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Surface finish effects on partial discharge with embedded electrodes

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Abstract: Partial discharge measurements have been used to characterize the response of dielectric insulation materials exposed to ac voltages. Electrode surface finish can affect such partial discharge characteristics. This paper provides comparisons to the effect of various surface finishes on electrodes embedded in a high temperature epoxy including roughness, electrode material work function, and thin coatings.

Introduction

Historically, an important purpose of partial discharge measurements in apparatus has been to promote life extension by identifying key trends in changes in partial discharge activity. The purpose of this work is to extend the success of those efforts to initial testing of new insulation systems in novel machines. This paper presents the results of a comparative study of partial discharge (PD) characteristics of brass electrodes embedded in an epoxy, where the electrodes have been subjected to various surface finishes.

Although electrode surface finish is known to affect PD, more information is needed concerning effects in particular insulation systems for engineering purposes. The choice of surface finish is often a cost consideration in building high voltage equipment and machines. Concurrently, increasing PD extinction voltages and lowering power losses are considered important in reducing dielectric aging [1].

We chose flat electrodes presenting a reasonable area of electrode to epoxy interface. Electrodes were embedded to reduce effects of humidity and other complications of surface discharges. The interfacial discharges in such configurations are expected to be representative of some embedded machine coils and magnet wire where multiple turns are encased or potted.

In this study, PD inception and extinction levels are given as rms voltages at 50 Hz. Charge populations were counted for 120 seconds. The average energy of a PD event is calculated as defined in [2]. The PD inception and extinction levels, however, are noted as the rms voltage at which PD is first observable within 120 seconds on voltage rise and at the rms voltage at which PD is no longer observed on voltage decrease, respectively. Some researchers prefer to define these characteristics in terms of the presence of one PD event per cycle.

Experimental Conditions

Partial Discharge Instrumentation

The digital detection system used in this work has been previously described [3]. The system has been shown to be extremely sensitive. The partial discharge events are timed using a zero-crossing detector. This is combined with a summing amplifier and digitizer. Pulses with amplitudes lower than 10 pC were not recorded. To produce the applied voltage, a sinusoidal signal from an SRS345 waveform digitizer is fed into a two to one Calex noninverting linear amplifier in line with a Trek 20/20a amplifier. The system is currently limited to ≤ 20 kV peak-to-peak voltages.

Sample Design

Samples are a simple parallel plate capacitor consisting of two brass electrodes potted in epoxy within a PVC ring of 3.9 cm inner diameter and 3.5 cm in height. The epoxy is an unfilled, two-part potting system meeting class H operating requirements [4]. The hardener is an anhydride amine blend. Samples were soaked, gelled, and then cured at 125°C for four hours following the manufacturer's recommendations. No post-cure heat-treatment was carried out.

Both electrodes are 0.635 cm diameter flat discs mounted on central threaded posts of 0.32 cm diameter. These posts extend linearly outside of the PVC ring at mid-height. We attempted to follow sample recommendations in [5] to produce a gap of 1.4 ± 0.1 mm (55 mils) for these equivalent electrode diameters. The edge of the disc was rounded, although not by a Rogowski radius, so for these samples the field is only approximately uniform from electrode center to electrode edge.

Electrode Surface Finishes

Pairs of brass electrodes were produced with five different finishes. These finishes are: A-smooth, B-very rough, C-stress grading layer, D-platinum sputter coated, and E-polyimide coated. The smooth surface of sample A was produced using wet SiC paper of 600 grit, followed by polishing with suspended colloidal alumina to <1 micron on a felt lap. The very rough electrode surfaces were produced by wet grinding with 320 grit

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SiC paper. Figure 1 gives a representative optical micrograph of surface B.

The stress-grading layer is a 30 volume % graphite powder, 70 volume % epoxy layer that was cured and polished smooth. This layer essentially consists of micron size conductive particles in a dielectric matrix and is semiconductive. The platinum layer on electrode surface D was sputtered from a platinum target in an argon plasma and deposited on the room temperature brass electrode surface that had been previously smooth and clean. The polyimide coating of surface E was cured from a commercial liquid precursor. [6]

Results

Pronounced differences in partial discharge behavior were observed between samples with different surface finishes. Values for PD characteristics of samples not previously exposed to voltages are listed in Table 1.

Effect of Roughness

The rougher sample B has a broader PD distribution than any of the other samples. An example PD distribution recorded at 13.6 kV is given in Figure 2. B is the only sample that exhibited significant positive PD. B also exhibits a high mean charge and a relatively high energy per PD event. Although the difference between inception and extinction voltages is within 0.1 kV, both characteristic voltages are significantly lower than those of sample A, which were above our system's ability to measure.

Effect of Stress-Grading Layer

The layer chosen to apply to sample C for this study does not improve the inception or extinction voltages. Although the mean PD charge is low, the difference between the two voltages is large. Once PD events initiate in this sample, they may catalyze more events. This appears to be a noted affect of some fillers.

Effect of Platinum Coating

Initial measurements of sample D consisting of platinum-coated electrodes were considered of interest due to a change in work function (~5.7 eV) from that of brass (~4.5 eV). Concurrently, the resistivity of pure platinum (~11×10^{-8} ohm-m) is twice that of brass. For this type of coating process, however, these features did not improve the characteristic inception and extinction voltages first measured, and the mean charge per event is the highest of all the samples studied.

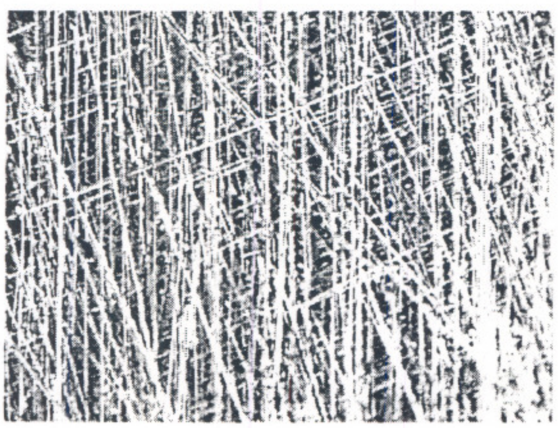

Figure 1. Optical Micrograph of sample B (x80).

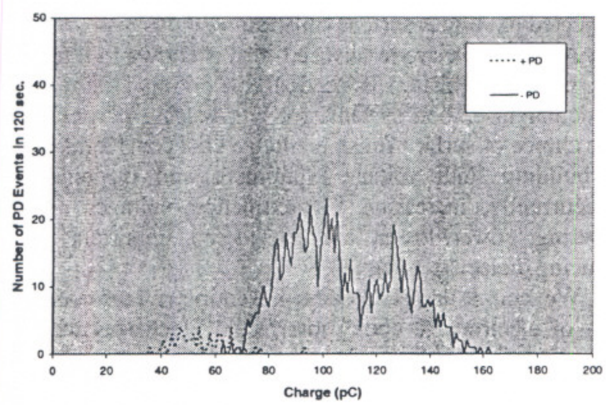

Figure 2. Charge populations for sample B at 13.6 kV.

Table 1. PD characteristics of samples upon initial voltage exposure.

Sample	Gap (mm)	Inception Voltage (kV)	Extinction Voltage (kV)	Mean Charge (pC) @ Voltage	Energy per PD event ($\times 10^{-6}$ Joules) @ Voltage
A	1.24	>14.1	-	-	-
B	1.22	13.1	13.0	68 @ 13.3 kV	0.90 @ 13.3 kV
C	1.22	12.6	11.7	22 @ 12.6 kV	0.28 @ 12.6 kV
D	1.19	12.0	11.9	93 @ 12.0 kV	1.12 @ 12.0 kV
E	1.17	11.2	11.2	21 @ 11.4 kV	0.24 @ 11.4 kV

Table 2. Results of repeated measurements on sample E.

	Frequency (Hz)	Inception Voltage (kV)	Extinction Voltage (kV)	Mean Charge (pC) @ Voltage	Energy per PD event ($x10^{-6}$Joules) @ Voltage
Initial	50	11.2	11.2	21.0 @ 11.4 kV	0.24 @ 11.4 kV
Measurements	500	7.8	7.6	19.2 @ 7.8 kV	0.15 @ 7.8 kV
Final	50	14.1	14.0	11.0 @ 14.1 kV	0.15 @ 14.1 kV
Measurements	500	13.9	13.8	16.0 @ 13.9 kV	0.22 @ 13.9 kV

Effect of Polyimide Coating

Polyimide is known to have excellent dielectric properties. Sample E, however, demonstrates the lowest inception and extinction voltages during initial measurements of all the samples studied. This sample also exhibits the lowest mean charge and energy per PD event.

Effect of Exposure on Subsequent Discharge Behavior

Typically samples demonstrated improved PD characteristics with time. Often several days lapsed between measurements. The samples were stored at room temperature during these lapses. Not only did the inception and extinction voltages increase, but the mean charge and standard deviations of the charge distributions decreased.

Some PD characteristics for sample E are listed in Table 2. The preparation of this sample is described above. The polyimide-coated electrodes have a gap of 1.17 mm. There was a lapse of ten days between the initial and final measurements. One set of interim measurements was made. The total exposure to both 50 Hz and 500 Hz sinusoidal voltage is on the order of four hours.

Discussion

Opportunities to change inception and extinction voltages by modifying electrode surfaces have been demonstrated on samples not previously exposed to electric stress. We must emphasize that these were initial measurements on new samples. Partial discharge testing, and other factors, can and do change the observed distribution of partial discharges. The significant differences among the charge deposited under various surface finishes of the electrode support the axiom that initially surface finishes have an important role in PD behavior. Earlier work has shown the importance of interfacial voids in determining partial discharge behavior in epoxy [7]. While that work showed some affect of early decrease in the discharge charge, in the early data it was not consistent. In addition, the early time was measured in hours so the effects seen here may have been masked.

The simple model of a discharge causing irreversible damage to the epoxy leading cumulatively to failure is not consistent with much of the data measured. As usual, a number of processes are likely to be competing. One mechanism that could raise the inception voltage is changes to the electrode surface, itself. A discharge can lead to microscopic plastic deformation in the metal of the electrode surface, typically increasing the field strength for subsequent emission [8].

A second possible mechanism is that the emitted electrons or the ac field may encourage further crosslinking that could lower the loss tangent. The epoxy curing process used to produce the measured samples followed the manufacturer's recommendations. However, post-cure heat-treatment to maximize properties was not carried out. There may be sufficient unpolymerized molecular groups in this epoxy processed in this manner to permit molecular rearrangements and consequent increase in the degree of crosslinking.

A third possible mechanism is based on interfacial orientation incited by ac voltages, especially at electrode interfaces where electric fields are pronounced. The ability of gaseous and liquid dielectrics to reconfigure and restore dielectric integrity during low-level PD events is well known [1]. In the case of a solid dielectric, such voltage conditioning may permanently remove defects through molecular reorientation.

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