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SIMULATION OF CHAOTIC SURFACE TRACKING ON THE POLYMERIC INSULATORS WITH BROWNIAN MOTION

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ABSTRACT

Dielectric breakdown of insulators frequently results in tree-like patterns. The resulting tree-like patterns have been known to be fractal character. In this paper, chaotic surface tracking patterns observed on polymeric outdoor insulation materials of electrical industry are investigated and simulated. The polymeric samples have been tested according to the IEC 587 Inclined Plane Tracking Test Standard. These samples are subjected to external moisture, vibration and fatigue effect. The carbonized tracking patterns are investigated by calculating their fractal dimensions. The last part of this study was about computer simulation of surface tracking patterns with Brownian motion.

Keywords: *Fractal dimension, Brownian motion, Polymeric insulator, Electrical Treeing*

1. INTRODUCTION

In recent years due to the rapid developments in technology and increasing energy demand, the requirements of electrical industry were specialized. The variety of insulator materials used in energy sector has increased with the improvements in material science. Therefore, in order to provide the optimum solution it became compulsory to analyze the specific situations in detail in consideration of these reasons.

The concept of fractal geometry, introduced by Mandelbrot [5] has provided a strong tool for the analysis of various shapes in nature. Random and complex patterns are characterized and classified quantitatively only by fractal dimensions [9]. With classical dimension concept it is quite difficult to analyze chaotic figures like surface tracking patterns, however fractal geometry and hence dimension are quite useful in analyzing and producing self similar natural structures [20].

The surface tracking is one of the severe conditions, which may cause discharge patterns all over the polymeric insulator. Several standards and test methods have been developed to simulate tracking phenomena artificially. In this study the surface tracking patterns of the composite polymeric insulators under moisture and vibration effects have been analyzed respectively. Later on carbonized surface tracking patterns were simulated with a computer program [2].

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Brownian motion method, which is fundamentally based on the probability and random processes, is very effective and convenient for the simulation of random walk shaped figures. Brownian motion is the unique random process with independent increments, stationary and finite standard deviation properties [6].

Chaotic figures of these test samples are initially digitized by a commercial scanner and then transferred to the computer. A special program has been written in order to analyze the carbonized tracking patterns according to their fractal dimensions [2]. In the second part of the project a Brownian motion based computer simulation is fulfilled. These simulated figures were also investigated with the fractal dimension concept. Finally simulated figures and test sample figures are compared according to their fractal dimensions and shapes respectively.

2. FRACTAL GEOMETRY AND BROWNIAN MOTION MODEL

The classical geometry deals with objects of integer dimensions, however fractal geometry describes non-integer dimensions. Zero dimensional points, one dimensional lines and curves, two dimensional plane figures like squares and circles, and three dimensional solids such as cubes and spheres are the elements of classical geometry. Fractals are the figures which have subsets completely similar to the whole figure. Shrinking or expanding the figure never causes shape loss of the original figure [5].

The reason for the formulation of the fractal theory is derived from the need for describing the previously developed unusual geometrical shapes, based on theories of mathematical sets of points. This paper will focus on the fractal analysis and computer simulation of surface tracking (real electrical trees) patterns [18].

Several methods are used to estimate fractal dimension and they are classified into the following categories [3].

1. Box Counting.
2. Fractal measure relation.
3. Correlation function
4. Distribution function
5. Power spectrum

In this paper box counting method is used to calculate fractal dimension. This method [9], [19] is often called box-counting method or a covering method, and is performed by covering the Figure by some basic shape such as a square, circle or cube. Box counting method is classified into three categories. These are capacity dimension, correlation dimension and information dimension [2], which are some of the effective methods for the fractal dimension calculation.

The surface tracking patterns of polymeric samples are tested under standard conditions with and without external effects and are subjected to a computer program. Fractal dimensions are calculated by using this program. It can be assumed that for any fractal object (of size P, made up of smaller units of size k), the number of units (N) that fits into the larger object is equal to the size ratio (P/k) raised to the power of d, which is called the Hausdorff dimension [9], [19].

$$d = \frac{\log N}{\log p/k} \qquad (1)$$

Brownian motion originally refers to the random motion observed under microscope of pollen immersed in water. Brownian motion is the observed movement of small particles while they are randomly bombarded by the molecules of the surrounding medium. This phenomenon was first observed by the biologist Robert Brown and eventually explained by Albert Einstein [3].

Brownian motion is a family of Gaussian processes and fractional brownian motion is a model that combines fractal geometry and brownian motion. Hurst used these processes as a model for the water level in reservoirs along the Nile [14]. Mandelbrot [5], [6], used these processes to model some economic data. In this paper fractional brownian motion is used to simulate surface tracking patterns of polymeric insulators.

This model is the best way to simulate rough structure shapes of nature (cloud, tree, mountain, etc…). This model, which is based on random iteration algorithm [4] is also occur to be the most effective method to simulate surface tracking patterns of polymeric insulators.

For each $H \in (0,1)$, a real-valued Gaussian process $\left(B^H(t), t>0\right)$ is defined such that $\mathrm{E}\left(B^H(t)\right)=0$ and for all $s,t \in \Re_+$.

$$\mathrm{E}\left[B^H(t)B^H(s)\right]=\frac{1}{2}\left[|t|^{2H}+|s|^{2H}-|t-s|^{2H}\right] \qquad (2)$$

The process $\left(B^H(t), t>0\right)$ is said to be a (standard) fractional Brownian motion with Hurst parameter H. If H = 1/2, then the corresponding fractional Brownian motion is a standard Brownian motion. If H > 1/2, then the process $\left(B^H(t), t>0\right)$ exhibits a long range dependence [10].

The mean square replacement technique was used for the Brownian motion. With the increasing time random walk was produced [16].

$$\mathrm{var}\left[X(t_2)-X(t_1)\right]=|t_2-t_1|\sigma^2 \qquad (3)$$

In this replacement equation random variables with zero mean and σ^2 variance are used. We have obtained new replacement equation by adding scale parameter H to the equation.

$$\mathrm{var}\left[X(t_2)-X(t_1)\right]=|t_2-t_1|^{2H}\sigma^2 \qquad (4)$$

The replacement gets smaller and figures get smoother for higher values of the H parameter. Also fractal dimension is dependent on the H parameter. The H parameter coefficients were used for the simulation.

3. CALCULATION AND SIMULATION

The Fractal dimensions of carbonized surface tracking patterns are calculated by a specific computer program written in C programming language [2] Correlation dimension, capacity dimension and information dimension methods are selected among several algorithms.

The Capacity dimension method depends on covering whole figure with the boxes which have the same side length. Counting the box number for different side lengths is a good estimate for the fractal dimension. Correlation dimension method also uses box counting concept except it has time behavior information of dynamic systems additionally. Information dimension method depends on the probability of finding a point within a certain box.

Several models have been proposed to simulate the surface tracking patterns on the solid insulator materials. To simulate naturally shaped structures Fractional Brownian Motion seems to be the optimum and fastest method. This model is used to simulate the river shaped carbonized black surface tracking patterns [13], [7]. Then experimentally obtained tracking patterns of polyester samples are simulated by using a recursive technique based on Brownian motion method.

4. FRACTAL DIMENSION CALCULATION

4.1. Without External Effect

Polymeric samples were tested under standard conditions (4kV voltage and 36ml/h liquid flow rate), without external effects [1]. These conditions define the standard which provides optimum discharge energy and shortest breakdown time. Five test samples have been tested without external effect and average fractal dimensions are presented in table 1. A polymeric sample which was tested under standard conditions without external effects is given in figure 1.

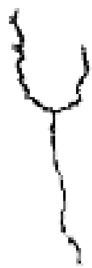

Figure 1. Carbonized tracking pattern without external effect

Table 1. Fractal dimensions of test samples without external effect

Method	Fractal Dimension
Capacity dimension	1,186
Correlation dimension	1,112
Information dimension	1,257

4.2. External Moisture Effect

In this part of the study samples were tested under moisture effect. Test samples classified according to their moisture percentage. At 23°C room temperature, samples were subjected to %40, %60, %80 and %99 relative moisture respectively is given in figure 2.

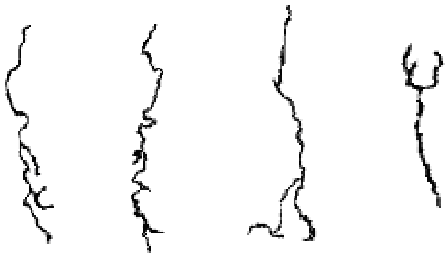

Figure 2. *Surface tracking patterns of polymeric samples tested %40, %60, %80 and % 99 external moisture effects.*

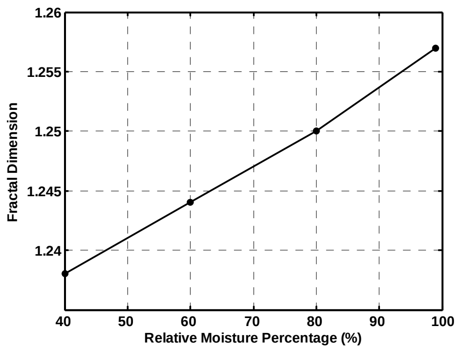

Figure 3. *Average fractal dimensions and moisture percentage relations.*

The widths of the surface tracking patterns were calculated. By using a commercially available software program, widths of the carbonized tracking patterns have been measured. Average surface tracking widths is important information about the degree o damage on the polymeric insulator. Average fractal dimensions and surface tracking widths versus relative moisture percentage relations of the samples are given in the figure 3 and figure 4 respectively.

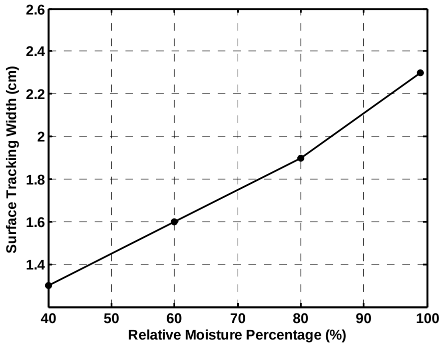

Figure 4. *The width of surface tracking patterns according to the relative moisture.*

4.3. Longitudinal Vibration Effect

The relation between the longitudinal vibration and the surface discharge energy has been investigated. A variable speed vibration motor has been employed to produce horizontal movements at variable frequencies. The samples which were tested under vibration effect (12 Hz, 22 Hz and 64 Hz respectively) are given in the figure 5.

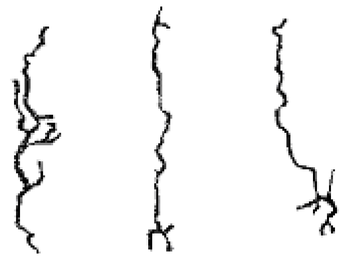

Figure 5. *Surface tracking patterns of polyester samples tested under low (12Hz), medium (22Hz) and high (64Hz) frequencies.*

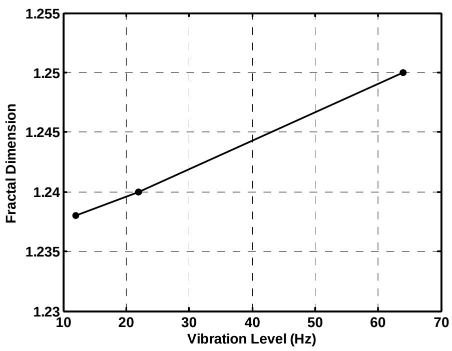

Figure 6. *The relation between the fractal dimensions and the vibration*

The fractal dimension versus the vibration level and the surface tracking width versus vibration relations of the samples are given in the figure 6 and figure 7, respectively.

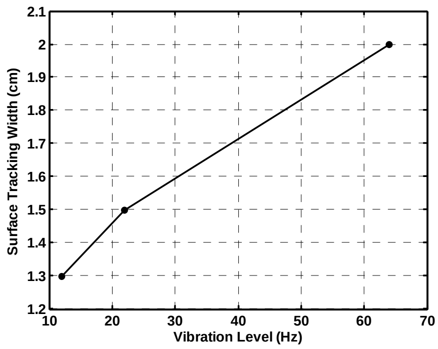

Figure 7. The width of the surface tracking patterns according to the vibration level

4.4. Fatigue Effect

The relation between the longitudinal vibration fatigue and the surface discharge energy has been investigated. Some samples were subjected to vibration effect (22 Hz) for 8 hours and then they were tested under the standard conditions. Then they were analyzed according to their fractal dimension. The fatigued samples exposed to the longitudinal vibration and the samples under vibration effect were compared according to their fractal dimensions and the surface tracking widths.

Figure 8. The samples under the fatigue effect (22 Hz and 8 hour longitudinal vibration)

Table 2. Longitudinal vibration fatigued samples and the samples under vibration effect comparison

TEST TYPE	DİMENSİON	WİDTH (cm)
The samples under fatigue effect (22 Hz and 8 hour longitudinal vibration)	1,491	1,6
The samples which were tested under vibration effect (22 Hz)	1,240	1,5

4.4. Colemanite Effect

Colemanite is a borate mineral found in evaporated deposits. This part of the study the test samples with colemanite additive, were used. The relation between fractal dimension of the samples and the percentage of the colemanite added test samples has been investigated. Besides the combination of fatigue and colemanite effect on test samples were taken into consideration.

Table 3. Colemanite effect comparison on fatigued and not fatigue added test samples

% Colemanite	Fatigue	Dimension
%0.1	NO	1,461
%0.1	YES	1,522
%0.3	NO	1,476
%0.3	YES	1,574
%0.5	NO	1,481
%0.5	YES	1,730

5. SIMULATION WITH BROWNIAN MOTION

Several surface tracking patterns are obtained by using a computer program based on Brownian motion method. Then these figures are investigated according to their fractal dimension and width properties related to the external effect they are subjected. Fifty different computer program output according to different H values are generated to simulate surface tracking patterns under external effects. The input H parameters (coefficients) are obtained for various external effects. Then best simulation outputs according to external effects are chosen and examined. H parameter, fractal dimension, width and external effect relations are given in table 4 and 5.

Table 4. The fractal dimensions width and the coefficient relations according to the moisture effect

% MOISTURE	FRACTAL DIMENSION	WIDTH (cm)	COEFFICIENT (H parameter)
%40	1,235	1,3	20
%60	1,240	1,5	14
%80	1,252	2	1
%99	1,258	2,3	9

Table 5. The fractal dimensions width and the coefficient relations according to the vibration effect

VIBRATION	FRACTAL DIMENSION	WIDTH (cm)	COEFFICIENT (H parameter)
LOW (12Hz)	1,235	1,3	20
MEDIUM (22Hz)	1,240	1,5	14
HIGH (64Hz)	1,252	2	1

Figure 9. Simulated figures with the coefficients 3, 20 and 1, respectively

In figure 9, a number of simulation outputs are given according to their H parameters.

6. CONCLUSION

In this work, unsaturated polyester samples are tested by using Inclined Plane Tracking Test Standard (IEC 587). The effect of external conditions has been investigated by observing and calculating the degradation level on the surface of polyester insulators.

A special software has been employed which is capable in measuring the fractal dimension of the carbonized tracking patterns. Also the width of the tracking patterns appeared to be a good indication in determining the effect of external conditions.

Test performed without external effects revealed clearly that the standard test conditions provide maximum discharge energy and consequently minimum lifetime. Since the carbonized track propagates quite fast down to the bottom earth electrode, the width of the path and also the fractal dimension of the patterns get quite small values.

By increasing the relative moisture level of the test rig, the liquid contaminant tends to spread out all over the surface of the insulator, which eventually led to decrease discharge energy and the increased lifetime. Therefore the temperature and the number of hot spots (caused by the discharges) reduced by the constant wetting the surface due to the excessive liquid, the tracking patterns become wider with lower deepness. Also the calculation of the fractal dimension of the tracking patterns revealed clearly, that the discharges scattered over the surface and lead to the higher dimension values. As with the external moisture, the longitudinal vibration effect also provided similar results. In this case, the liquid is also scattered over the surface due to the rapid movements of the test sample within a certain range.

The implemented experiments revealed that the level and the path of the liquid contaminant define the shape of the carbonized tracking patterns, which is also related to the useful lifetime. External moisture charges the flow rate and longitudinal vibration changes the path of the contaminant.

The relation between the longitudinal vibration fatigue and the surface discharge energy is another essential topic to be considered. The fatigued samples exposed to the longitudinal vibration were examined in order to define the effect of the fatigue. The fatigued samples have greater dimension values and scattering area then the samples under vibration effect.

Unsaturated polyester samples were used to determine the external effect so far in this study. To obtain distinguished results, the polyester samples with colemanite additive have taken into consideration. By increasing the percentage of colemanite additive, higher fractal dimension values and higher discharge energy on the surface observed. Besides fatigue effect on unsaturated polyester samples and polyester samples with colemanite additive has similar results. So results gives us the idea that colemanite spreads in the polyester homogenous.

On the last part of the study several surface tracking patterns were obtained by using a computer program based on Brownian motion method. Then these figures were investigated according to their fractal dimension and width properties related to the external effect they were subjected. The input the H parameters (coefficients) are obtained for various external effects. These coefficients are not precise however they satisfy the required condition for the external effect. For higher values of the H parameter replacement is smaller and smooth figures are obtained. Also fractal dimension is dependent on H parameter. With the increasing coefficient value, width of the simulated figures increases. The simulated figures and the experimentally obtained figures are mostly similar. Brownian motion is a quite effective method to simulate this kind of figures. In this study we presented that chaotic systems can be analyzed and simulated with Brownian motion theory.

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