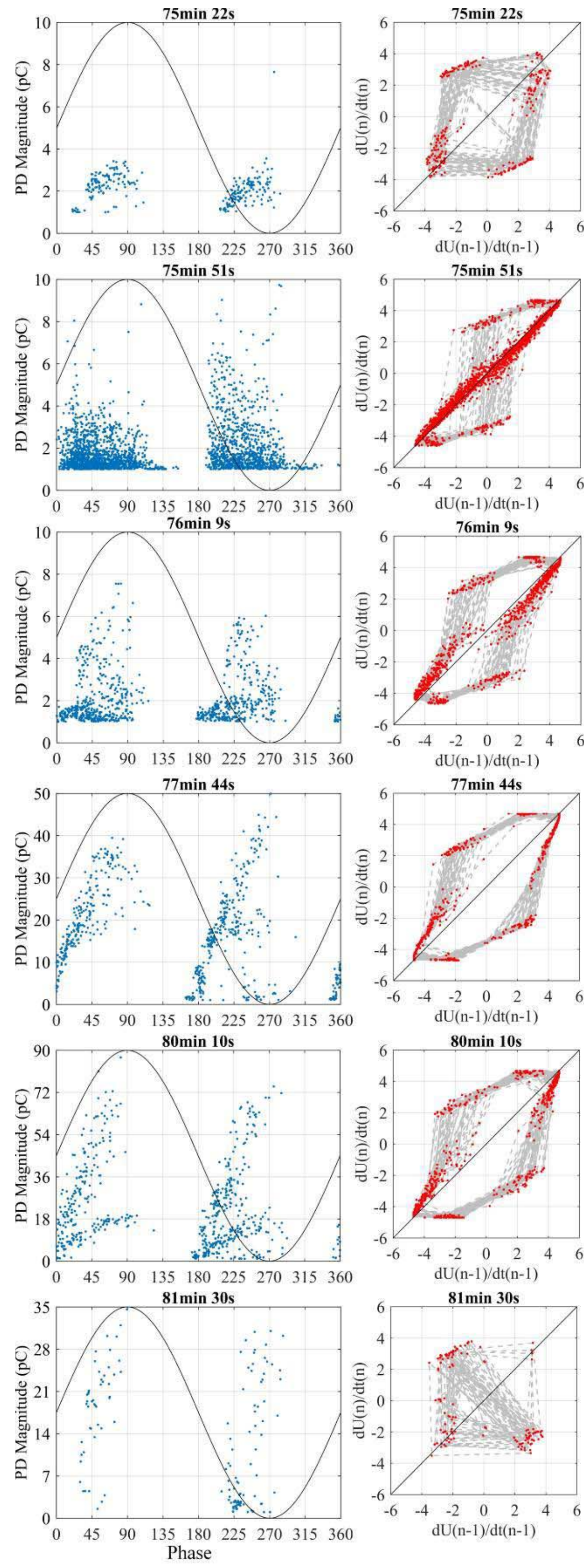

Figure 8. Phase-resolved partial discharge patterns and the pulse sequence analysis of partial discharge signals on the basis of scatter plots of *ΔU/Δt* in kV/ms. (a threshold of 1 pC was applied for raw PD signals though the equipment sensitivity was 0.5 pC)

At this time small tree segments in the filamentary tree channels near the needle electrode rapidly increased in radius. These local breakdowns resulted in darkened segments. Once such a local breakdown was observed, as shown in Figure 6d, PD activity in the reverse tree started to diminish. After the 81st minute, no further growth of the reverse tree was observed. The PD pattern of Time 5 shows higher discharge magnitudes than that of Time 4 when the reverse tree was still growing, though the shapes of the PD pattern and PSA plot are similar for both periods. The shape of the PSA plot for Time 4 suggests a discharge density variation with phase angle. The PD rate is largest at the highest voltage/time derivatives, *dU/dt*, i.e. at voltage zero crossings, and the rate decreases as *dU/dt* decreases.

Before the abrupt drop of Q_{IEC} at 82min 30s, there was a period of stable PD from the 81st minute. During this time, only a few (1 – 5) discharges occurred in each cycle. The PD pattern and PSA plot are similar to that at Time 1.

4.3 SUMMARY OF PD MEASUREMENTS

The observed PDs in reverse tree channels are consistent with the simulation work in [19] and the experimental work on artificial single channels in [20]. At early stages of reverse treeing, the PD magnitudes did not correlate to the point-on-wave voltage and therefore result in a 'turtle-like' [20] phase-resolved PD pattern. The rapid extension and widening of the reverse tree trunk is associated with a burst of PD, consistent with the findings in [21] and [22]. When the reverse tree trunk stopped further extension in length, it started to grow branches. As the reverse tree branches developed, the maximum PD magnitudes increased and the individual PD magnitudes became proportional to the point-on-wave voltage. Consequently a 'wing-like' [20] pattern formed. The double-wing shape at Time 5 is attributed to either: the simultaneous growth of two reverse trees, or two critical discharge lengths existing in a single tree. The PD pattern at Time 6 is similar to that measured on a needle-initiated tree of ~10 μm length [23]. This may be because, during this period the main damage occurred in short darkened tree segments, perhaps near the needle tip.

Based on the phase-resolved PD patterns and the proportional relationship between the Q_{IEC} magnitude and the length of the reverse tree, we conclude that the reverse tree is a non-conducting tree [24], although this conflicts with the understanding that conducting trees generally form in glassy resins [26]. It is clear that the filamentary tree is radically different from both the initial dark tree and the reverse tree. The PD characteristics of the filamentary tree fit the patterns expected of an electrically conducting tree in which most discharge magnitudes are less than 0.3 pC [26].

5 DISCUSSION

None of the sample preparation conditions (aluminum coated planar surface, exposure to air, or immersion in silicone oil) determined the formation of a reverse tree, nor did the features of the forward treeing process (whether an initial dark tree formed or the filamentary tree bridged the insulation). However, the likelihood of reverse tree formation seems to be highest when the sample was tested in air, with the formation of an initial dark tree and if the filamentary tree did not bridge the insulation. Testing in air seems to be necessary for a reverse tree to lead to breakdown. In addition, samples have to be exposed to air before a test for a filamentary tree not to bridge the insulation. Here we do not attempt statistical analysis of each factor as this requires far more data. Instead, the experimental results are used to verify the understanding of reverse tree formation.

When the reverse tree was first observed [8-10], the first hypothesis for its formation was that defects on the planar surface promoted such tree growth. However no such evidence can be found by visual inspection or controlled sample preparation.

Previously, most reverse trees observed in the same type of samples accompanied the formation of partially extended filamentary trees which did not bridge the insulation [10]. However, this work shows that filamentary trees which bridge the insulation can still result in reverse tree formation. The formation of partially developed filamentary trees may be attributed to increased treeing resistance adjacent to the bottom surface of the sample. This property may be due to the absorption of moisture [27] and even exposure to oxygen [28]. This is supported by the observation that samples exposed to room conditions in T1 and T2 could almost be guaranteed to form a partial filamentary tree while, on the contrary, only bridging trees were observed in T3 and T4 whose samples were sealed until testing/coating. The reason for a partially developed tree favoring reverse tree formation may lie in the fact that the local breakdown tunnels between darkened filamentary tree tips and the ground electrode have large diameters and thus are easier for PD excitation.

If the sample under test is not immersed in silicone oil, the likelihood of reverse tree formation and subsequent breakdown is much increased. This may be because that in practice the bottom surface of a sample will not be perfectly flat and there will be air gaps between the sample and the bulk electrode if the test cell is not immersed in the silicone oil. Therefore, if a vented filamentary tree channel is connected to ambient atmosphere, it is easier for partial discharge to occur [15] and consequently to develop a reverse tree. An alternative explanation is that if the vented tree is exposed to silicone oil, the oil may have some healing effect as the tree progresses, penetrating large voids in the tree channels, and so damping discharge activity and preventing a reverse tree.

The relationship between the initial dark tree and the reverse tree is not yet clear. However they may share similarities in formation mechanisms. Specifically, the necessity of the presence of filamentary trees to the formation of a reverse tree may be analogous to the impact of micro-cracks (near needle electrode) [29] promoting the initiation of a dark tree. The transition between an initial dark tree and the filamentary tree is yet to be explained.

A necessary condition for the formation of a reverse tree, in the work presented, is the prior existence of a filamentary tree.

However, the nature of the filamentary tree is not yet clear. As a result of the lack of PD measurements during the filamentary tree propagation, the tree might be expected to be electrically conducting, and the growth related to discharges or hot electrons at the tree tips in associated high electrical fields [30]. However, this seems unlikely given that the propagation of the filamentary tree did not accelerate when approaching the ground electrode (see Figure 4 in comparison with Figure 13 in [5]). Considering the fine radius of the tree channels, the growth of filamentary trees may be an electro-mechanical process, such as the electrofracture mechanics introduced by Zeller and Schneider [31] and the electro-mechanical breakdown proposed by Fothergill [32]. However, the erosion of the filamentary channels by homogenously distributed discharges released after new tree segments formed, as predicted in [31], was not observed in this work.

Considering the submicron diameter of filamentary tree channels, it is reasonable to suspect that in materials less transparent than epoxy (such as polyethylene), such growth, if it did exist, would not be apparent. Therefore it is not possible to draw directly on published data on semicrystalline materials. However we note that reverse tree growth takes the same form as electrical trees initiating from vented water trees. Specifically, water trees bridging insulation may not lead to breakdown [33]. However, subsequent electrical tree growth can occur back through the water tree to ground, resulting in failure [34].

The measured PD activity during reverse tree growth is consistent with a typical PD-driven tree that grows conventionally from a needle electrode. However this is extraordinary as the discharges occurred at a place of low Laplacian field. To mimic this in a simulation, for example [35], requires a variation in either the conductivity or PD inception voltage within a filamentary tree channel. For example, if the tips of the advancing filamentary tree are less conductive than the rest of the tree, the highest fields will occur in those channels as they approach the electrode. If fields are high enough, discharges will occur and consequently erode and widen the filamentary channels. Afterwards, PDs might be sustained in a widened region of a channel. Likewise, this chain reaction can be triggered when a tree channel has an increased radius, as with the local breakdown tunnels between a partially developed filamentary tree and the planar electrode.

6 CONCLUSIONS

This work describes in detail the distinct but coexisting tree structures of a filamentary tree and a reverse tree, developed in a glassy epoxy resin under AC stress. An interesting feature revealed by reverse treeing is that gas discharges and new trees can be initiated at a point of apparent low Laplacian field, from the planar surface.

The filamentary tree differs from classical electrical trees, i.e. branch and bush trees, in both tree shape and channel radius. A filamentary tree can be initiated from either a metallic needle electrode or from a thick (in radius) tree tip. Its propagation did not feature a runaway process to breakdown, instead the growth rate was found to be relatively constant. No discharge larger than 0.5 pC can be detected during its growth, which therefore seems consistent with an electro-mechanical process. Depending on the propagated structures, filamentary trees were described as either bridging or partially-developed. Whether the filamentary tree bridges the insulation appears to be primarily determined by the influence of ambient conditions on material properties, especially close to exposed surfaces.

The formation of a reverse tree may be a combined result of material properties, sample conditioning, and external experimental factors. So far we can only conclude that the growth of the filamentary tree seems to be a necessary precursor. Moreover, a reverse tree can be initiated from either a fine filamentary tree channel which reaches the ground electrode or a thick local breakdown channel between a filamentary tree tip and the ground electrode.

Partial discharge measurements and the trees' visual aspect suggest that the tree growth mechanisms for the filamentary tree and the reverse tree are fundamentally different. Analysis of partial discharge activity during reverse tree growth implies that the reverse tree belongs to the electrically non-conducting tree family, in which discharges can occur in the tree channels. This fundamental difference in nature may enable asset managers to differentiate ageing processes (filamentary tree growth) from the degradation processes (reverse tree growth) which are closer to the point of failure.

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This paper contains data which is openly available from www.manchestertrees.com.

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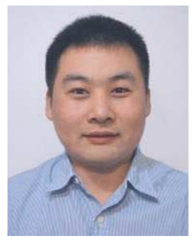

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