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The Impact of Interfaces and Space Charge Formation on Breakdown Strength of Epoxy Resin

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***Abstract*- The re-emergence of HVDC necessitates re-evaluation of dielectric materials. Epoxy resin is employed as a dielectric material for joints and terminations in HV electrical systems up to about 75 kV, and higher ratings are required. Under DC however, space charge accumulation is a problem especially where interfaces are encountered. In this study, epoxy-epoxy laminates were fabricated and tested for space charge formation, using the PEA method, and breakdown strength under AC and DC were investigated. It was found that negative charges are accumulated at the layer interface and the breakdown strength under DC conditions is about 39% and 35% higher than that under AC condition for single and double layer samples respectively.**

I. INTRODUCTION

Epoxy resin is used as a dielectric material in high voltage (HV) electrical power applications such as power cable joints, bushings and in transformers due to its excellent physical, thermal and electrical properties [1]. The re-emergence of high voltage direct current (HVDC) and its advantages in bulk power over long distance transmission, and possibilities of medium voltage direct current (MVDC) in distribution networks, require re-evaluation of dielectric materials in this context. It is generally the case that the challenge of insulation design and reliability lies in terminations and joints. Charge injection, storage and transport at dielectric interfaces and laminates is an on-going research activity [2-5]. However, very little work has been done on epoxy-epoxy laminates. In this paper, thin layers of epoxy-epoxy laminates were fabricated and investigated for space charge formation and breakdown strength under AC and DC conditions. Space charge accumulation is associated with many pre-breakdown phenomena and it is more prominent under DC applications, particularly in the presence of interfaces. The pulsed electro-acoustic (PEA) technique [6-7] has been employed in this study.

II. EXPERIMENTAL

A. Sample preparation

A low viscosity epoxy resin Araldite® LY 5052 and the corresponding hardener Aradur ® HY 5052 both supplied by Huntsman was used in this study. The mixing ratio of the resin/hardener system was 100:38 (parts by weight). The required volume was mixed for about 5 minutes and degassed in a vacuum chamber for 60 minutes at room temperature. The mixture was then poured onto a steel mould plate coated with Polycoat™ release agent and allow to cure for 24 hours at room temperature. Single layer (SL) and double layer (DL - i.e. one epoxy-epoxy interface) samples were fabricated for both breakdown tests and space charge measurements using spacer gaskets between the mould plates. The epoxy-epoxy laminates have been formed by first curing a SL plaque of epoxy and then forming a second layer of epoxy, by doubling the gasket thickness. With this process, and following the same curing regime, an epoxy-epoxy interface region is created with identical material properties. The cured materials were laser cut into discs of 55 mm diameter and post-cured in an oven at 100 ^{0}C for 4 hours. Prior to post-cure, the thicknesses of the samples were measured at 5 points on each sample and the average was recorded. The SL plaques have been moulded with two different thicknesses; one with a thickness of 100 µm and another of 200 µm, similar to the thickness of a DL plaque.

B. Space Charge Measurement

Fig. 1, shows the schematic diagram of the PEA measurement technique. The working principle of this technique is the application of a short pulsed voltage coupled via a charging capacitor which perturbs the internal charges in a sample sandwiched between the anode and cathode. The perturbation causes the charges to vibrate which launches an acoustic wave proportional to the charge distribution. A piezoelectric sensor (PVDF) is used to detect and transform the acoustic wave into electrical signal which is then amplified and viewed with an oscilloscope. A 9 µm thick PVDF sensor and an electric pulse of 10 ns width with amplitude of up to 1 kV was used. This gives a spatial resolution of about 20 µm [8]. In this experiment, single and double layer epoxy samples of thicknesses 219 µm, and 212 µm respectively were tested. Measurements were taken with a voltage applied at a rate of 1 kV/min in the first 8 minutes on each sample, and the field was maintained at 8 kV for 3 hours. The voltage was switched off, and measurements taken again during charge decay. A semicon plaque was used as the anode and an aluminium plate as the cathode. Silicone oil was applied between the interfaces

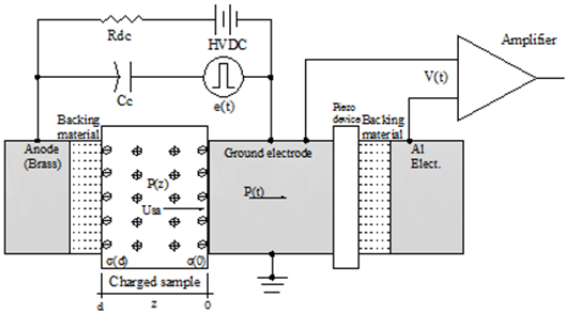

Fig. 1. Schematic diagram of the PEA technique

of the samples and the electrodes to improve acoustic impedance matching. The system was calibrated at 1.5 kV DC and de-convoluted using LabView program to process the data and recover the original signal [9-10].

C. AC and DC Breakdown Tests

Fig. 2, shows the circuit diagrams for AC and DC breakdown tests. For an AC breakdown test, an 80 kV AC transformer was used, while for the DC breakdown test, a Brandenburg 100 kV reversible desk-top HVDC power supply was used.

Protective resistors of 10 MΩ were connected to the outputs of the HV supplies and the output voltages monitored and measured via a 10,000:1 voltage divider (North Star VD100) and a digital oscilloscope. Single and double layer samples were tested for three test types namely; DC breakdown tests in air, DC breakdown tests in oil and AC breakdown tests in oil. For each test type, four samples were tested for 40 breakdown sites (10 sites per sample). Positive and negative breakdown tests were performed under DC. For breakdown tests in air, commercially obtained PET film was used as reference samples and epoxy samples (fabricated in-house) of ~100 µm were tested to compare the strengths of the fabricated materials.

Breakdown tests in oil were carried out in silicone oil to prevent flashover. The oil was dried at 85 ^{0}C for 24 hours in a vacuum chamber and the temperature reduced to 23 ^{0}C and then left in the vacuum for 72 hours prior to the test. The average temperature and relative humidity at the time of tests was23±2 ^{0}C/47±5% in the test cage. The test electrodes were made of brass spheres of 20 mm diameter, and were designed according to IEC 60234-1 [11]. The rate of voltage rise was about 1kV/s. The voltage (AC or DC) was applied continuously to the test sample until breakdown occurred. Breakdown occurred within 60 seconds of voltage application in all samples. The use of a digital oscilloscope allows the breakdown voltage to be accurately determined by freezing the waveform after breakdown, and using the cursors to determine the peak voltage at which the breakdown occurred. The breakdown fields were determined as the ratio of the breakdown voltages and the sample thicknesses between the electrodes for each sample and breakdown event. The test results were tabulated and plotted on Weibull axis.

III. RESULTS AND DISCUSSIONS

A. Space charge Measurements

Fig. 3 (a) and (b) shows the profiles of the charge distribution obtained from a 219 µm single layer epoxy sample under poling at 37 kV/mm. A gradual accumulation of hetrocharges can be seen next to the electrodes as the poling voltage is increased from 1 kV to 8 kV shown by arrows 1 and 2 in Fig. 3 (a). One hypothesis of the observed space charge behavior is associated with homocharge injection at the anode and cathode where bipolar charges travel across the bulk of the sample and get blocked at the opposite electrodes. The second

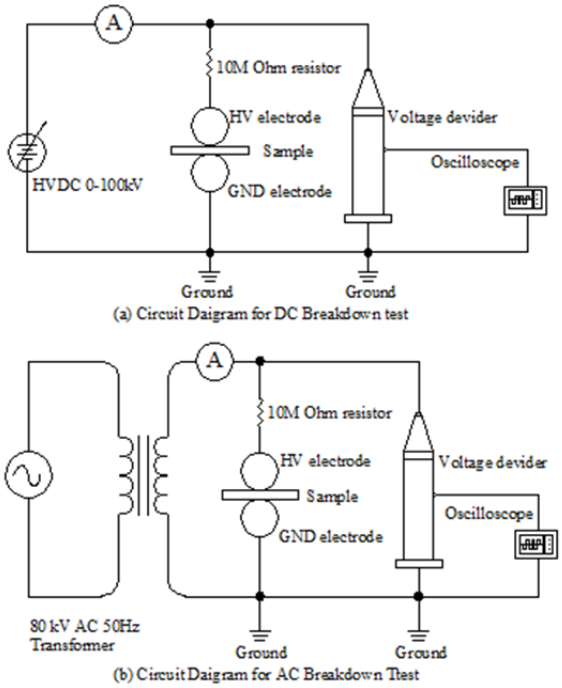

Fig. 2. Circuit diagrams for AC and DC breakdown tests

one is that positive and negative charges already exist in the sample, perhaps in the form of ions, and once the voltage is applied they are attracted towards the electrodes. The reason they accumulate at the adjacent electrodes could be because these heterocharges do not have enough energy to get extracted or they are too big to be extracted. They could also accumulate due to different charge injection and extraction rates at the electrode/material interface. Fig. 3 (b) shows the plots when a DC field of 37 kV/mm is maintained across the sample for 3 hrs followed by a charge decay measurement at 5 and 60 sec when the poling field is removed. It can be seen that the accumulated heterocharges decay quickly suggesting that these charges reside in shallow trap depths.

Fig. 4 (a) and (b) shows the profiles of charge distribution obtained from 2- layer epoxy-epoxy sample of thickness 212 µm. At 1 kV, only capacitive charges are observed at the electrodes. However, beyond 3 kV it is observed that negative space charge is being trapped at the layer interface as the poling voltage is increased up to 8 kV shown by arrows 1 and 4 in Fig 4 (a). It appears that the anode attracts negative charges while the cathode attracts positive charges which accumulate at their vicinities as heterocharges shown by arrows 2 and 3 in Fig. 4 (a). Fig. 4 (b) shows the plots when the poling field of 38 kV/mm was maintained for 3 hrs followed by subsequent charge decay measurement at 5 and 60 sec. Negative space charges trapped at the layer interface shown by arrow 1, have substantially decayed after only 60 sec. Similar interface charge behavior was observed in multi-layer low density polyethylene in [4-5].

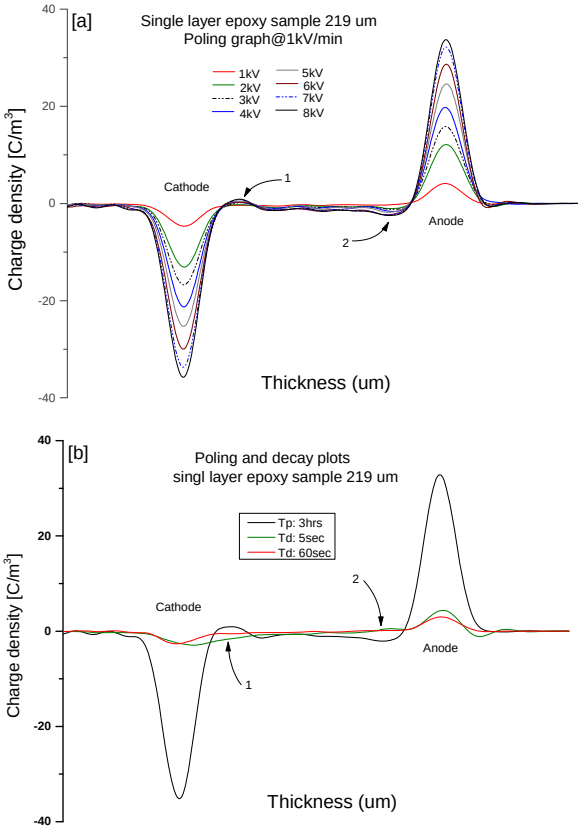

Fig. 3 (a) and (b). Space charge profiles of single layer sample

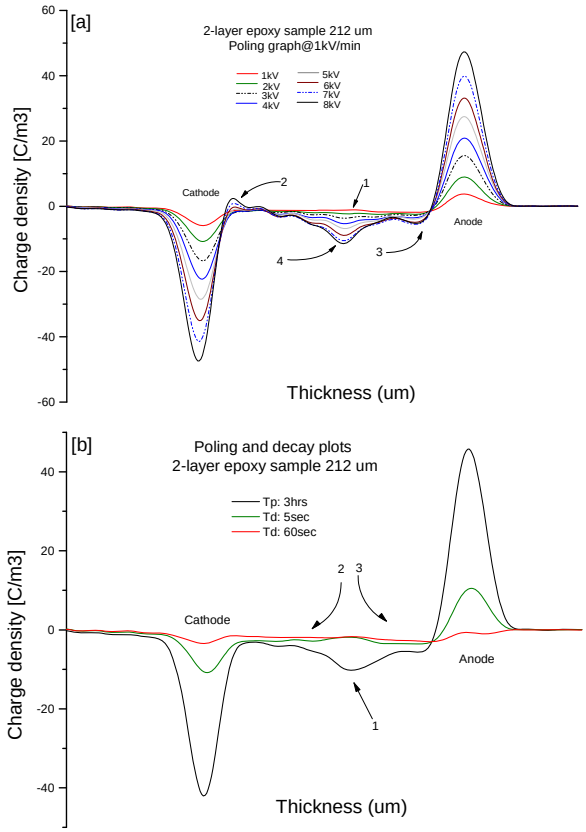

Fig. 4 (a) and (b). Space charge profile of double layer sample

B. Breakdown strength

Fig. 5, shows the Weibull plots of electrical breakdown strength of the tested samples from which the Weibull parameters (α); the characteristic value representing the cumulative failure probability at 63.2% and (β); the shape parameter showing the measure of scatter, were extracted and are presented in Table 1. From Table 1, it can be seen that the breakdown strength (α) of the reference sample for positive and negative breakdown test in air is about 26.4% and 29% higher than that of the epoxy resin samples, while it is 1.6% and 5.1% higher for positive breakdown test in the reference and epoxy resin samples respectively. The lower values of (α) in epoxy resin samples is related to defect and impurities during fabrication as the laboratory condition is not super

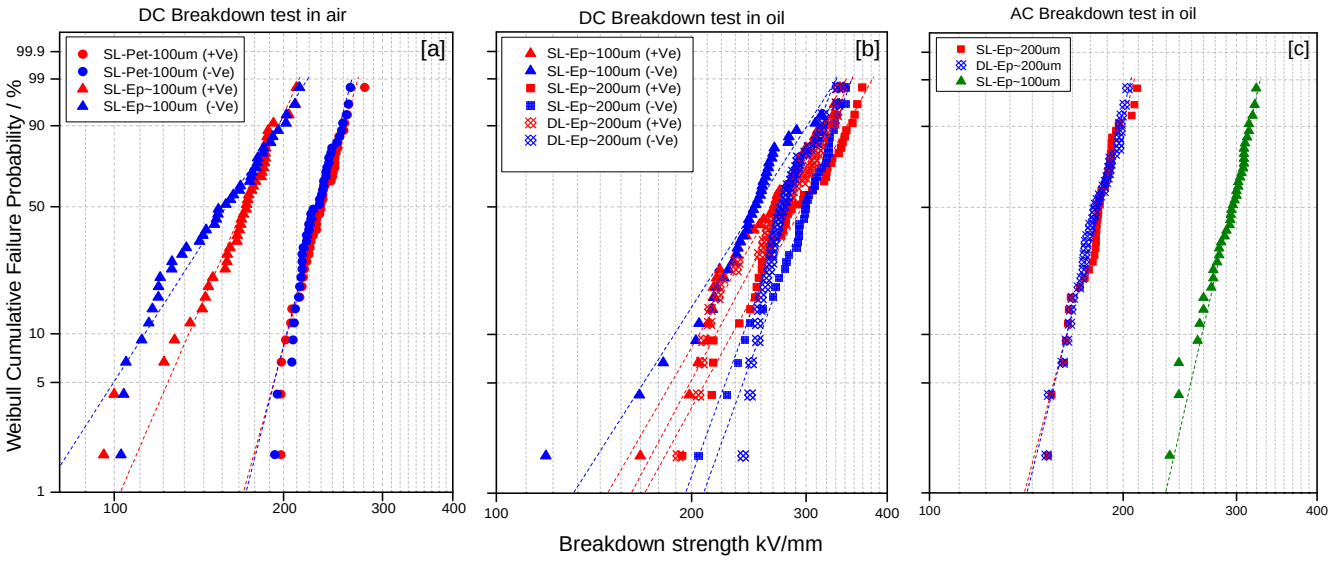

Fig. 5 Weibull plots comparing DC breakdown test in air and AC and DC breakdown test in oil

Table 1. Weibull parameters from AC and DC breakdown plots

Test type: DC Breakdown in Air				Test type: DC Breakdown in Oil				Test type: AC Breakdown in Oil			
Sample ID	Voltage polarity	α (kV/mm)	β	Sample ID	Voltage polarity	α (kV/mm)	β	Sample ID	Voltage	α (kV/mm)	β
SL-Pet-100 μm	Positive	241.32	13.07	SL-Epoxy~100 μm	Positive	280.26	7.23	SL-Epoxy-100 μm	AC	300.22	18.
SL-Pet-100 μm	Negative	237.4	14.16	SL-Epoxy~129 μm	Negative	265.04	6.56	SL-Epoxy-200 μm	AC	188.72	15.5
SL-Epoxy-116 μm	Positive	177.68	8.68	SL-Epoxy~200 μm	Positive	310.49	7.58	DL-Epoxy-209 μm	AC	187.39	16.4
SL-Epoxy-108 μm	Negative	168.66	5.66	SL-Epoxy~200 μm	Negative	309.52	11.64				
				DL-Epoxy~215 μm	Positive	290.62	7.82				
				DL-Epoxy~205 μm	Negative	291.7	11.5				

clean. This has reflected in the lower β values of 8.68 and 5.66 in the epoxy resin samples compared to 13.07 and 14.16 in the PET samples. These lower values of β in epoxy resin samples are indicative of defects in the sample which is observed as deviation from the straight line of the plots shown in Fig. 5 [a]. Also, the breakdown strength of epoxy resin samples of 100-129 μm, increased by ~36% for both positive and negative voltage polarity when the test was carried out in oil compared to the that in air indicating the influence of surrounding medium on breakdown strength.

Comparing AC and DC breakdown tests in oil on single and double layer epoxy samples of ~200 μm thick, it was observed that the breakdown strengths under AC condition were lower by ~39% and ~35% for single and double layer samples respectively compared to that under DC test, and the single layer sample recorded ~6% and ~1% higher breakdown strength than the double layer sample in both DC and AC test. Less than 1% difference is observed in breakdown strengths for positive and negative voltage polarity test, which is not statistically meaningful.

IV. CONCLUSIONS

From the space charge profiles in Fig. 4, it is evident that interface provides a location for charge traps. Depending on the depth of trap, charges can remain trapped at the interface for long or short time depending on conditions such as field magnitude and temperature, which will eventually control the conductivity of the material. In the presence of defects such as voids and protrusions, higher local fields are generated due to difference in permittivity and conductivity under AC and DC conditions, which results in other ageing mechanisms such PD activity and electrical treeing which may eventually lead to breakdown of the material.

In breakdown tests, it was observed that, the surrounding medium as well as the type of voltage applied to the test samples has impact on breakdown strength. This is clear from the α values in Table 1, as the breakdown strength of ~ 100 μm samples increased by ~ 36% when the test was carried out in oil compared to that in air. It is also seen that, for the same sample thickness of about ~200 μm the breakdown strength under AC condition is about 39% and 35% less than that under DC condition for single and double layer samples. This phenomenon is likely due to more intense PD activities under AC than DC. However, the breakdown strength of double layer samples is about ~ 6% less than that of single layer sample under DC and similar to the AC value a situation attributed to charge storage at the layer interface which enhances local electric field and cause early breakdown in the double layer samples compared to the single layer samples.

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