DEIS Fellowship Proposal

A Study of the Direct Current Erosion Mechanism of Polymeric Materials

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Introduction and Motivation

In a deregulated power system network, high voltage direct current (HVDC) is an economical mode of transmitting electricity over long distances, but justification for its use must address the aspect of reliability. Outdoor polymer insulators, which are the backbone components of transmission lines, have demonstrated an electrical performance superior to ceramic or glass insulators. However, polymer insulators are prone to tracking and erosion, which may lead to insulation failure and consequently interruption of the supply of power.

In wet and polluted conditions, all outdoor insulators are susceptible to dry-band arcing (DBA), which occurs because of wetting of the pollutant on the insulators, giving rise to leakage current and evaporation by joule heating of the conductive layer, which leads to arcing across the dry bands so formed, and eventual erosion of the polymeric housing material. This erosion exposes the fiberglass rod to moisture and voltage, which are conducive to tracking failure of the rod, leading to insulation failure.

Standardized tests coupled with in-service observations have commonly been used as a means of developing insulator designs for AC applications. Although polymer insulators that have been designed for AC have been applied to DC, albeit in limited numbers, they are still a relatively unknown entity that requires further investigation, particularly in the light of the increased interest in DC, worldwide. The characteristics of DBA under DC are very different from those under AC, and an understanding of the DBA erosion mechanism under DC, can lead to new and improved polymeric composites for outdoor HVDC.

State of the Art and Objectives

Relatively few studies have evaluated polymeric materials to gain an understanding of the physical mechanism of DBA under DC. Recent studies have focused mainly on the validation of AC-designed composites for outdoor HVDC but with less emphasis on determining the mechanism of dry band formation and heat ablation of polymeric materials associated with DBA under DC; both areas to be studied in this proposal. A thorough study of the DC DBA mechanism as opposed to AC DBA, for which the latter is well understood, will lead to the optimization of polymeric materials for DC insulators. To this end, the study will closely examine base polymeric materials and inorganic fillers, which are vital for suppressing the effects of DBA, as a foundation for the development of optimum polymeric composites for outdoor HVDC.

Materials and Methods

The inclined plane tracking/erosion test (IPT), which has been used for evaluating polymeric materials for outdoor AC insulation applications, is utilized in this research [1]. The study has begun with measurements of the leakage current (LC), enabling an analysis of the modified wetting characteristics of surfaces under DC; thus, testing voltage levels can be suitably chosen under DC with respect to the corresponding standard AC.

During the IPTs, temperature measurements have been made to couple the thermal mechanism of erosion with the DBA characteristics, and thermogravimetric analysis (TGA) has been used to predetermine the temperature at which the erosion process begins. The performance of two commonly used polymeric materials will be studied; namely, silicone rubber (SiR) and ethylene propylene diene monomer (EPDM). In addition, with the goal of determining the suppression mechanism of the DBA under DC, the study will include the effects of various types and levels of fillers, employing those commonly used for outdoor insulation applications: alumina trihydrate (ATH) and silica. Table 1 summarizes the materials and the equipment required in the proposed research along with their availability.

Table 1. Availability of the materials and the equipment required for the study

Method	Test setup	Materials	Availability
LC measurement	IPT	30 wt% silica filled RTV SiR	Available
Analysis of the DBA mechanism under DC	IPT, TGA and Infrared camera	10 wt%, 30 wt% and 50 wt% silica and ATH filled RTV SiR	Available
Erosion of EPDM and SiR	IPT	25 wt%, 40 wt% and 58 wt% ATH filled HTV SiR and EPDM	Available
The suppression mechanism of the inorganic fillers to the heat ablation caused by DBA under DC	IPT and Infrared camera	10 wt%, 30 wt% and 50 wt% silica and ATH filled RTV SiR	Available

Preliminary Results

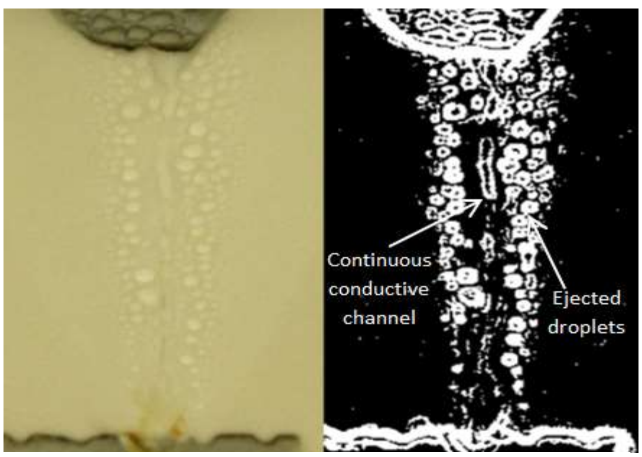

Figure 1. Typical expulsion pattern observed during the surface measurement study under the IPT voltage (this case is under 1.75 kV +DC, processed (black and white) image is to the right and actual image is to the left)

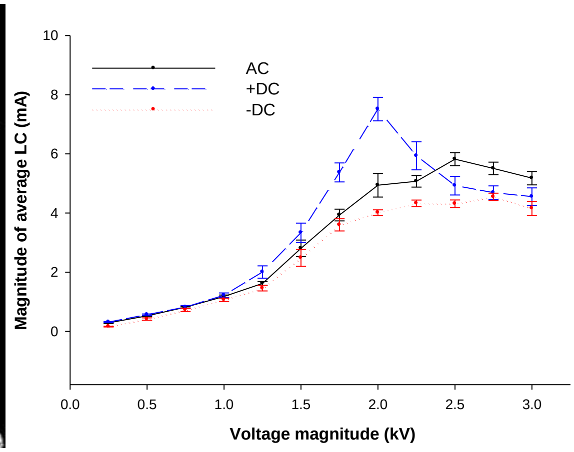

Figure 2. Average LC under AC, +DC and –DC for voltage ranges of 0.25-3 kV

Figure 1 shows the behavior observed for the IPT liquid contaminant at a pre-dry-band formation stage, where the observation of intermittent discharges was associated with the saturation of the LC measured (Figure 2). Expulsion of small droplets from the contaminant rivulet was observed under all polarities, but to different extents. As the volume of ejected contaminant increases with the applied voltage, the rivulet is reduced and therefore its conductance. The expulsion of water droplets was reported by Vallet et al. as an indicator of instability at the triple point (air, solid, and liquid contaminant) that occurs due to the overcoming of the capillary force by the electrostatic force [2], [3]. The presence of a surfactant in the contaminant has been reported to contribute to the instability at a lower voltage [3]. Unstable behaviour has also been reported at a later stage after electrowetting. Electrowetting refers to the reduction of the contact angle of an electrolyte on the surface of a solid due to the application of a DC electric field but is also entirely associated with AC at the power frequency [4], [5]. Since the average LC is highest under +DC at the pre-DBA stage (Figure 2 at 2kV), it follows that the lowest ejection volume occurs at +DC. The DBA current has been reported to be limited by the surface resistance of the contaminated layer [6]. As a result, the maximum degree of DBA severity can be obtained under +DC. The degree of severity was verified using the initial tracking voltage (ITV) test method [1], where the lowest ITV could be obtained under +DC. Although greater ejection of contaminant under –DC than under AC can be inferred, the nature of the DC voltage applied as opposed to the AC at power frequency seems to play an important role in obtaining a lower ITV under –DC. The equivalent DC IPT voltages were accordingly determined with respect to the AC and DC ITVs obtained [1].

Despite the application of the equivalent test voltages, comparable erosion measurements were obtained under +DC and –DC but not for AC. The resulting relative erosion values suggest that, in order for performance to reach a level similar to that of the AC, an improvement is needed in the SiR material to be employed for DC. Similarly, Mailfret et al. recommended material improvement for DC insulation [6]. The improvement was recommended to compensate for the reported severity of DBA under DC as more intense and stable DBA activity was observed as compared to AC [6]. This recommendation does not match that of Bossi et al., who suggested that no additional improvement is required as long as operational voltages are selected with respect to a specific creepage distance (flashover voltages) [8]. The DC flashover voltages found by Bossi et al. for SiR insulators were determined to be equal to 0.75-0.85 of the corresponding AC [8]. Creepage distances comparable to those reported by Bossi et al. have, nevertheless, already been applied in this study, and it seems that for the selection of the DC creepage distance, tracking/erosion is an additional factor that must be added to the criteria related to the withstand voltages.

The percentage mass loss with respect to temperature in the TGA of different SiR composites shows significant erosion begins at a temperature of >400^{o}C. The eroding DBA should be, therefore, able to induce a hot spot temperature (HST) of >400^{o}C. This finding, which agrees with that of Kumagai et al. [9], was utilized in analyzing the eroding DBA under DC as compared to AC. The analysis of the development of HST throughout the IPTs conducted has demonstrated that surface residues play a more significant contribution on inducing the eroding DBA under DC as compared to AC.

It is evident that the preliminary results confirm the need to further study the DBA mechanism under DC. In addition, the study will continue with a thorough examination of the influence of the type of base material and the inorganic filler on suppressing the DBA mechanism with the goal of producing materials that can perform reliably in outdoor HVDC environments.

Potential Contributions

- Development of practical and reliable testing guidelines for the validation of composites designed for AC and to be utilized under DC
- An understanding of the physical mechanism of DBA that leads to erosion under DC
- Investigation of the role of the type of base material (SiR vs. EPDM) on the erosion mechanism under DC
- Investigating the role of inorganic fillers, in particular, the filler level and type (silica vs. ATH) on the suppressing the heat ablation by DBA under DC

References

[1] ASTM D2303-97, Standard Test Methods for Liquid-Contaminant, Inclined-Plane Tracking and Erosion of Insulating Materials.

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[9] S. Kumagai and N. Yoshimora, "Tracking and Erosion of Silicone Rubber and Suppression Mechanism of ATH," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 8, no. 2, pp. 203-211, April 2001.

Summary of Research Contributions

Refereed journal publications:

[1] R. A. Ghunem, S. H. Jayaram, and E. A. Cherney, "Erosion of Silicone Rubber Composites in the AC and DC Inclined Plane Tests," paper accepted to be published in the *IEEE Transactions on Dielectrics and Electrical Insulation*.

Refereed conference publications:

[1] R. A. Ghunem, S. H. Jayaram, and E. A. Cherney, "Inclined Plane Initial Tracking Voltage for AC, +DC and –DC," *IEEE International Symposium on Electrical Insulation*, pp. 459-463, 2012.

[2] R.A. Ghunem, S. H. Jayaram, and E. A. Cherney, "Erosion of ATH and Silica Filled Silicone Rubber in the DC Inclined Plane Test," in proceedings of the *IEEE international Conference on Properties and Applications of Dielectric Materials*," 2012.

[3] R. A. Ghunem, S. H. Jayaram, and E. A. Cherney, "Statistical Parameters as Indicators of Silicone Rubber Tracking/Erosion in the DC Inclined Plane Test," paper accepted to be published in the proceeding of the *Conference on Electrical Insulation and Dielectric Phenomena*, 2012.