Epoxy Electret: A Remedy for Partial Discharge at Cryogenic Temperature

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Abstract. Epoxy-based composites exhibit mechanical compatibility at cryogenic temperatures. Owing to these properties, composites based on epoxy are used as electrical insulators in high temperature superconducting (HTS) power applications. However, the inevitable presence of voids in solid insulators, triple points, and airgaps at high-voltage conductor-insulator interfaces increase electric fields locally. The intensified electric field around these defects and interfaces is the main cause of partial discharge (PD), which is a dielectric challenge for numerous power applications including HTS cables. Recently, electret has been introduced as a promising solution to mitigate PD activities caused by voids and triple points. In this work, we intend to report the PD mitigation performance of electrets fabricated from epoxy resin, which is suitable for cryogenic power applications.

1. Introduction
In recent years, high temperature superconducting (HTS) power cables have become preferable over conventional cables in serving the increasing electric demand [1]. High power density provided by the HTS power cables substantially reduces the weight and volume of electric power system. HTS power technology is useful in all-electric shipboard and electric aircraft power system, where high-power ratings with reduced weight and size are demanded [2]. Gaseous helium (GHe) is used as a coolant in HTS systems owing to its extended operating temperature range [3]. In the gas-cooled HTS power cable, lapped tape is commonly used for electrical insulation [1], [2], [4]. Lapped tape insulation is helically wrapped around the cable and butt gaps are introduced to avoid mechanical stress. Butt gaps are filled with the coolant that has comparatively low permittivity than the insulation tape. This causes local electric field enhancement; the main cause of partial discharge (PD) [4] that occurs actively at sharp edges, triple points, and cavities leading to dielectric material ageing and the increased risk of device failure.

Numerous studies have been proposed based on geometry [5] and material [6]–[8] to address the challenge of electric field enhancement in the field of high voltage and dielectrics. Recently, an electret-based approach was proposed in [9], in which it was numerically shown that the local field enhancements at sharp edges, triple points, and cavities can be substantially reduced by incorporating electret layers. In [10], the same research group showed experimentally the PD mitigation performance of electrets. Electrets are the electrostatic analogy of permanent magnets holding charge with significantly high lifetime. It has been reported in the literature that the charge decay rate of electret made from Teflon is 1 percent per year [11]. These materials are fabricated from either
silicone dioxide (SiO$_2$)-based inorganic materials or polymer-based organic materials. Based on the triode-corona charging method, we charge polyvinylidene fluoride (PVDF) under various charging conditions including charging voltage, duration, and temperature. The charge stored in the electret surface are utilized to neutralize the intense local electric field and mitigate PD activities [11], [12]. Epoxy-based composites show exceptionally high electrical and mechanical strength at cryogenic temperature [13]. For these reasons, epoxy spacers are widely used in HTS power cables [15]. However, butt gaps filled with cryogens are the main source of PD activities caused by cavities, which is equivalent to butt gaps from a physical standpoint. The PD mitigation performance of uncharged epoxy and charged epoxy (electret) are compared while they are both stressed under same power electronics switching voltage.

2. Electric field neutralization by electret

![Figure 1](image1.png)

To demonstrate the electric field neutralization of electret, we assumed a model shown in figure 1. Here, two surfaces with arbitrary surface charge $Q_1$ and $Q_2$ is assumed. An electret layer with surface charge density $\sigma_e$ and thickness $d_e$ is inserted between them. The potential difference between the top surface and the top surface of the electret layer is $V_1$ and the bottom surface of the electret layer and the bottom surface is $V_2$. We define two electric fields $E_1$ and $E_2$ such that $E_1$ pointing toward the top surface and $E_2$ pointing towards the bottom surface. If there is a point of high electric filed on the bottom surface, then the required surface charge density to neutralize the electric field is defined as below [9], [10].

$$\sigma_e = \frac{\varepsilon_o \varepsilon_{r1} V}{d}$$  

(1)

3. Fabrication of epoxy-based electret

![Figure 2](image2.png)

**Figure 2.** Fabrication of electret from epoxy-based composites. (a) Schematic diagram of triode-corona charging method used for charging epoxy coated aluminium plate at elevated temperature, (b) experimental setup used to fabricate electret based on triode-corona charging method, (c) a close view of the testbed (c-1) and epoxy electret (c-2).
An aluminium (Al) plate with thickness 0.25 mm was coated with a thin layer of epoxy. The epoxy used for this purpose was 820 resin that is a very low viscosity resin, and 824 hardener of minimum cure schedule 24 hours was added to the resin in 5:1 volumetric ratio for the curing purpose. The thickness of the epoxy coating was 0.2 mm. Once the coating was done, the Al-plate was placed on an induction heater controlled by a PID controller to accelerate the curing process of the epoxy in air. The epoxy layer was charged based on the triode-corona charging method during the whole curing process. In figure 2(a), the schematic diagram of the triode-corona charging method along with the temperature control system is shown. The needle electrode was supplied with high voltage (17 kV DC) to generate corona discharge that ionizes air surrounding the needle electrode. These ions were forced downwards due to the presence of electric field. The grid electrode, a uniformly spaced copper mesh, was placed 5mm above the epoxy coated Al-plate. The main reason for placing the grid electrode is to create a uniformly distributed electric field such that the electret sample is charged uniformly. Temperature was kept at 60 °C to accelerate the curing process and to increase the stability of the surface charge by allowing charged particles to penetrate into deep traps. Figure 2(b) shows the experimental setup used in the lab to fabricate epoxy electret using the triode corona charging method. For the grid voltage, a DC source was used to supply 600 Vdc to the grid electrode. Needle electrode was supplied with 17 kV DC voltage generated and amplified by a function generator and high voltage amplifier, respectively. After the curing process, we stopped the charging process and measured the surface potential with an electrostatic voltmeter. The surface potential of the epoxy electret achieved by this process was 164 V, which translates 26.17 µC/m² surface charge density. To compare the effectiveness of epoxy electret in mitigating PD activities, an uncharged epoxy coated Al-coated sample was prepared and cured under the same temperature.

4. PD mitigation by epoxy electret

4.1. Experimental Description

With the uncharged epoxy layer and charged epoxy layer, we conducted a series of PD experiments under same square voltage waveform and compared PD signals. PD occurs actively on sharp edges, triple points, and cavities. In this study, a spherical electrode shown in figure 3 was used as the high voltage electrode to avoid the effect of sharp edges causing PD. However, the presence of triple points at the interface of metal electrode, dielectric material, and surrounding medium (air) cause local field enhancements and promote PD occurrence. A 3D printed solid insulator was used as the dielectric material as shown figure 3(a). The micro-scale cavities inherently created in the 3D printed solid insulator are the main sources of PD activities. Below the 3D printed solid insulator, the uncharged epoxy layer was placed. A function generator was used to generate the square voltage, which is amplified with a high voltage amplifier and supplied to the high voltage electrode. PD activities caused by the presence of triple points and cavities are detected with the coupling capacitor and PD

![Figure 3](image-url)
detecting device (Omicron MPD 600). PD signals achieved with the uncharged epoxy were recorded with a computer-based software provided by Omicron. Later, uncharged epoxy was replaced with the charged epoxy (electret) and PD signals under same square voltage were recorded. Figure 3(b) shows the testbed used to conduct the PD measurements.

4.2. Comparison of PD mitigation performance

PD measurements were conducted with uncharged and charged epoxy (electret) layers under same unipolar square voltage waveforms. We applied three different square voltage levels on the high voltage electrode and maintained a constant $dv/dt$ of 560 V/$\mu$s for all voltage levels. To this end the square voltage magnitude and rise time were both increased systematically. The PD signals achieved at each voltage level with uncharged and charged epoxy are presented in figure 4. Figure 4(a) is the case with uncharged epoxy and figure 4(b) is the case with charged epoxy electret. It is shown that when square voltage magnitude varies between 0 to 4.5 kV with a rise time 8 $\mu$s, both uncharged and charged epoxy caused same PD magnitudes of 0.5 nC. Subsequently, the voltage was increased to 5.6 kV and to maintain same $dv/dt$ ratio, rise time was set to 10 $\mu$s. It is observed that, PD magnitude with uncharged epoxy (1.9 nC) is 90 % higher than that of the charged electret (1 nC). Once the voltage level is further increased and set to 6.8 kV with the rise time of 12 $\mu$s, there is a drastic rise in PD magnitudes in the case of the uncharged epoxy (7.5 nC). However, PD magnitudes achieved with the charged epoxy is 3.8 nC which only 50% of the PD magnitude resulted with the uncharged epoxy. This significant reduction in the PD magnitudes achieved with the electrets fabricated from epoxy suggests that the charge stored in the electret surface neutralizes the high electric field caused by triple points and cavities. In order to confirm the results achieved with the epoxy-based electret in PD mitigation, we prepared one more electret sample by charging epoxy coated Al-plate under identical conditions and the results shows significant reduction in the electric field.

5. Discussion

In this paper, epoxy- based electrets are fabricated using the triode corona charging method while curing. We did not use degassing prior to casting. The objective of this paper is to prepare epoxy-based electret and observe if they are able to mitigate PD. Several samples of charged and uncharged epoxy sheets were cured under identical condition that did not involve a degassing process. Despite the possibility of having bubbles, the results show that epoxy-based electrets can mitigate PD. The next step is to fabricate electrets that does not have bubbles by degassing the resin while curing. The
charge retention characteristics of epoxy-based electrets have yet to be investigated. Charge retention both at room temperature and at cryogenic conditions will be characterized in our future work.

6. Conclusion
In this study, we experimentally demonstrated the performance of epoxy-based electrets in mitigating PD activities caused by the presence of triple points and cavities. The results show that electrets with a surface charge density of 26.17 µC/m² can reduce PD magnitude by 50%. Further improvements in PD mitigation are expected as improved epoxy-based electrets are developed. With higher surface charge density and increased stability, the epoxy-based electrets will enable PD-free conditions in cryogenic and HTS power applications.

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