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Analysis on surface discharge patterns caused by harmonic AC voltages

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Surface roughness and fractal analysis is carried out on the surface discharge patterns formed on epoxy nanocomposite, by harmonic AC voltages. The surface discharge patterns are obtained be adopting IEC(b) electrode configuration, and surface degradation levels are compared. It is observed that discharges initiated from the high voltage electrode propagates over the surface of the nanocomposites, the extent of discharge propagation are different for AC voltages with different harmonics and THDs. Surface roughness does not linearly increase with the increase in order of harmonics. Fractal dimension of surface discharge patterns in air medium varies between 1.4 – 1.72

Keywords : *Surface discharge, surface roughness, fractal dimension, harmonics, epoxy nanocomposite,*

1.0 INTRODUCTION

In recent times, with the increase in use of nonlinear loads, such as UPS, variable-speed drives, and electronic fluorescent lighting ballasts, etc., can cause harmonic pollution in the power system network leading to distortions in the AC supply voltage profile [1-3]. Considerable research work has been carried out on understanding the mechanism of surface discharge formation under AC voltages. The mechanism of surface discharge formation in epoxy nanocomposite insulation under AC voltages with harmonics, are scanty. Epoxy nanocomposites are gaining importance as practical insulating material in power equipment because of its good electrical, thermal, chemical and mechanical properties compared with the conventional polymers [4-6]. One of the major problems with the polymer insulator is the Surface Discharge (SD) initiated damage during operation leading to catastrophic failure of the equipment [7-10].

In the present work, an attempt has been made to find the correlation between Fractal dimension and the severity of degradation on epoxy nanocomposite, due to surface discharge activity. A methodical experimental study was carried out to understand the surface discharge formation in epoxy nanocomposites with harmonic AC voltages (fundamental power frequency wave with different order of harmonics (K) and Total Harmonic Distortions (THD)). Mandelbrot had explained in detail that any pattern having self-similarity could be analyzed by fractal geometry principles [11]. The characteristic variations in surface discharge patterns with harmonic AC voltages need to be understood.

2.0 EXPERIMENTAL STUDIES

Epoxy nanocomposites were synthesized by use of high speed shear mixing of organo clay in the epoxy resin bath, at room temperature. The clay mineral used in this study was organophillic Montmorillonite (MMT) clay, procured from Southern Clay Products Inc. (Gonzales, Texas) under the trade name of Garamite 1958 [11]. After uniform mixing of clay particles in epoxy resin (DGEBA, CY205, Ciba Geigy Inc.),

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Tri-Ethylene Tetra-Amine (TETA) hardener was added and then cast into a mould of required dimension and degassed. The hardener used is of room temperature curing type and for stabilization; the mould was kept in oven at 75 °C for three hours, after 24 hours of room temperature curing. Epoxy nanocomposites with different (1-10) weight percentage (wt%) of clay were prepared and characterized, 3 wt% specimens were used for surface discharge studies in the present study [12].

The IEC (b) electrode system was used to compare Partial Discharge (PD) resistance of the nanocomposite material under harmonic AC voltages [9]. The IEC (b) electrode configuration is a rod-plane electrode with the rod electrode diameter of 6 mm with its edge having a curvature radius of 1 mm. The epoxy nanocomposite sheet of size 30 x30 x1 mm was used as specimen. The epoxy nanocomposite material was cleaned with acetone and dried in hot air oven at 60 °C for 5 hours before carrying out the test. Experiments were performed by mounting the test electrode in an acrylic cell of 15 cm^3 volume, with silica gel filled at bottom to maintain humidity at room temperature.

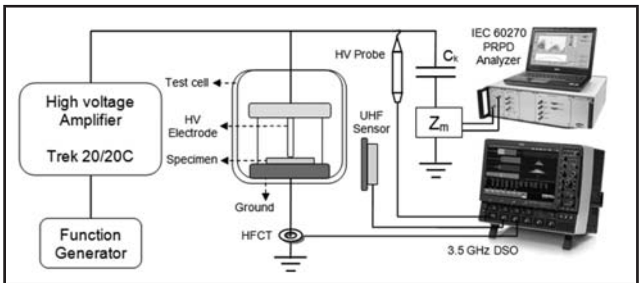

FIG. 1. EXPERIMENTAL TEST SETUP FOR SURFACE DEGRADATION STUDY

The test electrode setup and some of the analysis tools used for the present study is shown in Figure 1. The top rod-electrode is connected to the high voltage source and the other electrode connected to ground. The harmonic AC voltages were generated by signal generator (Agilent 33250 A) and amplified using high voltage amplifier (Trek 20/20C). The applied harmonic AC voltage was measured by using an AC high voltage probe (LeCroy, USA model No.PPE 20 kV). In the present study, an optical surface profilometer from Bruker® (3D profiler) is used to examine the degraded and un-degraded surfaces of the specimens. The harmonic AC voltages are named as xfy, where x denotes the order of harmonic (3, 5 or 7) and y denotes the THD% (4 or 40).

3.0 RESULTS AND DISCUSSION

3.1 Time domain analysis of UHF signals

UHF signals are captured and measured by a broadband antenna connected with DSO (Digital Storage Oscilloscope) during surface discharge process. Time domain analysis is carried out on the captured signals to understand the degradation mechanism, under various harmonic AC voltage inputs.

Table 1. UHF signal formed due to surface discharge under harmonic AC voltages with different THD (K – Order of harmonics, T – time taken to capture 100 UHF signals. V_{avg} – average of 100 UHF signal)

TABLE 1

UHF SIGNAL FORMED DUE TO SURFACE DISCHARGE UNDER HARMONIC AC VOLTAGES WITH DIFFERENT THD (K – ORDER OF HARMONICS, T – TIME TAKEN TO CAPTURE 100 UHF SIGNALS. V_{AVG} – AVERAGE OF 100 UHF SIGNAL)

K	THD %	Crest Factor	Nano-filler wt%	Air	
				T	V_{avg}
1	0	1.41	3	46.1	122
3	4	1.36	3	39.2	277
5	4	1.46	3	1.3	105
7	4	1.38	3	38.2	386
3	40	1.30	3	17.5	326
5	40	1.84	3	0.9	107
7	40	1.71	3	1.5	372

Table 1 shows the variation in UHF signal magnitude and time taken for UHF signal during various surface degradation process. Magnitude (V_{avg}) and time taken (T) by UHF signal were arrived based on the average of 100 UHF signals measured in a sequence and time taken by the sequence, respectively. It is observed that UHF signal magnitude generated under harmonic AC voltage were higher for 7f4 and 7f40 (in Figure 2 e and f). The crest factor of the applied wave plays a role in determining the time taken by the sequence, time taken by the UHF signal sequence for 5f4 and 5f40 were lower although the surface damage was minimal (in Figure 2 c and d).

In general it could be concluded that, higher amplitude of PD (V_{avg}) is responsible for more surface erosion, whereas the shorter time taken by the sequence is responsible for quicker flashover.

3.2 Surface Discharge Patterns

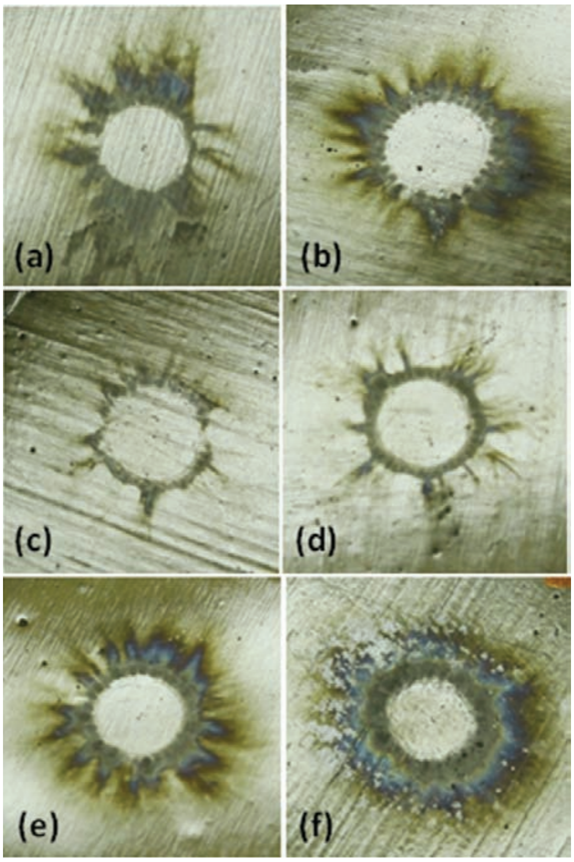

FIG. 2. TYPICAL OPTICAL PHOTOGRAPH OF SD PATTERN FORMED WITH DIFFERENT HARMONIC AC VOLTAGES (A) 3F4 (B) 3F40 (C) 5F4 (D) 5F40 (E) 7F4 AND (F) 7F40

Analysis of surface damage is carried out with the use of surface profilometer, and by optical photographs. Degradation on the surface of epoxy nanocomposites are caused as a result of surface discharges, with harmonic AC voltages. Fig. 2 shows the typical photograph of the degraded zone caused due to surface discharge under harmonic AC voltage of 6 kVrms, for 2 hours. The inner light colored circle represents the un degraded zone which was directly under the contact of High Voltage (HV) electrode, 6 mm in diameter. Fibrillar structure formed around the HV electrode increases with the order of harmonics. Increase in dimension of thick dark ring formed around the HV electrode is observed with increase in THD on the surface of the epoxy nanocomposite specimens. The discharges have propagated from the edge of the high voltage electrode and the discharge patterns formed are different with harmonic AC voltages. It is observed that increase in harmonic contents in fundamental wave have caused severe damages on the surface of material.

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3.3 Surface Roughness Measurement

A typical surface roughness profile of epoxy nanocomposites after degradation due to surface discharge with 50 Hz AC voltage is shown Figure 3 [13]. Surface roughness of the degraded samples for various harmonic AC voltages are measured to understand the level of degradation, and is shown in Table 2. Un-degraded epoxy clay nanocomposite (3 wt%) samples had an average surface roughness of 165 nm. Higher amounts of surface roughness for 3rd and 7th order harmonics & lower amounts of roughness for 5th order is observed also from the surface roughness analysis, which correlates with the time domain analysis in 3.1.

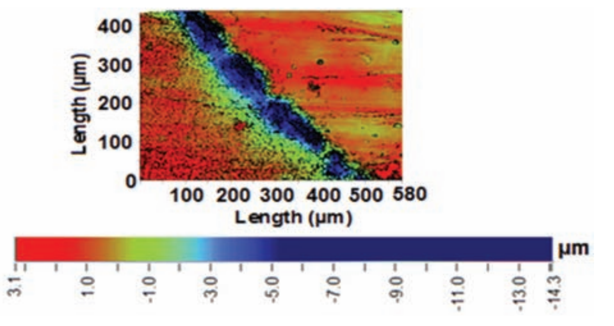

FIG. 3. TYPICAL SURFACE PROFILE OF SD PATTERN FORMED

3.4 Fractal Analysis of Surface Discharge Patterns

Fractal analysis is useful in analyzing self-similar structures by calculating Fractal dimension. The patterns formed due to surface discharge activity is observed to form self-similar structures. An attempt has been made to correlate the amount of degradation to crest factor of the applied waveform.

Optical photographs of surface discharge patterns (Figure 2) are converted to binary format for calculating the Fractal dimension as shown in Figure 4. It is observed that the effective area of surface discharge zone have increased with increase in THD but not with increase in the order of harmonics in linear order. It is observed that crest factor of the harmonic AC voltage plays an important role on the level of damage that occurred.

Fujimori *et al.*, adopted fractal dimension technique to identify the shape of electrical tree [14]. Barclay *et al.,* made a statistical analysis of electrical tree propagation estimating growth length and concluded that trees with lower fractal dimension cause early failure of electrical insulation [15]. In the present study box counting technique is carried out to calculate fractal dimension, the number of boxes N(r), covering the surface discharge pattern with changing box size 'r' is measured and log N(r) – log(r) is plotted and slope of the curve directly provides fractal dimension 'D'. Fractal dimension computed for harmonic AC voltages in Figure 5 shows nearly an inverse relationship with their corresponding crest factors. Amount of surface damage (Figure 2) and surface roughness values (Table 2) are showing a relationship with the fractal dimension of the corresponding samples.

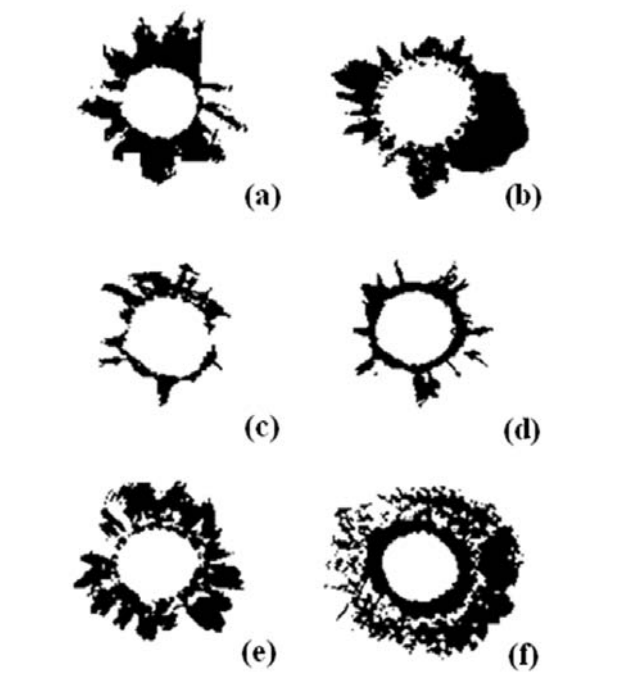

FIG. 4. BINARY IMAGES OF SURFACE DISCHARGE PATTERNS BY (A) 3F4 (B) 3F40 (C) 5F4 (D) 5F40 (E) 7F4 AND (F) 7F40

TABLE 2
SURFACE ROUGHNESS VALUES FOR VARIOUS APPLIED WAVES

Applied wave	K	THD %	Crest Factor	Average Surface Roughness (nm)
50	1	0	1.41	1040
3f4	3	4	1.36	1096
5f4	5	4	1.46	1004
7f4	7	4	1.38	1255
3f40	3	40	1.30	1200
5f40	5	40	1.84	1080
7f40	7	40	1.71	1346

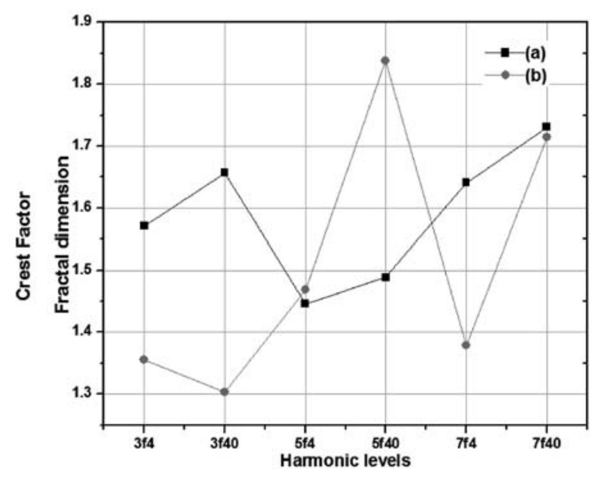

FIG. 5. (A) FRACTAL DIMENSION OF SURFACE DISCHARGE PATTERNS UNDER HARMONIC AC VOLTAGES AND THEIR CORRESPONDING (B) CREST FACTORS

4.0 CONCLUSIONS

The important conclusions obtained based on the present study are the following.

- High magnitude of PD discharges are becoming responsible for more surface degradation, than high number of discharges.
- It is realized that surface discharge initiated degradation is more near to the high voltage electrode in IEC (b) configuration. Thickness of the dark ring around high voltage electrode increases with the increase in THD. But, the amount of degradation doesn't increase with the increasing order of harmonics.
- Higher amounts of surface roughness for 3^{rd} and 7^{th} order harmonics & lower amount of roughness for 5^{th} order harmonics are observed.
- Fractal dimension of surface discharge patterns in air medium varies between 1.4 – 1.72. Amount of surface damage and surface roughness values are showing a relationship with the fractal dimension of the corresponding samples.

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