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Tree Growth in Epoxy Resin Under Unipolar and Bipolar Square-Wave Voltages

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Abstract- **The influence of DC bias on electrical tree growth under 13 kV square-wave voltages at 50 Hz in epoxy resin is investigated. Tree growth is captured in a needle-plane configuration using a CCD camera and digital microscope. Tree growth is accelerated under positive unipolar square waves in comparison with a bipolar square waves and negative square waves. Tree growth under positive and negative unipolar square wave voltages can be described as a three-stage process, while under bipolar square wave voltages tree growth follows a five-stage process. Reverse tree growth is observed before breakdown only under bipolar square waves. No reverse tree growth was seen under unipolar square waves of either polarity. Damage was observed at the bottom of the plane surface of epoxy where the reverse tree channels initiated.**

Keywords— epoxy resin; electrical tree; bipolar; positive unipolar; negative unipolar; reverse tree.

I. INTRODUCTION

The move toward HVDC transmission systems and the demand for reliable equipment raises a need for insulation materials that can operate under working conditions. Fast switching operations of power electronic converters introduce harmonics into DC systems [1]. These harmonics distort voltage waveforms and are known to reduce equipment lifetimes by increased heating and raising local stresses in insulation materials [1]. Therefore, it is important to investigate and understand the influence of harmonics and noise on a DC voltage on insulation material ageing.

Electrical trees are one of the most common mechanisms leading to high voltage polymeric insulation failure [2]. The initiation of electrical trees is not fully understood and while careful design and manufacturing processes can reduce their likelihood, they are difficult to eliminate entirely. There are several proposed mechanisms for electrical tree initiation: for example Tanaka suggested that trees can initiate by mechanical fatigue, partial discharges, and charge injection and extraction [3,4]. Electrical trees are often characterized by their physical appearance: the most common reported are described as bush trees, branch trees and bush-branch trees. These names come from their observed shapes and structural appearance. Many factors affect growth including applied voltage, frequency and temperature [1,5,6]. In service conditions, electrical tree growth is assumed to be a long-term aging mechanism and it may take years of operation before electrical trees initiate. Therefore, to accelerate the process of tree formation, needle-plane geometries are used in most laboratory experiments. According to Dissado and Fothergill [7] electrical tree growth in insulation systems can be described by three stages: inception, progression and runaway. However, Iddrissu et al. [8] found that some tree structures could have more than three processes, and divided the treeing into five stages: tree initiation, fast forward growth, fine tree growth, darkening of the fine tree, and reverse tree growth.

The stage of reverse tree growth witnesses electrical tree growth from the planer electrode toward the needle tip, which is in stark contrast to typical tree initiation and growth from sharp points and away from a highly divergent field. Reverse trees usually propagate through a fine tree structure previously grown from the needle. There are few papers addressing the behavior of reverse tree phenomena [8-10].

There has also been some work considering the impact of AC voltages superimposed upon DC voltages and their impacts upon electrical tree growth. Tian [11] analyzed electrical treeing when superimposing ± 20 kV DC on 15 kV sinusoidal AC within epoxy resin. The tree shape tended to be branch-like under positive DC while under negative DC a bush-branch-like structure was observed. The growth rate of electrical trees under positive DC was higher than negative DC. The samples stressed with positive DC voltages tended to breakdown faster compared to the samples under negative DC. Iddrissu [8] investigated the effect of ± 15 kV DC superimposed with 15 kV sinusoidal AC voltages on electrical trees within epoxy resin. The average breakdown time of the samples stressed with positive polarities was shorter compared with a negative polarity. The time to breakdown under positive and negative DC bias tests were shorter than under sinusoidal AC. Fine trees were observed in all tested samples while reverse trees were observed only under sinusoidal AC voltages without DC bias.

In this paper, the influence of DC bias on square wave aging is studied by superimposing 13 kV square-wave voltages with 13 kV DC voltages.

II. EXPERIMENTAL

A. Sample Preparation

Epoxy resin and hardener LY 5052/HY 5052, supplied by Huntsman, were used. HY 5052 was added to LY 5052 and mixed using a magnetic stirrer. The mixture was degassed in a vacuum chamber for 40 minutes to remove any air bubbles trapped during mixing process. Then the mixture was carefully poured into acrylic cubes and an Ogura® needle (3 µm tip radius) was embedded 2 mm from the bottom surface. The samples were then allowed to cure at room temperature for 24 hours and post cured for 4 hours at 100°C.

B. Experimental Setup

A schematic of the experimental set-up for treeing and partial discharge detection is in Fig. 1. A Trek HV amplifier was used to supply the voltage waveform. A 1 MΩ resistor was used to limit the current in case of failure. The output of the HV amplifier was monitored by oscilloscope through a 10000:1 voltage divider. Samples were immersed in silicone oil during testing to avoid surface discharges. A CCD camera with a ×50 magnification lens was used to capture electrical tree growth. An MPD 600 Omicron system was used to detect PD activity during the growth of a tree. The MPD 600 was connected to the MCU which transmits between the MPD and the computer, and the signal is transferred via optic fiber.

Five samples were stressed with each of the 50 Hz waveforms shown in Fig. 2 and are identified as:

a. 13 kV bipolar square wave (switching between ±13 kV)
b. 13 kV square wave –13 kV DC (negative unipolar square wave switching between 0 kV and -26 kV)
c. 13 kV square wave +13 kV DC (positive unipolar square-wave switching between 0 kV and 26 kV)

The rise-time of the square-wave voltage was 81 µs.

A digital Keyence microscope VHX- 7000 by was used to examine the tree in detail after testing.

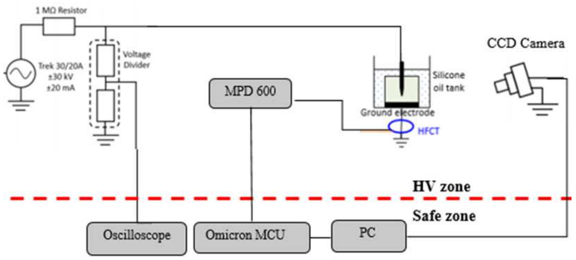

Fig. 1 Experimental setup for electrical tree growth.

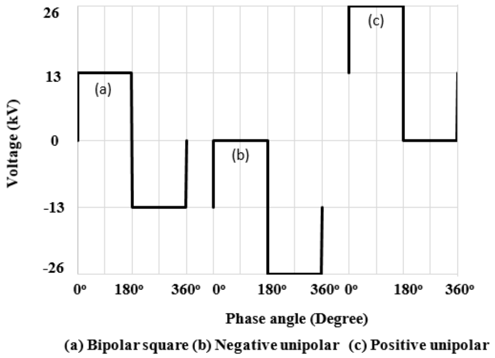

Fig. 2 The square waveforms used in this study.

III. RESULTS

A. Growth rate of electrical tree

Fig. 3 shows the average tree length under the 13 kV bipolar square wave and 13 kV unipolar square waves as a function of time from 5 samples in each case. The growth rate of an electrical tree is defined by the radial propagation of the tree from the needle tip towards the ground electrode as a function of time. It is seen that the trees extend faster under positive unipolar square compared to bipolar square waves and negative unipolar square waves. The growth rate under bipolar square-wave and negative unipolar square waves are comparable. The growth rate of the tree tends to be constant in time under all conditions.

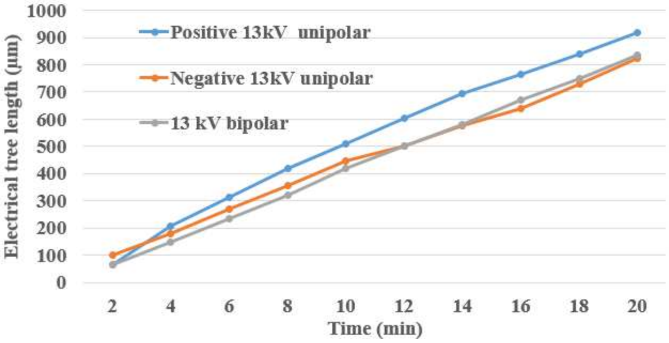

Fig. 3. Average of electrical tree length as function of time.

B. Structural characteristics of electrical trees

Fig. 4 (a,c,e) shows typical images of an electrical tree for each applied voltage waveform 10 minutes after tree initiation, reverse tree formation in a bipolar case in (b), and immediately prior to failure in unipolar cases in (d) and (f). Fig. 4 (a) and (b) show the growth under 13 kV bipolar square wave voltages. In Fig. 4 (a) a small bush tree has formed close to the needle tip; this was followed by growth of fine tree channels extending across the insulation towards the ground. This electrical tree structure is best described as a low-density bush and was seen in all tested samples. Samples did not fail immediately after reaching the ground electrode, as shown in Fig. 4 (b). Instead, a reverse tree was initiated from the planar electrode towards the needle tip by widening and darkening of fine tree channels at the planar electrode. The channels in the reverse tree are darker and thicker than any channels formed in the original tree (including those in the bushy area around the needle tip) as shown in Fig. 4 (b). Usually, reverse trees cause damage to bottom surface of sample in the form of large indentations as shown in Fig. 5. The larger of these depressions had a width of 244 µm and the smaller 139 µm.

Fig. 6 (a) and (b), taken 1 s apart, shows a large change in a fine channel as the reverse tree develops through it. This large change is attributed to the release of mechanical stress which had built up within the channel. Two seconds after the image of (b), Fig 6 (c) shows the channel had reduced in apparent size from (b), but permanently expanded into a larger, thicker channel than seen in (a). This differs from the expectation of gradual tree growth, showing a quick and significant growth within only 3 seconds. Further study using a digital microscope, Fig. 6 (d, e), shows discoloration along the newly grown channel. This suggests that reverse tree growth causes mechanical stress to build up, which can lead to distinctive crack formation inside the sample. Reverse tree widths are significantly larger than forward-growing tree channels with typical widths of 28 µm. The fine channels in this sample were found to be commonly between 1-2 µm in width. From literature fine tree channel widths are usually below 1 µm [9].

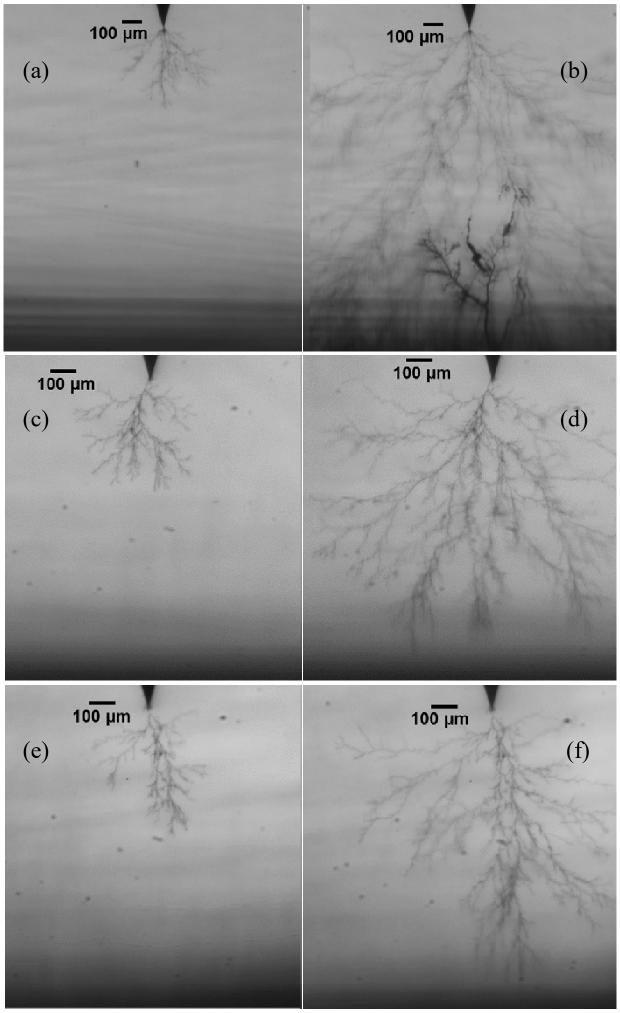

Fig. 4. Images of tree growth (a, c, e) after 10 min of tree initiation and (b,d,f) prior to breakdown. Trees are grown under: (a, b) 13 kV bipolar square wave, (c, d) -13 kV unipolar square wave, (e, f) +13 kV unipolar square wave.

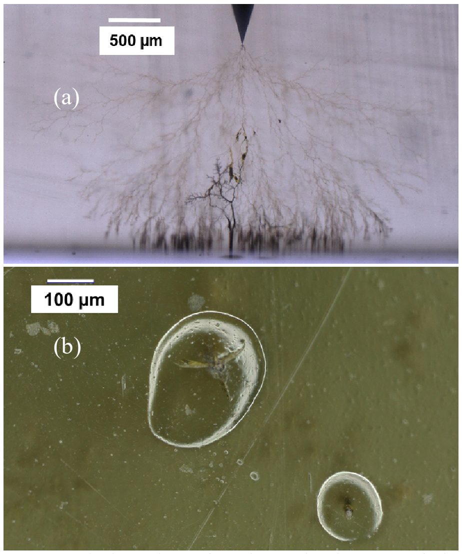

Fig. 5. Large indentations found on the bottom of the epoxy sample in locations in which reverse trees have formed: a) Typical needle-plane view of sample with reverse trees, b) Bottom of sample.

Fig. 4 (c) and (e) show the growth of electrical trees under negative unipolar square waves and positive square waves respectively after 10 mins of ageing. Under negative unipolar stresses, dark trees initiated from needle tip followed by fine tree channel growth. Similar growth behavior was recorded under positive unipolar square waves. The tree structure under negative unipolar was low-density bush tree-like while it is more branch tree-like under positive unipolar seen in Fig. 4 (e) and (f). Both negative and positive unipolar square waves cause immediate breakdown after reaching the ground. Fig. 4 (d) and (f) show trees immediately prior to breakdown under negative and positive unipolar square waves. For all tested samples, fine tree channels spread widely, as is typical for such sinusoidal trees [9], in contrast to the dark tree channels which initially formed around the needle tip for ~300µm.

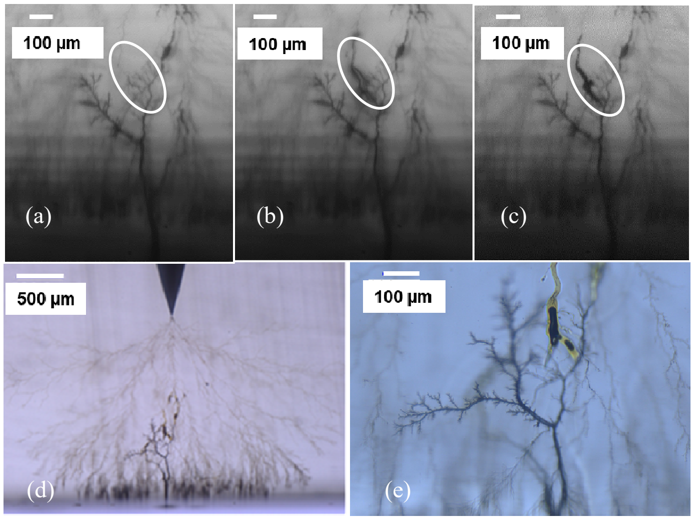

Fig. 6 Optical image of the reverse tree and suspected cracking inside the epoxy under 13 kV bipolar square wave. CCD images: (a) after 4125 s, (b) after a further 1 s, (c) after a further 2 s. Images (d) and (e) were taken after test completion (5880 s).

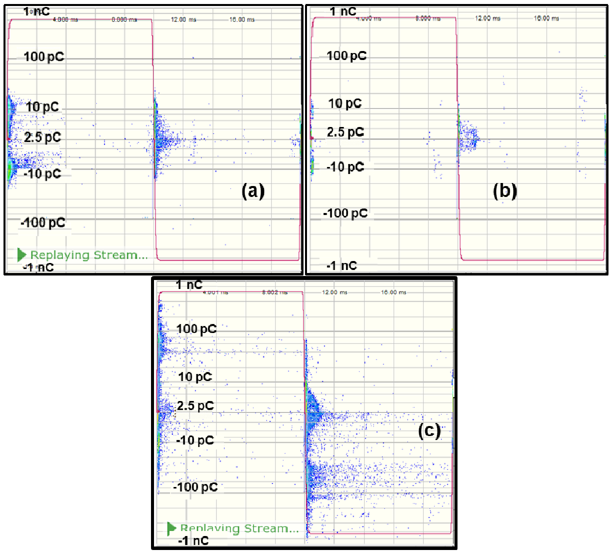

Fig. 7 Typical PD pattern of electrical tree under bipolar square wave. (a) pattern from forward tree grown for 10 min, (b) pattern during fine tree growth, (c) PD pattern during the growth of reverse tree.

Fig. 7 shows the PRPD patterns for the growth of initial forward trees, fine trees, and that of reverse trees under 13 kV bipolar square wave. The magnitude of the PD was ~25 pC in the first 10 minutes after initiation, which corresponds to initial short dark tree channel formation in front of the needle tip, as shown in Fig. 7 (a). PD activity reduced to 14 pC during the growth of the fine tree for about 1h and 20 min, as shown in Fig. 7 (b). Then, high level of PD magnitude of 400 pC was recorded during the initiation and growth of the reverse tree at the polarity reversal, as shown in Fig. 7 (c).

IV. DISCUSSION

Fig. 3 reveals that electrical trees grow marginally faster under the positive square wave compared to the bipolar square wave and negative square wave. A similar result was found under biased sinusoidal voltages [11]. Slower growth under negative unipolar is expected as electrons can be injected more readily than holes under positive unipolar voltages. This means that the shielding effect of space charge and subsequent reduction of the electric field at the needle electrode are greater under negative voltages. This is thought to physically extend beyond the initial tree growth [8].

With DC bias, electrical tree growth involved three stages: inception, progression and runway under both positive and negative unipolar square waves, whereas the electrical tree showed five stages of development without DC bias: tree initiation, fast forward tree growth, fine tree growth, darkening the fine tree, and reverse tree growth. This is probably because the absolute voltage applied across the sample is larger in cases of square wave with DC bias. The higher voltage leading to immediate breakdown rather than requiring a reverse tree to grow before breakdown occurred through the fine tree which had already extended across the insulation. As seen in trees grown under sinusoidal voltages, reverse trees grew from the planar electrode by widening and darkening of existing fine trees [9]. The growth of fine trees and subsequent reverse trees was reproducible for all tested samples under a 13 kV bipolar square wave. Compared to sinusoidal fine trees, square wave fine trees channels were slightly wider with a width of 1-2 μm (compared to <1 μm with sinusoidal waves). In the sinusoidal case it was also reported that PD was not observed (i.e., it was extinguished or became too small to be measured) during fine tree growth, but in this case, PD was not completely extinguished during fine tree development, though magnitudes did drop to 14 pC or below. It is not clear where this PD occurs in the tree structure and this maybe PD within the original darker tree structure. Despite this difference, overall comparison with the Iddrissu description [8] suggests these are best described as fine trees.

Reverse tree growth causes significant damage to the bottom of the sample through pitting at the site of reverse channels on the planar surface. This and tree imaging suggests mechanical cracking forms larger channels in the reverse tree as it develops back though the fine tree. The damage on the planar surfaces is associated with the higher levels of partial discharge sustained with in the reverse trees.

V. CONCLUSIONS

This work shows the influence of 13 kV bipolar square waves, and positive and negative 13 kV unipolar square waves in epoxy resin. Positive bias on the square waves accelerates the growth of electrical trees. In other words, positive polarities cause more severe damage than negative polarities. Electrical tree growth under positive and negative unipolar voltages see insulation failure once tree channels reach the planar ground electrode, while under the bipolar square wave it goes through an extra stage of reverse tree formation before failure. The reverse trees consisted of wider channels of ~30 μm in diameter, 10 times wider than typical forward trees.

It is shown that the magnitude of the AC component of the waveform essentially drives tree growth, with DC components having a relatively minor impact on growth speeds. However, the breakdown process of an aged sample which already includes the reverse tree is determined by the maximum voltage applied across the sample (i.e. including the DC component).

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REFERENCES

[1] I. Iddrissu and S. M. Rowland, "The impact of harmonic frequencies on electrical tree growth in epoxy resin," IEEE Conference on Electrical Insulation and Dielectric Phenomena, 2017, pp. 753-756

[2] H. Ding and B. Varlow, "Thermodynamic model for electrical tree propagation kinetics in combined electrical and mechanical stresses," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 12, no. 1, pp. 81-89, 2005

[3] T. Tanaka, "Tree initiation mechanisms," International Conference on Properties and Applications of Dielectric Materials: pp. 18-24, 1991.

[4] T. Tanaka and A. Greenwood, "Effects of charge injection and extraction on tree initiation in polyethylene," IEEE Transactions on Power Apparatus and Systems, no. 5, pp. 1749-1759, 1978

[5] F. Noto and N. Yoshimura, "Voltage and frequency dependence of tree growth in polyethylene," IEEE Conference on Electrical Insulation and Dielectric Phenomena, pp. 207-217, 1974

[6] L. Zhu, B. Du and K. Hou, "Effects of Temperature Gradient on Electrical Tree Initiation and Breakdown Phenomenon in XLPE Under Harmonic Superimposed DC Voltage," IEEE Access, vol. 9, pp. 7586-7596, 2021

[7] L. A. Dissado and J. C. Fothergill, Electrical Degradation and Breakdown in Polymers, Peter Peregrinus, London, 1992.

[8] I. Iddrissu, S. M. Rowland, H. Zheng, Z. Lv and R. Schurch, "Electrical tree growth and partial discharge in epoxy resin under combined AC and DC voltage waveforms," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 25, no. 6, pp. 2183-2190, 2018

[9] H. Zheng, S. M. Rowland, I. Iddrissu and Z. Lv, "Electrical treeing and reverse tree growth in an epoxy resin," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 24, no. 6, pp. 3966-3973, 2017

[10] M. Pattouras, A. Tzimas, and S. M. Rowland, "The effect of material interfaces on electrical tree growth and breakdown time of epoxy resin," IEEE Conference on Electrical Insulation and Dielectric Phenomena, pp. 796-799, 2013

[11] M. Tian, B. Du, J. Su, J. Li, L. Zhu, and Y. Yu, "Electrical tree in epoxy resin under combined DC-harmonic voltage," IEEE Conference, Condition Monitoring and Diagnosis, 2018