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Effect of Insulating Gases on Electrical Treeing in Epoxy Resin

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Abstract - Electrical trees initiated from defects in solid insulation are one of the main causes of cable insulation failure. Both the initiation and propagation of electrical trees are linked to PD activity in the free volume and interfaces between electrode, gaseous and solid dielectrics. This work investigates the potential of suppressing partial discharge (PD) during tree propagation by displacing air with a higher electron affinity gas. Epoxy resin samples with pre-existing trees were energized under 7 kVrms in atmospheric air and SF6 under 2 bar absolute for 3 hours. PD measurements indicate that the permeation of SF6 into the epoxy sample could significantly reduce the discharge energy and lead to a reduced number of discharges. However, the tree length growth was comparable for both gases. This is attributed to offsetting of reduced PD energy by SF6 within the tree channels and subsequent reaction between gas by-products and the epoxy.

I. INTRODUCTION

Polymers are ubiquitous as insulating materials for high voltage insulation cable systems. However, formation of defects and impurities is inevitable during manufacturing and processing. Defects such as protrusions, contaminations and voids can cause a higher localized electric field and lead to PD, electrical tree growth and eventually breakdown during normal operations [1]. This work is targeted at understanding whether there is the potential to slow down tree growth in polymers, and extend asset life, by displacing air with electronegative gases. Epoxy resin and SF6 have been chosen as model materials. The latter has been widely used in gas insulated equipment for high dielectric strength gases like SF6. In this work, a comparison of the PD behavior of epoxy sample under air and SF6 was made.

II. EXPERIMENTAL DETAILS

A. Sample Preparation

In order to accelerate the electrical treeing process, a point-to-plane configuration was used. The detailed preparation method is described in [6]. In brief, an Ogura tungsten needle with diameter of 1 mm and tip radius of 3 μm was inserted into an epoxy resin block (25*25*25 mm) before curing. The bottom of the epoxy resin block was coated by aluminum by vacuum evaporation method. The gap distance of needle to plane electrode is fixed at 2 mm. To ensure repeatability, six samples had trees incepted by applying 11-15 kVrms under atmospheric air to create initial tree lengths of ~50 μm. These samples with pre-incepted trees were then assembled within a pressure vessel with the help of a needle holder and a stainless steel plane electrode as illustrated in Fig. 1.

B. Gas Handling

The pre-incepted samples were assembled in a 5 liter pressure vessel fabricated in stainless steel and rated up to 10 bar. All pressure values in the present work are in absolute. Samples tested under atmospheric air were directly tested within an enclosed vessel. Gas handling procedures are required for filling and recycling SF6. Prior to testing, the pressure vessel was vacuumed down to 1 mbar and then left for 5 hours to allow
the air to diffuse out of the sample. The vessel is vacuumed again for 20 minutes to ensure any residual gas is removed. After vacuuming, the vessel was filled with SF₆ up to 2 bar. A digital gauge was used to ensure the accuracy of the gas filling process. The test setup was left to settle for 50 hours to ensure that SF₆ was homogeneously distributed within the epoxy sample.

C. Experimental Setup and Test Procedure

PD measurement was performed in accordance to BS EN 60270, and the test circuit is shown in Fig. 2. Prior to applying a voltage, an input discharge of 50 pC was injected into the test system for calibration. The PD threshold was set as 5 pC. The sample was then subjected to a constant voltage of 7 kVrms for 3 hours. An Omicron MPD 600 was used to monitor the PD activity during tree propagation in both air and SF₆. After the electrical tests, samples were taken out for optical microscopic imaging.

III. RESULTS AND ANALYSIS

Optical microscopic images of electrical trees propagated in air and SF₆ for 3 hours under 7 kVrms are shown in Fig. 3. Imaged electrical trees exhibited branch characteristics for all samples tested in air and SF₆. The small tree branches were distributed from the main channel. It has been observed that the trees were darker close to the needle tip and became thinner away from the tip. To observe the effect of SF₆ on the tree morphology, tree length was measured under an optical microscope. Tree length was defined as the horizontal distance from the needle tip to the longest tree tip. Electrical trees in samples tested in SF₆ have an average length of 688 μm (690 μm for air) and width of 510 μm (350 μm for air) after 3 hours as shown in Table I. The electrical tree propagated in SF₆ is slightly wider than observed in air.

After initiation of an electrical tree, PD activity including time, phase and discharge magnitude were recorded by the Omicron MPD 600 software. Phase resolved partial discharge (PRPD) pattern of each sample over 3 hours are illustrated in Fig. 4. The overall discharge magnitude sustained by samples in SF₆ is comparatively lower than air. PRPD patterns of samples tested in air include two parts: a turtle-like pattern at lower discharge magnitudes (5-15 pC) and wing-like pattern of higher magnitudes (> 15 pC).

![Fig. 2. Schematic diagram of PD test circuit.](image)

![Fig. 3. Optical microscopic images of samples under an applied voltage of 7 kV after 3 hours in (a-c) SF₆ under 2 bar and (d-f) in atmospheric air.](image)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Length (μm)</th>
<th>Width (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF₆ 2 bar</td>
<td>615</td>
<td>541</td>
</tr>
<tr>
<td></td>
<td>599</td>
<td>587</td>
</tr>
<tr>
<td></td>
<td>851</td>
<td>401</td>
</tr>
<tr>
<td>Air</td>
<td>705</td>
<td>325</td>
</tr>
<tr>
<td></td>
<td>815</td>
<td>389</td>
</tr>
<tr>
<td></td>
<td>551</td>
<td>335</td>
</tr>
</tbody>
</table>

This is interpreted as the turtle-like pattern being originated from discharges in void and short channels which correlate to discharges that occurred at the front of tree propagation. Wing-like patterns are due to discharges in long narrow channels, which is related to discharges along the tree channel [7]. However, PRPD of samples tested in SF₆ is restricted to turtle-like patterns only. SF₆ is reported to have dielectric strength three times higher than air, which means it can suppress the discharge process more effectively than air. Due to the higher electron affinity of SF₆, the electrons emitted from the discharge surface can be attached by SF₆ gas molecules resulting in a lower discharge magnitude.

With the permeation of SF₆ in the tree channel, the discharges along the branches are suppressed. Therefore, there is little sign of the wing-like pattern in the PRPD pattern of samples tested.
in SF₆. However, the optic microscopic images for both batch of tests shows that there is not too much difference in terms of tree shape, thus the observation of turtle-like shape is because of the deionization due to SF₆ in the tree channel rather than no discharges along the channel.

Fig. 5 shows discharge magnitude of every discharge over 3 hours in the epoxy sample under 2 bar SF₆ and atmospheric air. As the energization time increases, the discharge magnitude increases due to further growth of electrical trees. The average discharge magnitude with 95% confidential interval of three samples tested in SF₆ is between 7.2 to 7.5 pC and 9.4 to 15.2 pC in air. Most discharges in sample tested in SF₆ are lower than 20 pC. Therefore, the use of SF₆ can significantly reduce the discharge magnitude.

Fig. 5. Discharge magnitude of samples under an applied voltage of 7 kVrms for 3 hours in (a-c) SF₆ under 2 bar and (d-f) in atmospheric air.

Fig. 4. Phase resolved partial discharge pattern (PRPD) of samples under an applied voltage of 7 kVrms for 3 hours in (a-c) SF₆ under 2 bar and (d-f) in atmospheric air.

Fig. 6. Number of discharges in samples under an applied voltage of 7 kVrms for 3 hours in (a-c) SF₆ under 2 bar and (d-f) in atmospheric air.

Fig. 6 provides the histogram of discharges over 3 hours and each column in the bar chart represents the number of discharges within a time interval of 6 minutes. The number of discharges increases with time in general due to the increasing discharge sites for discharges during tree propagation. The number of discharges and total discharge magnitude is higher in sample tested in air than SF₆ as shown in Table II. The increase of the number of discharges means there is more charge injection-extraction and recombination events. Therefore, the molecular chain of epoxy resin can be damaged more by increased PD activity. However, the vertical tree length did not show any significant difference which will be discussed further in Section III.
TABLE II
DISCHARGE STATISTICS OF TESTED SAMPLES

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of Discharges (10^5 counts)</th>
<th>Total Discharge Magnitude (10^9 pC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF\textsubscript{6} 2 bar</td>
<td>249.11</td>
<td>1.79</td>
</tr>
<tr>
<td>SF\textsubscript{6} 2 bar</td>
<td>74.56</td>
<td>0.57</td>
</tr>
<tr>
<td>SF\textsubscript{6} 2 bar</td>
<td>3468.03</td>
<td>32.80</td>
</tr>
<tr>
<td>Air</td>
<td>1338.73</td>
<td>20.35</td>
</tr>
<tr>
<td>Air</td>
<td>498.29</td>
<td>6.96</td>
</tr>
</tbody>
</table>

III. DISCUSSION

The propagation of electrical trees in epoxy resin sample tested with SF\textsubscript{6} under 2 bar show a significant reduction in PD activity and discharge magnitude. However, somewhat surprisingly, the tree length growth for samples tested in air and SF\textsubscript{6} are comparable. SF\textsubscript{6} has a high electron affinity of 1.4 eV, which is the energy released when an electron is attached on the gas molecule to form a negative ion. Electron affinity for O\textsubscript{2} and N\textsubscript{2} is 1.46 eV and -0.07 eV respectively. Therefore, electrons emitted from the needle tip can be attached to high electron affinity gases (SF\textsubscript{6}) and lead to deionization in the treeing channel. Hence, a lower discharge magnitude was observed in SF\textsubscript{6}. This is in agreement with the report that the presence of SF\textsubscript{6} can lead to a reduced level of electroluminescence [8].

The number of discharges of sample in SF\textsubscript{6} was found to be significantly lower than in air as shown in Table II. It is also clear that the plasma chemistry associated with SF\textsubscript{6} and air is quite different.

Sulphur has been reported to have an impact on epoxy networks [9]. Glass transition temperature, thermal stability and yield strain and stress decrease due to the presence of sulphur. A reduction of glass transition temperature means the polymer can be softened at a lower temperature and the effect of reduced thermal stability and yield strain or stress may promote electrical tree growth. It was reported that gas by-products such as SO\textsubscript{2}, CF\textsubscript{4}, SO\textsubscript{2}, CO\textsubscript{2}, SO\textsubscript{2}F\textsubscript{2}, CS\textsubscript{2} and H\textsubscript{2}S were generated in flashover tests with epoxy resin in SF\textsubscript{6} [10]. Simulation of decomposition in epoxy resin in ReaxFF program shows that H\textsubscript{2}O, H\textsubscript{2}, CO\textsubscript{2}, CH\textsubscript{2}O CO and CH\textsubscript{4} are the major by-products at 1300 K. Gas by-products such as SO\textsubscript{2} and SF\textsubscript{6} can react with H\textsubscript{2}O and form hydrogen fluoride (HF) [11]. Absorbed HF in epoxy resin can reduce the surface resistance and reduce flashover voltages.

It is argued then, that although the PD activity is lower in SF\textsubscript{6}, the decomposition of SF\textsubscript{6} could potentially increase chemical changes to the polymer and increase the gas pressure in the tree channel further stressing the channel wall. This may lead to an aggressive environment within a tree channel and thereby accelerating the tree growth despite reduced PD activity.

IV. CONCLUSIONS

This work reports the influence of ambient gas (atmospheric air and SF\textsubscript{6} under 2 bar) on the tree propagation process in epoxy resin under AC stress. PD measurements indicate that the permeation of SF\textsubscript{6} in the epoxy sample could significantly suppress the discharge activity. However, this reduced PD activity did not suppress the rate of tree propagation. It is argued that reduced PD activity could be compensated for by SF\textsubscript{6} decomposition within the tree channels and degradation of epoxy resin due to chemical reaction between gas by-products and solid insulation.

ACKNOWLEDGMENT

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