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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 kV_{rms} in atmospheric air and SF_6 under 2 bar absolute for 3 hours. PD measurements indicate that the permeation of SF_6 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 SF_6 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 SF_6 have been chosen as model materials. The latter has been widely used in gas insulated equipment, and has a dielectric strength three times higher than air [2].

Several researchers have investigated the role of pre-existing gas in tree initiation. The effect of ambient gas (air, N_2, Ar and SF_6) on initiation of electrical tree in polyethylene has been studied in [3]. The results show that electrons emitted from the needle tip can be affected by ambient gas. PD inception voltage of a polyethylene sample in SF_6 increased by around 1.4 times higher than a sample initiated in air. This is evidence that an alternative dielectric gas such as SF_6 can permeate into the free volume of the polymer and participate in the discharge process. It has been reported that the role of O_2 absorbed in the polymer can suppress the tree growth [4]. O_2 could promote the polymer chain scission by reacting with radicals produced and promote further tree growth. However, discharges only occur at the high electric field at the needle tip where the absence of O_2 limit the deterioration of the polymer chain. This is consistent with the results reported in [5] that absorbed O_2 can reduce the tree inception voltage by deterioration of the polymer base. XLPE immersed in dielectric liquids can also fill the free volume and cavities, which could limit the ionization resulting in a higher inception voltage. Although studies have proven the importance of atmospheric gases to the tree initiation, there is scant study focusing on the tree propagation process in high dielectric strength gases like SF_6. In this work, a comparison of the PD behavior of epoxy sample under air and SF_6 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 kV_{rms} 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.

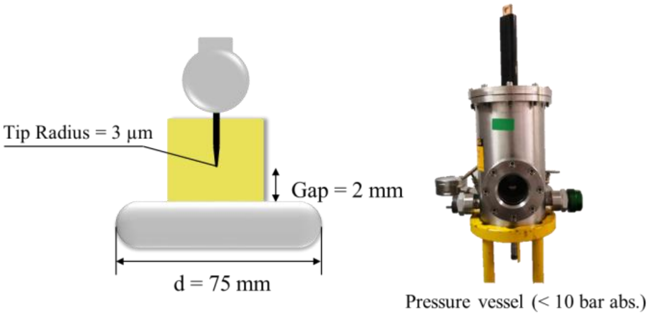

Fig. 1. Electrode configuration (left) and pressure vessel rated up to 10 bar (right).

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 SF_6. Prior to testing, the pressure vessel was vacuumed down to 1 mbar and then left for 5 hours to allow

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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 SF_6 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 SF_6 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 kV_{rms} for 3 hours. An Omicron MPD 600 was used to monitor the PD activity during tree propagation in both air and SF_6. After the electrical tests, samples were taken out for optical microscopic imaging.

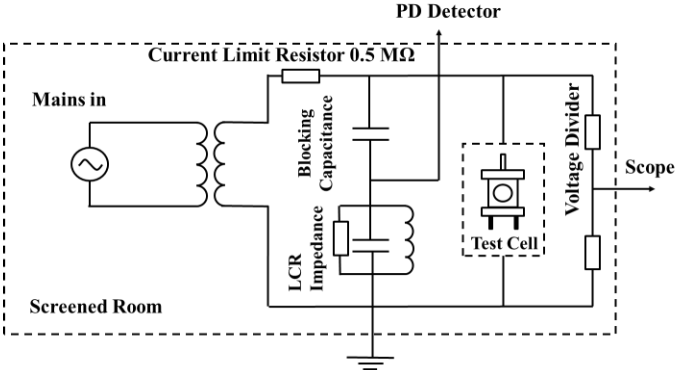

Fig. 2. Schematic diagram of PD test circuit.

III. RESULTS AND ANALYSIS

Optical microscopic images of electrical trees propagated in air and SF_6 for 3 hours under 7 kV_{rms} are shown in Fig. 3. Imaged electrical trees exhibited branch characteristics for all samples tested in air and SF_6. 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 SF_6 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 SF_6 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 SF_6 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 SF_6 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).

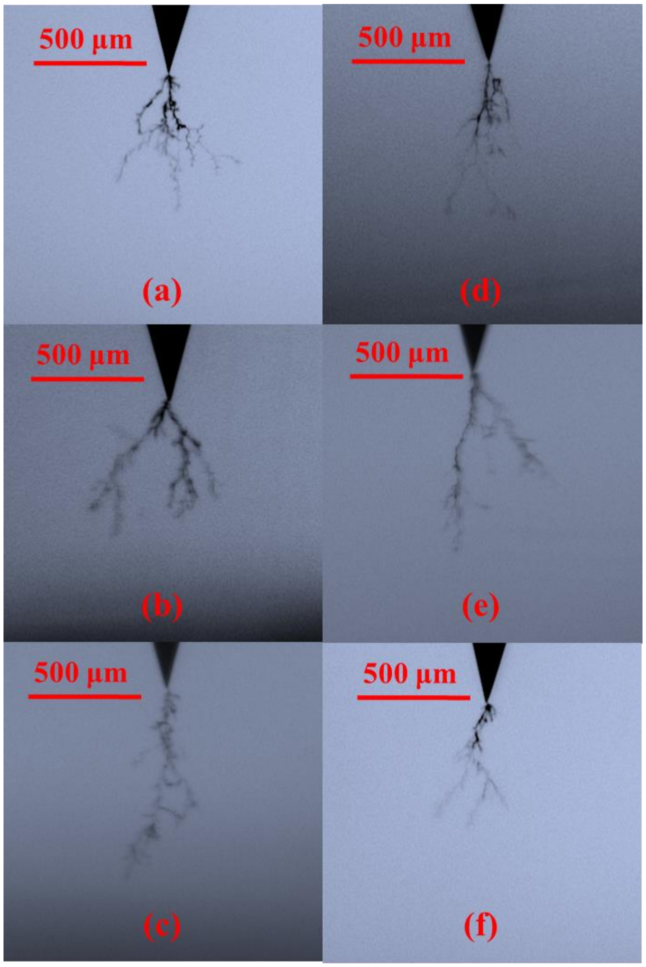

Fig. 3. Optical microscopic images of samples under an applied voltage of 7 kV_{rms} after 3 hours in (a-c) SF_6 under 2 bar and (d-f) in atmospheric air.

TABLE I
TREE LENGTH OF TESTED SAMPLES.

Sample	Length (µm)	Width (µm)
SF_6 2 bar	615	541
	599	587
	851	401
Air	705	325
	815	389
	551	335

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 SF_6 are restricted to turtle-like patterns only. SF_6 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 SF_6, the electrons emitted from the discharge surface can be attached by SF_6 gas molecules resulting in a lower discharge magnitude.

With the permeation of SF_6 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 SF_6. 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 SF_6 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 SF_6 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 SF_6 is between 7.2 to 7.5 pC and 9.4 to 15.2 pC in air. Most discharges in sample tested in SF_6 are lower than 20 pC. Therefore, the use of SF_6 can significantly reduce the discharge magnitude.

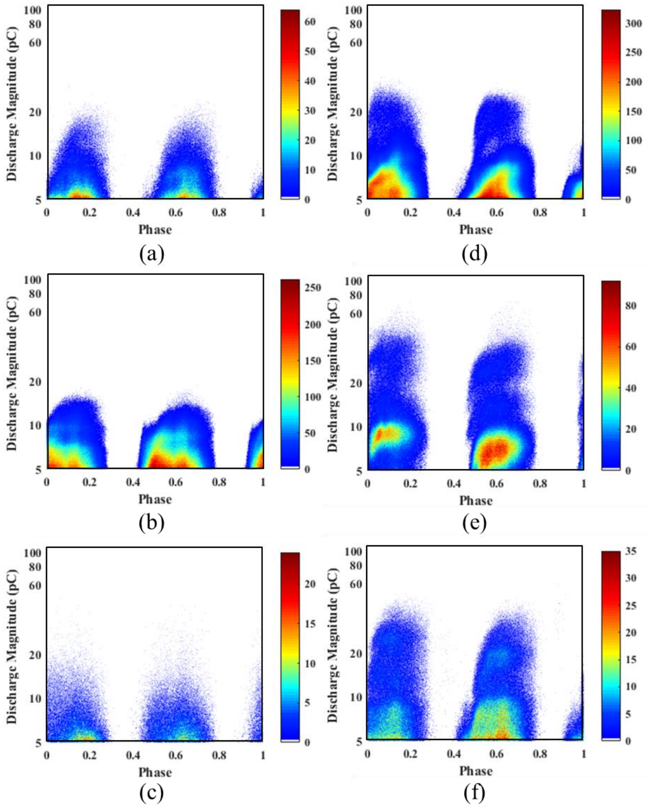

Fig. 4. Phase resolved partial discharge pattern (PRPD) of samples under an applied voltage of 7 kV_{rms} for 3 hours in (a-c) SF_6 under 2 bar and (d-f) in atmospheric air.

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 SF_6 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.

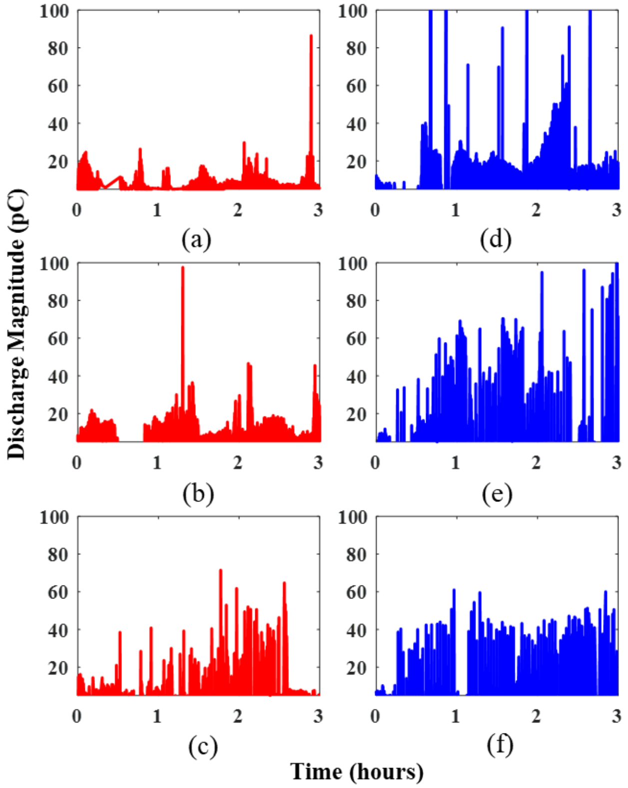

Fig. 5. Discharge magnitude of samples under an applied voltage of 7 kV_{rms} for 3 hours in (a-c) SF_6 under 2 bar and (d-f) in atmospheric air.

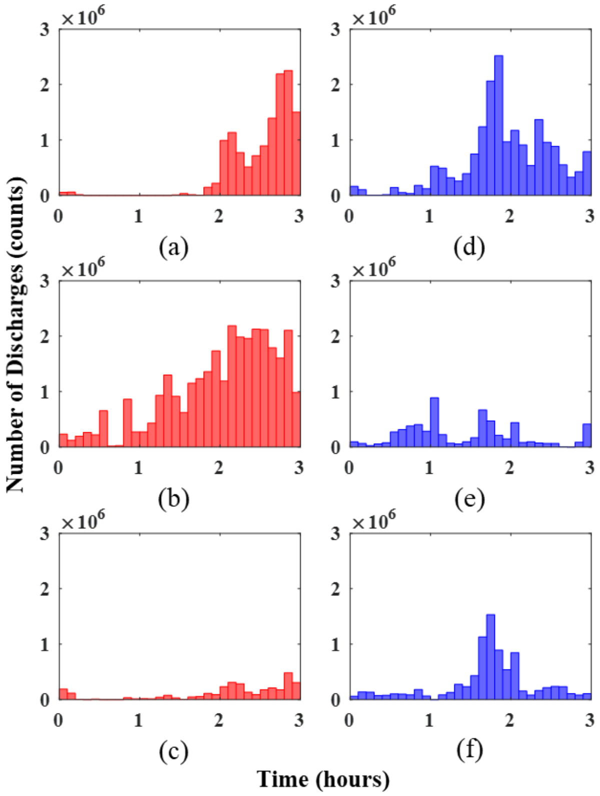

Fig. 6. Number of discharges in samples under an applied voltage of 7 kV_{rms} for 3 hours in (a-c) SF_6 under 2 bar and (d-f) in atmospheric air.

TABLE II

DISCHARGE STATISTICS OF TESTED SAMPLES.

Sample	Number of Discharges (10^3 counts)	Total Discharge Magnitude (10^6 pC)
SF_6 2 bar	247.60	1.79
	249.11	18.71
	74.56	0.57
Air	3468.03	32.80
	1338.73	20.35
	498.29	6.96

III. DISCUSSION

The propagation of electrical trees in epoxy resin sample tested with SF_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_6 are comparable. SF_6 has a very 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_2 and N_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_6) and lead to deionization in the treeing channel. Hence, a lower discharge magnitude was observed in SF_6. This is in agreement with the report that the presence of SF_6 can lead to a reduced level of electroluminescence [8].

The number of discharges of sample in SF_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_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 SOF_2, CF_4, SO_2, CO_2, SO_2F_2, CS_2 and H_2S were generated in flashover tests with epoxy resin in SF_6 [10]. Simulation of decomposition in epoxy resin in ReaxFF program shows that H_2O, H_2, CO_2, CH_2O CO and CH_4 are the major by-products at 1300 K. Gas by-products such as SOF_2 and SF_4 can react with H_2O 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_6, the decomposition of SF_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_6 under 2 bar) on the tree propagation process in epoxy resin under AC stress. PD measurements indicate that the permeation of SF_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_6 decomposition within the tree channels and degradation of epoxy resin due to chemical reaction between gas by-products and solid insulation.

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REFERENCES

[1] L. A. Dissado and J. C. Fothergill, *Electrical degradation and breakdown in polymers*. Iet, 1992.

[2] L. Loizou, L. Chen, Q. Liu, I. Cotton, M. Waldron, and J. G. Owens, "Technical Viability of Retro-Filling C_3F_7CN/CO_2 Gas Mixtures in SF_6-Designed Gas Insulated Lines and Busbars at Transmission Voltages," *IEEE Transactions on Power Delivery,* vol. 35, no. 5, pp. 2394-2402, 2020.

[3] J. Andrianjohaninarivo, M. Wertheimer, and A. Yelon, "Nucleation of electrical tress in polyethylene," *IEEE Transactions on Electrical Insulation,* vol. EI-22, no. 6, pp. 709-714, 1987.

[4] N. Shimizu, K. Uchida, and K. Horii, "Initiation mechanism of electrical tree—chain scission by injected charge and role of oxygen," *Conference on Electrical Insulation and Dielectric Phenomena*, 1987, pp. 419-424.

[5] L. A. Dissado, "Understanding electrical trees in solids: from experiment to theory," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 9, no. 4, pp. 483-497, 2002.

[6] I. Iddrissu and S. Rowland, "The impact of DC bias on electrical tree growth characteristics in epoxy resin samples," *Conference on Electrical Insulation and Dielectric Phenomena*, 2015, pp. 876-879.

[7] Z. Lv, S. M. Rowland, S. Chen, H. Zheng, and I. Iddrissu, "Evolution of partial discharges during early tree propagation in epoxy resin," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 24, no. 5, pp. 2995-3003, 2017.

[8] N. Shimizu, N. Nagura, S. Iemura, and T. Takahashi, "Electroluminescence caused by electron impact," *Int. Symp. on Electrical Insulating Materials*, 2001, pp. 566-569.

[9] W. Vogel *et al.*, "Synthesis and characterisation of new sulphur-containing epoxy networks," *High Performance Polymers,* vol. 26, no. 4, pp. 420-435, 2014.

[10] H. Wen, X. Zhang, R. Xia, G. Hu, and Y. Wu, "Decomposition characteristics of SF6 under flashover discharge on the epoxy resin surface," *Materials,* vol. 12, no. 9, p. 1408, 2019.

[11] H. Stuckless, J. Braun, and F. Chu, "Degradation of silica-filled epoxy spacers by arc contaminated gases in SF_6-insulated equipment," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-104, no. 12, pp. 3597-3602, 1985.