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The Impact of DC Bias on Electrical Tree Growth Characteristics in Epoxy Resin Samples

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Abstract— The effect of DC bias on electrical tree growth characteristics in epoxy resin samples is investigated, using three waveforms types: AC, AC with positive DC bias, and AC with negative DC bias. Point-to-plane samples were used. AC tests resulted in 62% and 48% longer average time to breakdown than positive and negative DC biased tests respectively. The negative DC bias test had 14% longer average time to breakdown than positive DC bias test. It is suggested that this is due to space charge injection modifying the field at the tree tip. 4 stages of distinct tree growth are identified in AC tests compared to 3 stages in DC bias tests. In particular, the phenomena of trees growing in the ‘reverse direction’ (from the planar to the point electrode) observed in the latter stages of AC tests, is not seen in the DC tests reported here. This is thought to be due to the peak field magnitudes involved in each case.

Keywords—Electrical treeing, Space Charge, AC, DC-bias

I. INTRODUCTION

Growth of an electrical tree in solid polymeric insulating material is evidence of a long term, irreversible path to failure [1]. Treeing resistance, in polymeric insulating materials for HV systems are thus widely investigated [2]. Published work in this area of research shows that higher voltages are required for an electrical tree to be initiated under DC as compared to under AC fields [3]. However, experiments using polarity reversal and impulses on DC insulation shows some materials have a vulnerability to space charge injection/accumulation and subsequent electrical treeing [4-5].

Increase in power demand and integration of renewable energy sources in the existing grid, has accelerated installation of HVDC power transmission projects around the world [6]. HVDC transmission is the preferred technology for bulk power transfer over long distances due to its economic advantages, and HVDC technologies are still being developed. Converters are required at both sides of HVDC links, and the proven technology for this is the traditional line commutated converters (LCC). LCC require voltage polarity reversal to change power flow direction, and this presents a threat to the insulation if not well managed due to space charge injection [7]. Recent voltage source converter (VSC) technology eliminates the need to reverse voltage polarity to achieve reversed power flow direction [8], but VSC technology presently has a limited voltage rating of up to $\pm 500\text{kV}$ [8] compared to LCC which is available at voltage ratings up to $\pm 800\text{kV}$. However, both converter types require extensive, and costly, filtering of harmonics. As a result, the impact of harmonics on the reliability of DC insulation requires investigation. In particular, there is potential financial

advantage if harmonics can be allowed on a network, with no consequential reduction in reliability.

Preliminary investigations in our laboratory reveal that superimposing 10 kV / 50 Hz peak ac ripple on a 30 kV DC source can readily initiate electrical tree in an epoxy resin sample. However, with 30 kV DC only no tree was observed. This observation suggests that, if noise of say 10 kV (only 2% of 500kV) magnitude is realized on a 500kV DC link for example, its reliability may be compromised.

In this paper, preliminary results of a study on the effect of DC bias on electrical tree growth characteristics in epoxy resin samples, using point-to-plane samples are investigated. The results show that different mechanisms of electrical tree growth are seen under AC with and without DC bias.

II. EXPERIMENTAL

A. Sample preparation

Fig. 1 shows the sample electrode configuration for this study. To simulate a structural defect generating high divergent fields in the epoxy resin block, a point-to-plane configuration method of sample preparation was used [9]. The samples were prepared from a low viscosity epoxy resin Araldite® LY 5052 and the corresponding hardener Aradur® HY 5052 both supplied by Huntsman.

The required volume of the resin/hardener system with mixing ratio 100:38 (parts by weight) was hand-mixed for about a minute followed by magnetic stirring for 5 minutes. The mixture was degassed in a vacuum chamber at room temperature for 60 minutes and then poured into a hollow acrylic cube. The mixture is allowed to cure at room temperature for 24 hours, followed by a further 4 hours at 100°C. Ogura needles of 1 mm diameter and 3 μm tip radius were used as the HV voltage electrode with gap distance of (1.9 ± 0.1) mm. The ‘plane’ surfaces of the samples were metallised with aluminium by vacuum evaporation to ensure

Fig. 1: Point to plane sample configuration

good contact with the ground electrode. In total, 36 samples were fabricated as described above for this study.

B. Experimental set-up and test procedure

Fig. 2 shows the experimental set-up, which consists of two main parts. The part enclosed in the solid line is the low voltage generation and monitoring side. This part is equipped with an oscilloscope, a pre-amplifier and a purpose built PC which integrates an arbitrary waveform generator (AWG-PCI 5421) and a waveform editor, both supplied by National Instruments. Also the PC is loaded with soft front panel and common vision blox software(s), which allow flexible control of both the HV amplifier and the image-grabbing capability of the CCD camera. The equipment enclosed by the dotted line, is in an HV interlocked cage and consists of a Trek HV amplifier (0 to ± 30 kV peak), the test cell, and a Manta monochrome progressive scan CCD camera with resolution; 2452 (W) x 2056 (H). A DC-powered light source is used to eliminate image flickering during image acquisition. The experiment is performed in two stages; a quick tree-initiation process and propagation. The quick initiation is employed in order to ensure all samples have a common tree inception process which results in the shortest possible tree initiated in them. In this way, the time to breakdown from the propagation stage can be equitably compared after initiation in all tests.

Stage 1: Quick initiation: In this stage of the experiment, the CCD camera is set to capture an image every second and is fitted with a c-mount macro lens of 8x magnification with maximum field of view 1(W) x 0.8(H) mm, to detect and capture the shortest possible tree image after voltage application. Immediately an initial tree image is detected, the experiment is stopped and the sample replaced with new sample. All the 36 samples fabricated for this study were initiated in this manner with an unbiased AC voltage (between 12 and 16) kVrms, and 30 samples with tree lengths not longer than 50 μ m, called hereafter the ‘initial tree’, were then used for the second stage of the experiment.

Fig. 2: Experimental set-up. Equipment in area (2) is within an interlocked high voltage enclosure

Stage 2: Propagation: In this stage, the 30 samples with their ‘initial trees’ were randomly divided into 3 groups of 10 samples. Each group was subjected to one of the following three voltage forms, shown in Fig. 3 and characterised in Table 1.

- AC test at 15kV peak
- AC at 15kV peak with +15kV DC bias
- AC at 15kV peak with -15kV DC bias

Fig. 3: Waveforms used for this study

TABLE 1: TEST VOLTAGES AND GEOMETRICAL FIELD*

Test type and calculated voltages and E-field	Point-to-point were used: Point radius = 3um and Gap distance = 2mm			
	Vpk (kV)	Vrms (kV)	Eav = V/d (kV/mm)	Etip = $2V/r \ln[(1+4d/r)]$ (kV/mm)
AC	15	10.6	5.3	895.9
+/-DC+AC	30	18.4	9.2	1555

*these fields are not those expected at the needle tip, but are those associated with the geometry only.

At this stage of the experiment, the CCD camera is fitted with a c-mount telecentric lens with 6 (W) x 5 (H) mm dimensions of field of view. This allows the whole tree length from the initiation stage until breakdown ensued to be captured. Tests were performed in silicone oil to prevent flashover. Prior to testing the silicone oil is dried at 85°C for 24 hrs and allowed to cool to room temperature under vacuum. Samples were kept under controlled humidity conditions in desiccator prior to testing, and between tree initiation and later growth tests.

In each test, the samples are continuously stressed with one of the voltage forms shown in Fig. 3 and images are taken either at 1 or 60 second intervals (depending which stage they are in) until breakdown occurred.

III. RESULTS

This section discusses the time to breakdown and tree growth characteristics from the three test types. Three particular samples with similar times to breakdown (i.e. 70, 77 and 81 minutes) are considered in detail, to compare and contrast typical differences observed in all of the samples tested from the three test types. These differences relate to growth characteristics and differences in the tree growth features.

A. Time to breakdown:

Fig.4 shows the time to breakdown from the three test types. Under the AC test regime, 3 of the samples did not breakdown: two after 12hrs, and one after 4hrs of voltage application. The experiment was stopped for these samples due to the extensive damage suffered by the samples which almost turned the 2 mm gap into semi-carbonised material. The plot of the remaining samples shows that time to breakdown for an AC test is more widely distributed as compared to that of the positive and negative DC biased tests. The average time to breakdown under an AC test is 143 minutes; whereas under positive and negative DC bias tests are 54 and 78 minutes respectively. The difference in time to breakdown between AC and positive DC bias test is 62% and between AC and negative DC bias test is 48%. The difference between positive and negative DC biased test is a reduction of 14%. The possible explanations for the significant difference between pure AC and the DC biased tests is the substantially higher fields under DC bias tests compared to that under AC. However the absolute field of DC bias itself does not explain the difference since it is known that a 30 kV DC field (with high power quality) will not grow an electric tree. However, the 14% difference between positive and negative DC bias test is probably associated with space charge moderating the field at the electrode vicinity under negative bias more than under positive bias test [9-10].

B. Electrical tree growth characteristics:

Fig. 5 shows the plots of tree growth rate characteristics of the selected three samples for the three test regimes. The shape of the plots show progressive growth characteristics in all three test types as compared to the traditional growth characteristics described in [11], which consists of three distinct stages; the inception stage, the propagation (fast and slow growth) stages and the runaway stage. But the “lying S”. shape [12] obtained from the plots is a common observation on experimental tree growth characteristics found in the literature. The results shown in Fig. 5 should not be taken to show that trees grow at the same rate on average under the different voltage regimes. Fig. 4 shows this is not the case. But Fig. 5 does suggest that in the case of individual trees which lead to failures in the same times under the different stresses, they have the same changes to their growth rates during the entire process.

Fig. 4: Time to breakdown plots for the three test types

Fig. 5: Comparison of growth rate plot of three samples from the three test types after initiation

The images shown in Fig. 6 reveal four stages of growth propagation herein defined as:

1. *Thick initial growth stage*; characterized by dark, wide tree channels immediately in the vicinity of the point electrode. This is an extension of the ‘initial tree, formed after the initiation stage and grows for up to about 10 minutes of voltage application, but is not necessarily fast growth.
2. *Fine tree growth stage*; marked by spreading of fine tree channels growing the visible aspect of the tree in both length and width, during 10 to 50 minutes of voltage application.
3. *Thickening of the fine tree channels stage*; characterized by darkening and widening of the fine channels on approaching the ground electrode or touching the ground electrode, shown by images at 70 minutes in Fig. 6.
4. *Reverse tree growth stage*. This stage is characterized by a tree growing in the opposite direction from the ground electrode towards the HV electrode. This characteristic is observed only under AC tests but was seen on all samples tested.

The ‘reverse tree’ seen in AC tests can apparently grow independently of the existing fine channels, and grows from the ground electrode toward the needle.

Stages 3 and 4 can both lead directly to breakdown, depending on the magnitude of the applied voltage as shown in Fig. 6.

IV. DISCUSSION

From the plots of Fig. 4 and images from Fig. 6, the differences between AC tests and AC with DC bias tests can be clearly seen. It is demonstrated that AC tests go through 4 stages of propagation before breakdown occurs, while in the AC with DC bias tests, only 3 stages are observed for both positive and negative DC bias.

Fig. 6: Comparison of growth characteristics of three samples from the three test types after initiation

That the time to breakdown under positive and negative DC bias tests are shorter than under AC test reveal that, the rate of tree propagation is driven by the combined effect of AC and DC components (effective rms value) of the applied waveform and not only the AC component. This is in agreement with the findings in [13] on tree initiation using superimposed voltages. It is suggested that the longer time to breakdown with negative DC bias compared to with positive bias is due to electric field moderation by homo-space charge at the negative electrode [9-10].

In stage 4, the reverse tree growth may be due to the relatively low field under AC test as compared to the tests with biased fields. Table 1 shows the calculated peak fields (i.e. determined from geometry and voltage alone) at the needle tip are nearly doubled in the DC biased tests. Also for all samples under DC bias tests, it is only the forward moving

channels which become dark and widened from the existing fine channels that facilitated path to failure.

V. CONCLUSIONS

It is observed that although pure DC stresses generally do not lead directly to rapid tree growth, when combined with AC stresses they do accelerate tree growth and lead to faster breakdown than if only the AC field was present. The positive DC bias test had a more detrimental effect than the negative bias.

The fourth stage of tree growth identified here, in which a tree grows backwards through the first tree from the plane electrode towards the needle electrode, only occurs at lower test voltage magnitudes. This is not a process seen at higher fields. Reverse trees or trees growing from the planar electrode have been observed previously [14] at 13 to 14 kVrms and in [15] at 15 kV as in this study. If this event is indeed associated with lower voltages, it will impact practical insulation design and require further investigation.

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