Analyzing and Modeling the 2D Surface Tracking Patterns of Polymeric Insulation Materials

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ABSTRACT
The structure and topography of surface tracking patterns generated on the surface of unfilled and filled samples of polyester resin using the international standard procedure (IEC 587, Inclined-plane Tracking Test) have been studied. The effect of contaminant flow rate, applied voltage and the percentage content of particulate zinc oxide on tracking behavior has been determined. Three alternative mathematical algorithms have been used to establish the fractal dimensions of the tracking patterns as a function of the above three parameters. To model the surface tracking patterns, two methods have been applied. Firstly, a resistive network has been used in which the insulator surface is assumed to consist of imaginary vertically and horizontally placed resistors. This model is capable of producing several types of trees observed in insulating materials. However, the surface tracking patterns are mostly unbranched and it is not possible to produce realistic images with this model. The second method, Brownian motion, is mainly a recursive technique and does not take Laplacian field values into account. The resolution of the images is high, hence the simulated patterns are almost indistinguishable from the real images.

1 INTRODUCTION
Since the beginning of this century major developments have taken place in insulation technology. Glass and porcelain insulators have been tried and tested for many years and accepted worldwide [1]. However, polymeric insulators are becoming popular due to their superior mechanical strength, performance in polluted areas and ease of fabrication. They are corrosion resistant, maintenance free and have a ~90% weight reduction compared to their porcelain counterparts [2, 3]. Several external and internal factors such as humidity, temperature variation, ultraviolet radiation, sunshine, mechanical stress and space charge can accelerate the aging of an insulator. These factors can reduce the hydrophobic performance of the glossy surface and lead to surface tracking, which is irreversible and can be described as a mixed process of discharge inception, carbon formation, carbon path propagation and molecular decomposition of a material [4]. A review of several test methods indicate that in addition to the lifetime, the shape of the tracking patterns also varies due to environmental conditions. In this paper initially the topological carbonized surface tracking features of polymeric insulation materials for various conditions are investigated. However visual inspection is quite subjective and often misleading, hence mathematical methods, such as fractal dimension are also used to categorize and quantify these structures. In the second part of the paper these tracking patterns are simulated by using two different techniques, a resistive network and Brownian motion.

2 EXPERIMENTAL SETUP
Polymeric insulating materials are exposed to several aging mechanisms during their service life. However in most cases this process takes quite a long time, hence several tests have been developed for assessing the relative tracking and erosion resistance of polymeric insulating materials in a relatively short time under laboratory conditions. All of the experiments here have been performed by using the Inclined Plane Tracking Test [5], which is useful in representing the ‘wet tracking’ phenomena. This test is easy to set up, and its results usually correlate well with the performance of the outdoor materials used [6–8]. Initially, samples prepared from polyester Resin C are tested at various conditions. The effect of ZnO on the tracking resistance is also investigated by mixing this substance with Resin C in different percentages. All specimens were tested in a closed cabinet with an open roof and minimum air circulation. For each set at least 4 samples were used. IEC 587 recommends testing until the tracking pattern reaches 25 mm from the lower electrode. However, to enable a complete structural pattern analysis, the test
was not stopped until the gap between the ground and HV electrode has been crossed completely. After each experiment, specimens exhibit carbonized, highly damaged, black tracking patterns and, due to the burning, discolored surface sections. Initially each specimen after the test was rinsed completely with distilled water. After complete drying, the discolored sections are cleaned smoothly with emery paper and a sharp knife. Finally the tracking patterns were filled with black drawing ink using a 0.4 mm isograph drawing pen. To compare the samples tested at different conditions realistically, only 40 mm from the track initiation point, regardless of the length of the total track, was painted. After the preparation phase, all images of the samples were digitized and transferred to the PC using a hand held scanner.

3 ANALYZING THE TRACKING PATTERNS

3.1 TOPOLOGICAL FEATURES

Initially for polyester resin the relationship between the flow rate and the thickness of the tracking structure was investigated. IEC 587 suggests that for 4 kV a flow rate of 36 ml/h provides the optimum results, which means short tracking initiation and track growth times. A similar criterion for maximum damage has previously been determined for polyester Resin C. [9]

![Figure 1. Thickness of tracking channel for various flow rates.](image1)

As expected, for low rates of contaminant flow, strong localized and stabilized arcing is not possible, hence heat dissipation on the surface is decreased. This leads to a narrow tracking path. Increasing the flow rate accelerates the arcing phenomenon and causes more damage during the track growth. However above a certain level (Figure 1), which was observed as 45 ml/h, the thickness of the main channel starts to decrease. This might be explained due to the fact that at higher contaminant flow rates additional branching is observed, which reduces the field strength and causes spreading of the damage over a wider area rather than concentrating on a particular conducting route.

For abraded polyester resin the curve (Figure 2) differs slightly, in which case the maximum channel thickness is observed at 36 ml/h flow rate. Abrading the surface causes loss of the glossy surface, hence the material becomes more hydrophilic and as a consequence a more stable contaminant flow is produced. Due to this fact it is possible to expect thicker tracking channels at higher flow rates. However, the reduction in spreading of the contaminant causes it to concentrate on a discrete, nearly straight path. Excessive water cools the specimen constantly, hence for high flow rates severe damage during the track growth is prevented.

![Figure 2. Thickness of tracking channel for various flow rates (abraded).](image2)

Finally the relationship between the flow rate and the propagation of the tracking pattern is investigated (Figure 3). In all cases the deviation from the main axis seems to be caused by the change of the flow path. At low flow rates, the conducting contaminant follows a straight path, hence the resulting structures develop slowly almost perpendicular to the ground electrode. At the optimum flow rate, due to strong arcing and heat dissipation, the evaporation process is accelerated. A conducting path propagates rapidly, bending occasionally sharply on one side of the surface leading eventually to the HV electrode. Such patterns have few branches and have an 'S' shape. At higher flow rates the contaminant spreads out over the surface, hence a discrete contaminant path cannot be maintained over a long period. As a consequence small scintillations occur over a wide area, but they are not strong enough and only produce small branches rather than changing the main tracking path. Experiments also revealed clearly that the shape and time of track growth is independent of the tracking initiation point.

![Figure 3. The total width of the tracking patterns for various flow rates.](image3)
3.2 MATHEMATICAL ANALYSIS

Visual inspection methods can be helpful in categorizing the tracking patterns. However by using mathematical algorithms the accuracy of the results can be improved. Since the introduction of fractal geometry nearly 20 years ago, fractal dimension estimation has become a standard tool used in many areas where a dynamic process is suspected of having some deterministic content, even though its output is not constant or periodic [10].

Fractals can be described as geometric shapes that repeat their structure on ever finer scales. Theoretically, fractal objects are infinitesimally sub-divisible in this way; each subset, however small, containing no less detail than the complete set [11, 12]. Basically the fractal dimension measures the way in which a distribution of a point fills a geometric space on the average. In other words it reveals precisely the nuances of shape and complexity of a given non-Euclidean figure. Several methods for estimating the fractal dimension of complex surfaces have been proposed, however during analysis of tracking patterns the most common methods: capacity, correlation and information dimensions are used.

3.2.1 CAPACITY DIMENSION

Capacity dimension, which can be denoted by $D_c$, is used to calculate the fractal dimension of complicated shapes [12, 13]. The basic idea is to cover the trajectory with equal square boxes until no part of the pattern remains uncovered. Then all the boxes containing a part of the pattern are counted. The capacity dimension can be shown as

$$D_c = \lim_{\varepsilon \to 0} \frac{\ln N(\varepsilon)}{\ln(1/\varepsilon)}$$

where $N(\varepsilon)$ is the number of boxes, $\varepsilon$ is the side length of the box. The capacity measure of the fractal dimension relies on whether small elements of the phase space contain any points and does not take into account the differing numbers of points in the various elements, hence small-scale variations of the density points are ignored.

3.2.2 CORRELATION DIMENSION

The correlation dimension method provides a relatively fast and easy solution to determine the value of the fractal dimension. It differs from capacity dimension in that the correlation dimension is a probabilistic type of dimension where the relative frequency of visitation of a typical trajectory is calculated. It can be denoted as

$$D_G = \lim_{\varepsilon \to 0} \frac{\sum_{i=1}^{N(\varepsilon)} P_i^2}{\ln \varepsilon}$$

where

$$P_i = \lim_{N \to \infty} \frac{n_i}{N}$$

$n_i$ is the number of points lying in the $i$th volume element, $N$ the total number of points in the trajectory.

3.2.3 INFORMATION DIMENSION

Information dimension is quite similar to the correlation dimension, however it is mainly based on calculating the probability of finding a point in a certain cell. It can be denoted as

$$D_i = \lim_{\varepsilon \to 0} \frac{\sum_{i=1}^{N(\varepsilon)} P_i \ln P_i}{\ln(1/\varepsilon)}$$

where $n_i$ is the number of point in the cell, $N$ the number of total points belonging to the image, $N(\varepsilon)$ the minimum number of boxes size $\varepsilon$ to cover the image.

![Figure 4. Change in fractal dimension due to flow rate.](image)

![Figure 5. Change in fractal dimension due to applied voltage.](image)

All of the algorithms mentioned above are purely static methods, which analyze the structure of the completed tree. The tracking process during the IEC inclined plane test is associated with burning of the surface, hence dynamic methods, which simultaneously investigate the growth of a tree in time, cannot be used efficiently. A software program was written which can estimate the fractal dimension of digitized images up to 6 decimal digits. However, several factors such as the finite size of the samples and the noise effect associated with each test, limits the accuracy of the results to only 2 digits. For each condition the three different fractal dimensions are calculated. An illustration of the dependence of the fractal dimension on various parameters such as flow rate, applied voltage and material type is given in Figures 4, 5 and 6 respectively. Increasing the flow rate cause an enhancement in the fractal dimension of the test samples (Figure 4). At low contaminant flow rates the visual inspection agrees with mathematical calculations. Minor damage (branching) occurs to the specimen, hence the fractal dimension is $\sim 1.28$. Increasing the flow rate to the optimum level causes rapid and considerable damage to the sample. Still branching is quite low, but thickening and bending the tracking path causes a slight increase in fractal dimension to 1.36 or 1.37. At higher flow rates the visual inspection conflicts with mathematically calculated results. Due to the excessive flow the strength of arcing is reduced and hence the main tracking path becomes thinner. However since the track propagation time is greatly increased, additional branching is introduced, which finally leads to an increase in the fractal dimension to 1.52 to 1.56.

In Figure 5 the voltage dependence of the fractal dimension is inves-
tigated. Increasing the applied voltage causes straight tracking patterns without much scattered damage on the surface. Track propagation occurs rapidly reducing the probability of branching. Actually, the tracking phenomenon at higher voltages is not much different from that observed at 4 kV. In fact the fractal dimension increases only slightly, which also can be regarded as staying the same, for this voltage range.

Finally, by keeping the test conditions at the same level (4 kV and 36 ml/h), the effect of ZnO mixed with polyester resin is investigated (Figure 6). A mixture of 10% ZnO with Resin C cause a slight reduction in the fractal dimension. The decrease becomes more remarkable if the additive is increased to 30%. Visual and mathematical results reveal that an increase in the percentage of ZnO in polyester dramatically reduces the electrical strength of the material. Track propagation lasts a very short time, \( \sim 10 \) s, which leads to very narrow tracking patterns (<10 mm). Despite this fact, also lots of minor branches are observed. However this might be explained by considering the reduction in the locally applied voltage and small scintillations spread all over the surface. Further increase of ZnO (to 50%) in polyester cause a total change in the material. Samples tend to erode rather than track, hence they also lose their fractal properties.

4 MODELING THE TRACKING PATTERNS

Several models have been introduced to simulate the breakdown phenomena in solid dielectric materials. One of the first models was proposed by Nieto et al. [14], in which a 2-dimensional square lattice a central point represents one of the electrodes while the other electrode is modeled as a circle at a large enough distance. The probability for a tree to grow depends on the electrical field \( E_{i,j} \) which can be calculated for each point within the grid. Wiesmann and Zeller [15, 16] extended this model by adding a critical field parameter \( F_c \), applying it to the point-plane geometry and to various situations of the stepwise propagation of electrical trees in solid dielectrics under alternating voltage excitations. If \( F_c \) is exceeded, a rapid flow of space charge occurs near the tip causing a local breakdown of the material. At each growth step a new bond is added to the structure. A discharge avalanche model has been proposed by Dissado and Sweeney [17], in which discharges in a void or electrical tree induce avalanches within the insulation. The number of ionizations in an avalanche is taken to be a measure of the damage produced. Barclay et al. [18] proposed a similar algorithm to that described by Wiesmann and Zeller, in which they simulated tree patterns by using a simple power function \( E^\eta \), where high values of \( \eta \approx 3 \) cause sparse trees (branch type), while dense trees (bush type) are obtained at low (\( \eta \approx 1 \)) exponents. Takayasu [19] introduced a resistive network model, in which an initial voltage \( V \) is applied to the resistors. If \( V \) exceeds the critical breakdown voltage, then resistor \( R \) is considered broken down and assigned to a value of \( \delta R \), where \( \delta \) is a small number. Many of these models are developed to simulate the 2D or 3D treeing phenomena in dielectric materials, however the 2D surface tracking phenomenon in solid dielectrics is a highly localized self growing process, which means the release of the energy (arching) is restricted to a limited area of the material. Since these local processes are mostly independent of the applied field, they produce almost unbranched tracks, bending occasionally to follow easy routes through the material [20]. To simulate these patterns, two different models, resistive network and Brownian motion, have been proposed and are compared. The resistive network is similar to the one proposed by Takayasu [19] and based on the idea of using a 2-dimensional imaginary grid consisting of maximum 40×40 resistors. Nonlinearity is obtained by assigning random values between 0.95 to 1.05 \( \Omega \) to the vertical and horizontal resistors. The current source \( I_0 \) is adjusted according to the number of horizontal resistors, hence initially \( \approx 1 \) A flows through each vertical resistor. By using the Gauss- Seidel iteration method the voltage drop on each resistor (Figure 7) is calculated and the process continues until the relative error between two iterations for the same node voltage becomes \(<0.001\%\). Since all resistors differ from each other, voltage and current levels are mostly different for each case. If the current in a certain resistor exceeds the critical value selected \( I_0 \), then the resistor is assumed to be broken down and assigned a value of 0.01 \( \Omega \). The field values are calculated continuously until the gap between the top and bottom electrodes is crossed completely. The critical field constants are calculated experimentally, however they may need to be modified slightly for major changes in selecting the grid size.

![Figure 7. Diagram of the resistive network.](image)

The structure (Figure 8) is not dependent purely on the Laplacian.
as exhibiting self similarity, could be more suitable for modeling the river shaped tracking structures. The model produces a trajectory with a mean squared displacement which grows with time raised to a power between zero and two [21]. If an image is produced for time $t$ between 0 and 1, then $X(0)$ can be selected as 0 and $X(1)$ assigned to a random value with mean 0 and variance $\sigma^2$. The total variance between the points can be indicated as

$$\text{Var}[X(t_2) - X(t_1)] = |t_2 - t_1|\sigma^2 \quad (5)$$

The placement at $t = \frac{1}{2}$ can be calculated as

$$X(0.5) - X(0) = \frac{3}{2}[X(1) - X(0)] + D_1 \quad (6)$$

where $D_1$ is the random offset with mean 0 and variance $\Delta_1^2$. The same is valid for values of $t$ between 1 and $\frac{3}{4}$. Hence if the time values are inserted into Equation (5), then

$$\text{Var}[X(0.5) - X(0)] = \left(\frac{3}{4}\right)\text{Var}[X(1) - X(0)] + \Delta_1^2 \quad (7)$$

where $\Delta_1^2 = \frac{1}{4}\sigma^2$. At each iteration the variance halves. Its value can be calculated by using the following relation

$$\Delta_n^2 = \frac{1}{2^{n+1}}\sigma^2 \quad (8)$$

With this method corresponding to time differences $\Delta t = 2^{-n}$, a random element of variance is added to the calculated mid-point [21, 22]. By adding a scale parameter $H$ to the Equation (5), it is possible to change the roughness of the simulated images, where higher values of $H$ reduce the displacement and hence cause smoother patterns.

$$\text{Var}(X(t_2) - X(t_1)) = |t_2 - t_1|2^{H}\sigma^2 \quad (9)$$

The proposed model initially defines the two end points randomly. Midpoints are then calculated by taking the average of these endpoints and adding some random variance to it, which is scaled down $2^{-H}$ on each iteration. The total number of branches is limited at 3, however the origin of the branch, either growing as a sub branch from a branch or trunk is selected randomly (Figure 9). To simulate a smoother pattern, the parameter $H$ is selected as 0.9. The method is quite easy to implement and mainly based on calculating the tracking patterns randomly by using a Gaussian distributed variance. Since it can be produced by a recursive technique and does not take the Laplacian field values into account, it can simulate the desired patterns in a short time. The resolution of the images is quite high, hence the simulated patterns are almost indistinguishable from the real images.

5 CONCLUSIONS

Analyzing the surface patterns of several test samples revealed that an increase in the contaminant flow causes small scintillations on the surface quite far from the lower ground electrode. Due to this non-stabilized and weak arcing, minor branches were observed in these regions which also lead to an enhancement in the fractal dimension. However introducing these new branching phenomena to the system reduced the local field and hence the accumulated damage on the main tracking path is reduced. Increasing the applied voltage over the region 4 to 6 kV, reduced the tracking initiation and track propagation time considerably. However it seems not to have any effect on the final shape and structure of the pattern, hence the fractal dimension does not vary over this range. Finally the effect of an additive (ZnO) on the fractal dimension is investigated. It has been found that after a critical level, the material tends to erode rather than track and hence loose
its fractal properties. To model the surface tracking patterns observed on polymeric materials two methods have been proposed. The resistive network assumes a surface consisting of imaginary vertically and horizontally placed resistors. The effects of voids, cracks, and other surface discontinuities are represented by assigning random values to each resistor. This leads to local field enhancements and track propagation, which in fact can be observed at regions with surface impurities. Tracking is a random local phenomenon, hence in most cases the propagation of the track is dependent momentarily on several conditions such as flow rate and air circulation, rather than the sudden local field enhancements. Due to this fact, instead of producing narrow tracking patterns, the images produced by the resistive network almost mimic the treeing phenomenon observed in solid polymeric insulating materials at high stresses after some time. The second method, Brownian motion is mainly a recursive technique and does not take the Laplacian field values into account. The direction of the growing pattern is selected randomly with a certain probability of bending to each side (except for reverse direction) and/or forming a new branch.

REFERENCES


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