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STUDIES OF EPOXY SPACERS SUBJECTED TO INTERNAL AND EXTERNAL PARTIAL DISCHARGE AND SF_6 BYPRODUCTS

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INTRODUCTION

The reliability of gas insulated switchgear (GIS) has generally been good. However, because of the complexities involved in servicing the enclosed components, maintenance and repair times can rapidly become a serious handicap affecting substation availability, particularly at the higher voltage levels. Because of the importance of high reliability of GIS for system security at the higher voltages, there is a concern over the long term aging characteristics of GIS.

Several long term aging mechanisms have been identified. While bulk failure by electrical treeing of solid dielectrics is a recognized aging phenomenon, failures linked to long term aging of spacer surfaces are also coming to the fore; however the corresponding mechanism is poorly understood. Corona discharge, exposure to corrosive SF_6 decomposition byproducts, and particle contamination can all contribute to the surface failure mechanism(s). The objective of the present study is to develop a better understanding of this failure mechanism, to probe the effects of localized corona discharges on filled epoxies and to characterize the early phases of the internal and external surface degradation process.

EFFECT OF INTERNAL PARTIAL DISCHARGES

Electrical treeing of GIS spacers is a major bulk dielectric failure process. Its relevance as a long term aging mechanism was underscored for us by a recent failure of a 500 kV spacer, revealing on the fracture path two small spherical voids believed to be the initiation sites of the failure. This spacer had been in service for about 8 years. The slowly developing failure is believed to proceed according to the following mechanism. Upon initiation of partial discharges (pd) in a void cavity, erosion of the void walls leads over time to enlargement of the cavity, generation of electrical "tree" channels and eventually failure [1]. As part of a major project on aging of GIS spacers, we are investigating the early phases of the discharge process in collaboration with ABB Research, the Technical University of Denmark and the University of Connecticut. The work is focussing on understanding the discharge process, detectability of pd in small voids and the existence of a critical void size below which no aging takes place. Pressure, gas and vapor content of voids in castings are important parameters in determining discharge characteristics. Preliminary reports on this research have been presented elsewhere [2-4].

Voids of controlled size, pressure and gas content were manufactured by injecting gas (nitrogen, air, SF_6) under slight pressure into a curing epoxy [3]. By fracturing the cavity inside a high vacuum system, void content and changes taking place during casting can be readily established. It was thus found that oxygen is consumed during the curing stage while the total organics in voids are fairly low, generally identical in composition to the residual casting volatiles. Work is underway to extent these techniques to filled commercial spacers manufactured under controlled conditions to "achieve" small voidage. While one might argue that GIS spacers operate in an atmosphere of SF_6, it should be recognized that gas content will ultimately be diffusion controlled. Given the substantial thickness of the castings and the extremely low diffusion coefficient for SF_6 in epoxies, void content during the factory pd test and for a number of years thereafter will in effect be similar to that derived from an air filled void. Similarly organics in the void will reach equilibrium with the bulk material.

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Voids were subjected to pd by encapsulating the above specimens between two electrodes. Early changes in void wall chemistry were probed on large (5 mm diameter) voids by ESCA (Electron Spectroscopy for Chemical Analysis). A typical spectrum obtained on the surface of a fractured void exposed to 48 hrs. of sustained pd is given in Figure 1, illustrating the sharp rise in nitrogen. The binding energy of the nitrogen peak (N1s) is consistent with the incorporation of the nitrogen into the epoxy as an amine. Given the high surface concentration of nitrogen (30 surface-%), substantially all nitrogen would have been reacted in the void. The ESCA technique is sensitive enough to detect changes in wall chemistry, long before SEM could find evidence of wall erosion. We are planning on using this approach to study the lower size limit at which pd can be considered harmless. Investigations are also underway to determine the corresponding pressure changes in the cavity as well as changes taking place in volatile organics in the void atmosphere. PD inception and extinction voltages, pulse magnitude and repetition rates, with and without X-ray irradiation were also determined and were reported earlier [4].

DEGRADATION OF SPACER SURFACES

Ideally epoxy spacers should be designed to withstand all forms of severe duty including commissioning test flashovers and exposure to SF_6 arcing byproducts. However, conditioning flashovers sustained during field testing impart a degree of aging to epoxy spacer surfaces. The severity of the damage depends greatly on the actual materials involved as demonstrated in earlier studies [5,6]. In addition, direct exposure of spacer surfaces to localized partial discharges can slowly compromise the surface electrical resistance of the epoxy spacers.

Long Term Exposure to Arcing Byproducts

GIS is a hermetically sealed system, initially filled with clean gas and free from external contamination. However, low level contamination can be generated over time from internal sources and affect long term performance. Arcing as a result of current interruptions, partial discharges, and component overheating is a direct source of contamination which can lead to the accumulation of SF_6 decomposition byproducts [5]. The chemical composition of arced SF_6 gas is highly complex, due to reaction with the GIS components,

$$SF_6 + Cu \text{ ---> } CuF_2 + SF_4$$

$$SF_4 + O_2 \text{ ---> } SO_2F_2 + 2F$$

$$SF_4 + H_2O \text{ ---> } SOF_2 + 2HF$$

$$SOF_2 + H_2O \text{ ---> } SO_2 + 2HF$$

$$4HF + SiO_2 \text{ ---> } SiF_4 + 2H_2O$$

While the metallic fluorides are solid, the other reaction byproducts are highly volatile and diffuse away from the arc vicinity. Most of the byproducts are highly corrosive and toxic, in turn attacking otherwise unaffected components, such as silica fillers as reported earlier [5,6]. The dominant oxyfluorides collected from gas compartments are SOF_2 and SO_2F_2. Concentrations of up to 20 μL/L (ppm) could accumulate in GIS chambers as a result of arcing at floating components.

The effects of low level arcing byproducts on epoxy spacer surfaces were investigated by determining the dielectric withstand of commercial spacer materials. The samples were exposed to 100 μL/L HF vapor for up to 4000 hours. The samples were subjected to repeated impulse voltage for determination of the breakdown strength in both air and SF_6 (energy of about 10 J) as described in detail elsewhere at higher byproduct concentrations [6]. Typical results of the exposure experiments are shown in Figure 2. A significant drop in the dielectric withstand of the sample occurred in the silica filled material after exposures of 1700 hrs. By comparison the alumina filled material was virtually unaffected by low level exposure to HF but underwent progressive deterioration in withstand voltage on subsequent impulses. Interestingly this decrease was only observed in SF_6 and not in air. The decrease is believed to be related to the change in surface chemistry (incorporation of S and F moieties into the epoxy chain) that we reported in earlier studies [5,6].

Effect of Partial Discharges

Solid particles generated by corona activity, be they solid metallic fluoride byproducts or metallic debris migrating from low field regions as a result of mechanical vibration, deposit on the surrounding spacer surfaces. The metallic particles can in some cases lead to microdischarges on the spacer surface. The interaction of the solid byproducts, direct electron bombardment and resulting surface modification is believed to affect the local electrical field, with the eventual formation of a track on the spacer surface. The track pictured in Figure 3 and found on a failed spacer is believed to be caused by such a process.

The effects of localized, low energy electrical discharges on dielectric surface degradation were investigated with the experimental setup of Figure 4 to simulate the above process. The voltage was raised to a level such that partial discharges were starting to occur from the sharp (3 μm diameter) tip of the needle. The samples were then aged under these conditions in an SF_6 atmosphere. Dielectric withstand and physical characterization were performed on the aged samples.

At first a liquid droplet formed on the spacer surface, underneath the needle, usually within about 30 hrs. The droplet became rapidly surrounded by a stained area. Analysis of the droplet, dried residue and stain by infrared, X-ray diffraction and ESCA indicated an aqueous fluorosulfate solution containing some iron counter ions; exact stoechiometry of the compound(s) is still under study. Both residue and stained surfaces exhibited high surface atomic concentration of sulfur and fluorine. The presence of iron on the epoxy surface is clear evidence of transfer of metallic species from the electrically stressed needle tip and reaction with, and decomposition of, the SF_6 atmosphere. The extent of surface modification taking place on the spacer is not clear because of material transfer onto the surface. However gas analysis in the aging chamber also revealed the presence of CF_4 in addition to SOF_2 and SO_2F_2, clearly confirming attack of the epoxy resin. Changes in surface composition are translated into changes in surface electrical properties as seen when the aged samples were also subjected to impulse voltage to determine the short term effect of exposure to low level discharges. Reductions of about 30% in dielectric withstand were observed after 300 hrs. of exposure to sustained pd (1200 pC). Experiments are currently in progress to determine the effects of atmosphere (air , SF_6), pd characteristics and spacer material composition on reduction in withstand voltage.

At longer aging times (about 500 hrs.) the track-like patterns of Figure 3 were obtained. While the deleterious effects of surface corona have been well known, past observations related more to global or diffuse effects on materials. The critical difference here is the high degree of localized damage leading ultimately to the formation of track-like features. While many questions remain to be answered, clearly the postulated surface aging mechanisms are plausible. Experiments are presently underway to refine our understanding of the critical parameters and material variables affecting the process.

CONCLUSIONS

Characterization of the early phases of the internal and external spacer surface degradation process was carried out by electrical and chemical techniques to develop a better understanding of the long term aging mechanisms. Reaction of nitrogen gas in a discharging cavity with the epoxy void wall was readily detected by ESCA and the technique could find application to investigate the void size below which no damage occurs. Similarly substantial modification of spacer surface properties could be brought about by exposure to localized corona discharges, associated with material transfer from the electrode and leading ultimately to the formation of track-like paths on the epoxy surface. Experiments are underway to refine our understanding of the critical parameters and material variables affecting the surface aging process.

Acknowledgement

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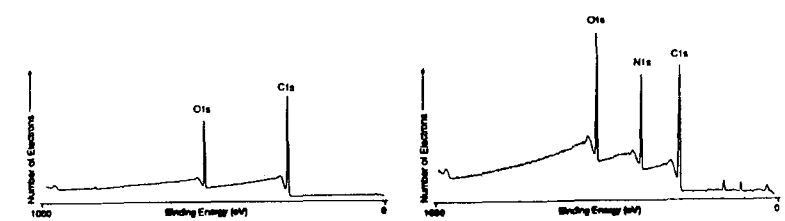

Figure 1. ESCA Scans of Epoxy Void Walls as Made (Left) and after PD.

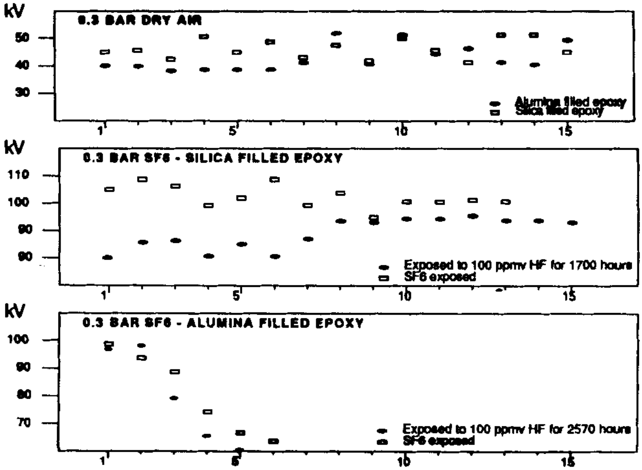

Figure 2. Dielectric Withstand Voltage of Filled Spacers Samples Exposed to Decomposition Byproducts

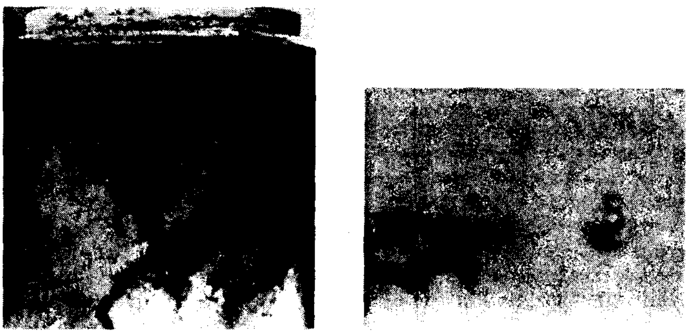

Figure 3. Photographs of Track on Failed Spacer (Left) and Laboratory Sample

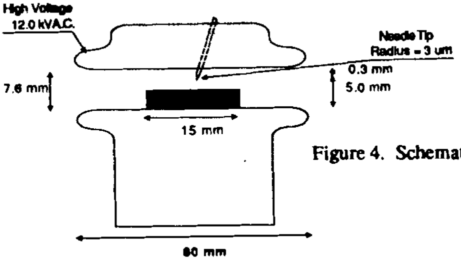

Figure 4. Schematic of Experimental Setup