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The Impact of Harmonic Frequencies on Electrical Tree Growth in Epoxy Resin

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Abstract—Electrical treeing in solid polymeric insulation is physical evidence of internal damage and ultimately leads to equipment failure. This study considers the effect of frequency on treeing breakdown times in epoxy resin between 50 Hz to 450 Hz. The tree structures generated from 50 to ~250 Hz were filamentary, had narrow channels and spread throughout the insulation. Tree structures generated from ~250 Hz to 450 Hz were darker, having wider channels and less branching. The rate of tree initiation and propagation increases with increasing frequency, resulting in reduced time to breakdown. This has implications that harmonics in AC and DC networks require careful management to ensure insulation reliability is not compromised.

Keywords—*Electrical treeing, frequency, acceleration, initiation and breakdown times, asset management*

I. INTRODUCTION

Electrical trees are channel defects of micrometre diameter which developed in high voltage solid polymeric insulating materials, and are a precursor to long term failure of electrical plant [1]. Investigation of cables removed from service shows that treeing degradation is an important physical indication of internal damage to cable insulation, typically emanating from points of high electrical stress or defects in the insulation system [2]. Tree initiation, propagation rate, structure and time to breakdown is influenced by the magnitude of the applied voltage, the frequency of the test voltage, as well as the local electric field in the material [3-6]. Tree channel expansion and extension is linked to partial discharges in the tree channel column and is frequency dependent [3].

Waveform distortion due to harmonic-generating loads may cause additional heating and raised local stress in dielectrics used in high voltage equipment [7]. For example, distorted waveforms on cable systems can overload the neutral cable of a balanced 4-wire three phase system by a harmonic current factor of about ~1.73 times that of the phase conductor [8]. A study on cable system in Rome [9] showed a significant reduction in power cable life under harmonic pollution. Bahadoorsingh et al [10] and Sarathi et al [11] investigated electrical treeing in the laboratory with superimposed harmonic frequencies on the fundamental power frequency in epoxy resin and XLPE samples respectively. In both studies, analysis showed that the life of insulation is reduced when distorted waveforms are used. Bahadoorsingh et al [10] found that a composite waveform containing the 7th harmonic was particularly detrimental to insulation life time.

With increased use of power electronic devices, the impact of harmonics needs further investigation. Previously the authors have shown that by biasing a 15 kV, 50 Hz power frequency supply with either positive or negative 15 kV DC, insulation lifetime was reduced significantly [12]. This study investigates the effect AC frequency on tree growth in the frequency range 50 Hz to 450 Hz.

II. EXPERIMENTAL

A. Test Sample

Blocks of epoxy resin samples were prepared from a low viscosity Araldite® LY 5052 and the corresponding hardener Aradur® HY 5052 using the classic point-to-plane sample configuration. Ogura™ needles of 1 mm diameter and 3 µm tip radius were used as the HV voltage electrode with gap distance of 1.8 ± 0.2 mm. The ‘plane’ surface of each sample was metallized with aluminum by vacuum evaporation to ensure good contact with the ground electrode. The sample preparation procedure and experimental set up are detailed in [12]. Data for 50 Hz has been taken from 10 test samples in [12]. For frequencies above 50 Hz, 48 samples were fabricated from four additional batches of 12 samples from which 24 samples were selected at random and divided into 4 groups of six samples for test in this study. After post curing at 100 °C for 4 hours, samples were kept under controlled humidity conditions in a desiccator prior to testing.

B. Test procedure

A Trek high voltage amplifier (model PD06035, ± 30 kV peak AC) with slew rate greater than 750 V/µs was used as the high voltage source. The input signal to the HV amplifier was generated from Arbitrary Waveform Generator (AWG-PCI 5421) integrated in a PC. Electrical trees were grown in the test samples using 15 kV peak AC in the frequency range of 150-450 Hz (i.e. $f_{150\text{Hz}}$, $f_{250\text{Hz}}$, $f_{350\text{Hz}}$ and $f_{450\text{Hz}}$). Each sample in each group of six test samples was stressed individually and continuously until electrical trees were initiated. Once an electrical tree was initiated, an additional 5 hours was allowed for tree propagation until breakdown. The experiment was stopped if test sample did not fail 5 hours after tree initiation. Tests were carried out at room temperature and in silicone oil to prevent flashover. Prior to testing the silicone oil was dried at 85 °C for 24 hours and allowed to cool to room temperature under vacuum. Treeing images were recorded every minute using a monochrome CCD camera (Manta G-504B) with a resolution of 2452 x 2056 pixels representing 6 mm width by 5 mm height of the tree images, captured with C-mount

telecentric lens. A DC-powered light was used as illuminating back light during image acquisition.

III. RESULTS

To clarify the effect of frequency on electrical treeing, the recorded tree images were cropped to 1801 x 1151 pixels (i.e. ~ 4.4 mm width by 2.8 mm height, as shown in Figure 1, from which, tree propagation times to 1 mm and to cross the 2 mm gap of the insulation, and breakdown times after tree initiation (or test duration if no breakdown occurred) were recorded for each test sample. The results are presented below.

A. Tree initiation time

Figure 2a shows a box chart plot of tree initiations times for all test samples in this study excluding those from previous study at 50 Hz. As mentioned above, data for 50 Hz samples has been taken from [12] and in that study, samples were pre-initiated at higher voltages (between 17 to 22.6 kV pk) before testing at 15 kV pk. For the samples presented in this study, an obvious decrease in mean time to initiate a tree (shown by the horizontal line on each box) can be seen with increasing frequency (i.e. between $f_{150\text{Hz}/f_{250\text{Hz}}}$ and $f_{350\text{Hz}/f_{450\text{Hz}}}$), although a wide distribution of the initiation times is seen amongst the group of samples tested at each test frequency. The box height represents the difference between the upper and lower 25% quartiles of the data set (the inter-quartile range). At 150 Hz, 50% of the samples initiated within one minute of voltage application, while the other 50% initiated almost 100 minutes after voltage application. At 350 Hz and 450 Hz, 66.7% and 33.3% of the samples initiated in the first minute of voltage application respectively while the remaining test samples initiated at various times as shown on the plot.

B. Tree growth rate and breakdown times

Figure 2b shows the plots of time taken for trees to traverse the first millimetre from the needle tip, and subsequently the second millimetre of the insulation gap for all samples. It can be seen that the times taken for trees to traverse the first and second millimetre of the gap decreases with increasing test frequency above 150 Hz. The tree growth rate at 50 Hz and 150 Hz were similar to each other and indistinguishable in the first and second half of the insulation gap distances (noting the data for 50 Hz is from a different batch of samples). At 250 Hz the tree growth rate increases, particularly in the second millimetre and an accelerated growth becomes more obvious at 350 Hz and 450 Hz respectively. Whilst at 250 Hz and 350 Hz the tree growth rates in the second millimetre of the insulation gap were faster than in the first millimetre. At 450 Hz, the opposite scenario was observed as shown by the black and red boxes of Figure 2b.

Figure 2c shows the sample breakdown times after tree initiation (black boxes) or survival time (red boxes and arrows indicating test samples did not fail by the time the test was terminated). After traversing the ground electrode, it took a time ranging from minutes to hours before breakdown finally ensued across all test frequencies. The shortest time for sample breakdown after the tree traversed to the ground electrode was 1 minute and this occurred in 3 samples only (1 sample at 450 Hz, and 2 samples at 350 Hz). In some cases, when breakdown did not occur after extended times (~5 hours) after tree initiation, and then tests were manually terminated. During this

Figure 1: A; Dimensions of the cropped image used for analysis B; time taken for trees to cross the first millimetre and then the second millimetre were used to compare tree propagation.

Figure 2: (a) Tree initiation times at $f_{150\text{Hz}}$, $f_{250\text{Hz}}$, $f_{350\text{Hz}}$ and $f_{450\text{Hz}}$ after application of 15 kV peak AC voltage; (b) times taken for trees to traverse the first mm and second mm of the insulation gap; (c) Samples breakdown times or de-energizing times when samples did not fail 5 hours after tree initiation

time, the trees continue to grow internally, including new side branches being formed. At the higher frequencies of 350 Hz and 450 Hz, all the samples failed within 5 hours. At 50 Hz, 7 out of the 10 samples failed, while at 150 Hz, only 1 out of the 6 samples failed and at 250 Hz 3 out of the 6 test samples failed. In the remaining test samples the experiment was stopped due to visibly dense damage suffered by the samples. Even considering only the test samples that failed, it is clear from the plot of Figure 2c that, time to breakdown decreases with increasing test frequency.

C Tree shape

Figure 3 shows the tree shapes observed at each test frequency. Images B, C, D and E are obtained in this study, while image A is from the previous study at 50 Hz [12]. The propagated tree lengths and shapes for each test frequency are shown. T_1 , is taken at 5 minutes after tree initiation and T_2 is the time prior to sample breakdown or the time when the experiment was stopped before sample failure. It has been shown previously that at 15 kV 50 Hz peak, electrical trees can grow in both towards and away from the planar electrode and can sustain the applied voltage for considerable amount of time (hours) before breakdown [12-13]. A typical example is the image shown in Figure 3A, for which the experiment was stopped after 727 minutes. In that experiment, the tree traversed the gap 72 minutes after initiation. At $T_1 = 5$ minutes a dark tree is observed growing from the needle. Later fine tree channels were observed occupying volume between needle and plane electrode. Subsequently, a tree is observed to be growing from the ground electrode through the fine tree towards the needle (reverse treeing [12-13]) shown by the inset image at time $T_3 = 73$ minutes in Figure 3A.

Tree structures observed at 150 Hz were similar to those observed at 50 Hz as shown in Figure 3A and 3B, except that at 150 Hz, reverse trees growing from the planar electrode were not observed in all test samples. However, trees occupied the insulation in both length and width at about the same rate at 50 Hz and 150 Hz, as shown in Figure 2(b).

At 250 Hz, generally a smaller volume of the insulation was occupied by trees in all test samples. The tree branches are sparse and on average traversed both the first and second millimetre gap of the insulation faster than at 150 Hz. However, a mixture of fine and thick dark tree shapes were observed with 4 out of 6 test samples having similar tree shapes to those at 150 Hz, while the remaining 2 samples looked like the one shown in Figure 3C.

Reduction in volume occupied by trees at 350 Hz and 450 Hz is apparent from Figure 3D and 3E. Tree shapes at 350 Hz and 450 Hz are similar to each other, having darker and thicker tree channels than at lower frequencies. In general they bifurcate less at 450 Hz and propagate faster in the field direction compared to those at 350 Hz. As can be seen from Figure 3E, 5 minutes after initiation at 450 Hz, the tree is already approaching the ground electrode whereas at 350 Hz the tree is only approaching the first 1 mm of the insulation gap distance as shown in Figure 3D at $T_1 = 5$ min. At 450 Hz, tree structures in 4 out of the 6 test sample looked similar to that shown in Figure 3E while at 350 Hz, half of the tree structures were as shown in Figure 3D. In the rest of the samples, similar tree shapes to those observed at 150 Hz and 250 Hz were observed,

Figure 3: Structure of electrical trees at: A; 50 Hz, B; 150 Hz, C; 250 Hz, D; 350 Hz and E; 450 Hz. T_1 = tree length 5 min after initiation, T_2 = Time and tree structure immediately prior to breakdown except for image A where the test was manually stopped due to huge damage at 727 mins. The 0.7 mm scale bar applies to all images.

but occupying a smaller volume of the sample gap distances and having faster growth rate.

IV. DISCUSSION

Frequency-dependent tree initiation: The results presented above showed a decrease in mean time to initiate a tree with increasing frequency, although wide variations in tree initiation times were observed at all frequencies. This observation is not surprising as tree initiation does not depend only on the magnitude of the applied voltage and frequency but also depends on the bonding between the electrode-sample interfaces, and whether air gaps are present at such interfaces. All of these will play a critical role in tree initiation times and subsequent propagation as observed in [4]. If short initiation times are attributed to poor needle epoxy interfaces, then the remaining data points show an even stronger frequency dependence than if all the data is averaged.

Frequency-dependent tree growth and time to breakdown:

The rate of tree propagation increases with increasing frequency of applied voltage, leading to reduced breakdown times. This trend is clearly shown in Figure 4 where the averages of the characteristic times from Figure 2 are plotted as a function of the applied voltage frequency excluding data for 50 Hz (from the previous study) for clarity. Note that only samples that breakdown were considered in Figure 4.

If the tree channel is assumed to be gas filled with conducting plasma as reported in literature, then it is likely that the applied field at the tips of the tree channels and through the plasma will depend on the frequency of the applied voltage as proposed in [3]. If the field at the tree tips is greater than the intrinsic breakdown of the material, then certainly local bond scission will occur and will be accelerated by the frequency of the applied voltage [4]. Considering this process, one can envisage erosion and widening of tree channels being driven by increasing frequency as observed in this study. This is evident in this study when only the time taken for trees to cross the first and second millimetres of the insulation or to cross the entire insulation gap was considered shown as T_{1mm} , T_{2mm} and T_{GD} on the plots of Figures 2 and 4.

Frequency-dependent tree shape: While fine tree structures were mainly observed at 50 Hz and 150 Hz, at and above 250 Hz changes in tree shapes begin to be evident with thicker and darker tree branches occupying less volume of the insulation gap as shown in Figure 3. Partial discharge activity (to be reported separately) during the development of the fine tree channels were quiescent typically measuring less than 1 pC. Partial discharge activity registering 100's of pC in magnitude were measured when wide and dark tree channels were developing at all the test frequencies. The fine tree channels may then be generated by crack propagation caused by released electrostatic energy and electromechanical strain energy stored in the material [14] which subsequently supports high discharge activity when dark tree channels develop. The dark and wide tree channels, observed from 250 to 450 Hz as

Figure 4: Averaged characteristic times of tree growth against frequency of applied voltage. T_i = time to initiation, T_{GD} = time to traverse the insulation gap distance after tree initiation. T_{BD} = mean breakdown times after tree initiation.

shown in Figure 3, may be caused by erosion of tree channels due to rapid charge injection and extraction every half cycle of the applied voltage frequency [5]. This is a primary reason for accelerated ageing at higher frequencies.

V. CONCLUSIONS

The effect of frequency on tree propagation and breakdown times in epoxy resin samples has been studied. It is concluded that increasing the frequency of the applied voltage increases every stage of the processes including the rate of tree inception, tree propagation and time to failure. The effect of frequency is more prominent above 350 Hz. This has important implications for the design of both AC and DC equipment and on acceptable limits of harmonics in high voltage networks.

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