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Fractal Characteristic of Electrical Trees Grown in Silicone Rubber under Environmental Stress

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ABSTRACT

One of the degradations of insulation is in the form of electrical treeing in which classified as a pre-breakdown phenomenon of electrical insulation. The electrical tree is commonly forming in the shape of tree-like or root-like which may have fractal structures. Due to this fractal structure, electrical treeing formation and patterns are analysed via fractal dimension and lacunarity to study the self-similarity patterns of electrical treeing. Many types of research have been conducted to study the fractal dimension and lacunarity of electrical treeing to fully understand the electrical tree mechanism and characteristics. However, fractal and lacunarity structures of electrical trees in silicone rubber correlated with humidity influence are not fully understood. This paper involves the experiment set-up for obtaining the electrical trees in silicone rubber. The purpose of this project is to investigate the correlation between the characterization of tree growth in silicone rubber with respect to the humidity influence. The obtained electrical tree patterns were measured by using a box-counting method to analyze the fractal dimension and sliding box lacunarity. Obtained results show that the growth of tree structures changes with the different value of relative humidity, in which dry humidity brought higher fractal dimension and lacunarity compared to that of moisture condition. It was suggested that the vulcanization network in silicone rubber with relative humidity led to the effect on treeing patterns and lifespan of solid insulation.

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1. INTRODUCTION

Electrical insulator is one of the essential equipment as the growing demand for the power system in the world is increasing rapidly. Silicone rubber (SiR) is the polymeric insulators and is used in the electrical power system as cable and cable accessories insulation for transmission and distribution lines. The investigations of electrical treeing mechanism of polymers such as cross-linked polyethylene (XLPE), polyethylene (PE) and epoxy resin have been widely performed, but less attention was paid on silicone rubber [1]. The lifespan of the insulation materials depends on a variety of stresses. The insulation material will degrade and cause damage by the variety of stresses. The degradation of insulation may be in the form of electrical treeing, space charges, partial discharges, surface erosion, tracking, electrochemical deterioration and cavity breakdown. Broad knowledge of the fundamental properties and characteristics of pre-breakdown is important to obtain an optimal design and efficient operation. The characterization of the pre-breakdown image can be measured by using fractal analysis. Currently, the fractal analysis is widely used to characterize in natural objects. Electrical treeing is one of fractal nature in which can be analyzed graphically using fractal dimension and sliding box lacunarity. Allain and Cloitre [2] demonstrated a simple example algorithm of sliding box method which the lacunarity of the textures can be calculated. In addition, environmental stress will affect the electrical treeing in the insulation in term of relative humidity in which classified as one of the crucial factors which affecting the properties and sustainability of the insulation material under services [3].

Fractal analysis is extensively used in medicine sciences and biological. Besides that, fractal analysis has various applications in electrical engineering field including in power systems fault analysis, testing of lightning strike in lab fractal lightning modeling, full scaling testing equipment in high voltage and dielectric breakdown and pre-breakdown phenomenon studies. The fractal dimension of tree structures is important for the statistical analysis of polymeric materials [4]. In this paper, fractal analysis will focus on dielectric pre-breakdown phenomenon and fractal dimension is used as a parameter to measure the growth of electrical treeing in insulating material with respect to the humidity influence so that the relationship between fractal patterns of electrical trees in silicone rubber and environmental stress can be achieved.

2. RESEARCH METHOD

In this project, the growth of electrical treeing or pre-breakdown phenomenon in the insulating materials was observed by conducting the experiment. Silicone rubber was used as the specimen to identify the pattern of electrical treeing under humidity condition. The electrical trees occur on the specimen between needle-electrode tip and plane electrode by injecting AC high voltage. The specimen was subjected to different conditions and depends on the relative humidity selected. Afterwards, the obtained electrical tree patterns were measured using a box-counting method to identify the fractal dimension under each condition. Details on the procedure to conduct experiments and sample preparation can be referred to reference [5].

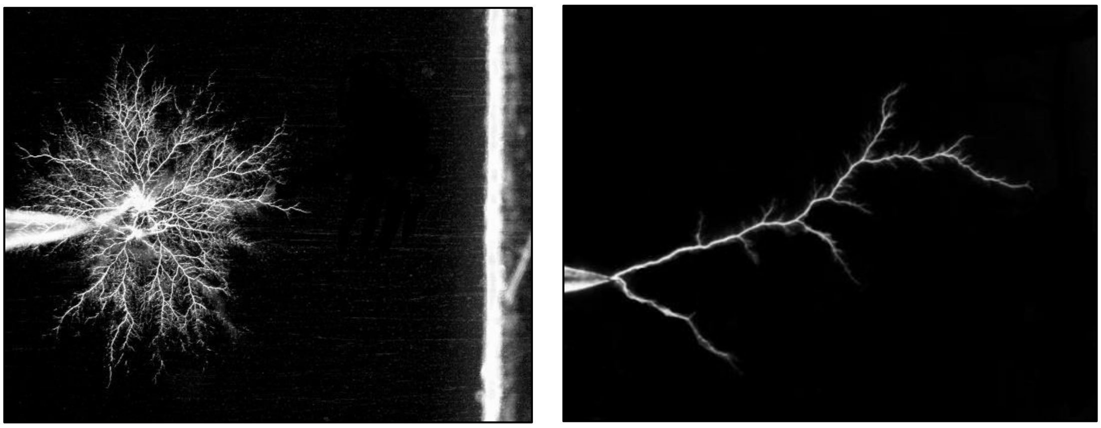
3. RESULTS AND ANALYSIS

The treeing patterns obtained from the experiment under dry condition with 20% relative humidity and moisture condition with 90% relative humidity were analyzed as shown in Table 1. The electrical treeing in Figure 1(a) depicts a bush type patterns with dominant tiny branches that were localized at the interface. This condition was due to dry condition in which less contamination occurred in the insulation. Figure 1(b) shows the growth of electrical trees in branch type with tiny branches that localized at the interface. The propagation of the long tree branch almost reached the ground electrode due to the present of the water layer and the insulation was moisturized thereby contaminating the insulation. This condition would eventually cause the insulation breakdown. The formation of water trees in insulation was a primary cause of insulation failures [9]. At the same time, each sample with different value of relative humidity came out with different direction of electrical treeing because the real propagation of the treeing was in 3-D. In this project, the growth and propagation of treeing were focused on 2-D due to the complex measurement in 3-D.

Based on the average calculation of fractal dimension and sliding box lacunarity in both dry and humid condition, the average of fractal dimension of treeing structures in dry condition was higher than in humid condition. This is because the treeing structures in dry condition were localized at the interface compared to the treeing structures in humid condition which grow without localized characters.

For sliding box lacunarity, the samples tested under dry condition provide the higher value of sliding box condition compared to the samples tested under humid condition. This is due to dry condition, the bush-type of electrical trees give large gaps or holes in the image. Lacunarity helps to describe the texture of the fractal and classify further on the treeing structure.

From the comparison based on different environmental stress, it can be stated that the higher fractal dimension and higher sliding box lacunarity would provide a good insulator with respect to dry humidity influenced. The lower fractal dimension and lower sliding box lacunarity would provide the worst performance of the insulation with respect to moisture humidity influence.



(a) (b)

Figure 1. Treeing Structures, (a) at 20% relative humidity and (b) at 90% relative humidity

Figure 2 shows the growth rate of the electrical trees at 20% and 90% relative humidity. The graph states that the growth rate of electrical trees at humid condition increases drastically than in dry condition. This is because of the presence of water and moisturized condition to the insulation. Figure 3 illustrates the relationship between the tree length and fractal dimension under environmental stress with different relative humidity. In dry condition with 20% of relative humidity would give large number of tiny branches that localized at the RTV silicone rubber interface, leading to the higher fractal dimension of the tree patterns compared to that in humid condition.

Table 1. Fractal Dimension and Lacunarity of Electrical Tree Grown Under 20% and 90% RH

Relative Humidity (RH)	Average of Fractal Dimension	Average of Lacunarity
20%	1.56	0.19
90%	1.35	0.091

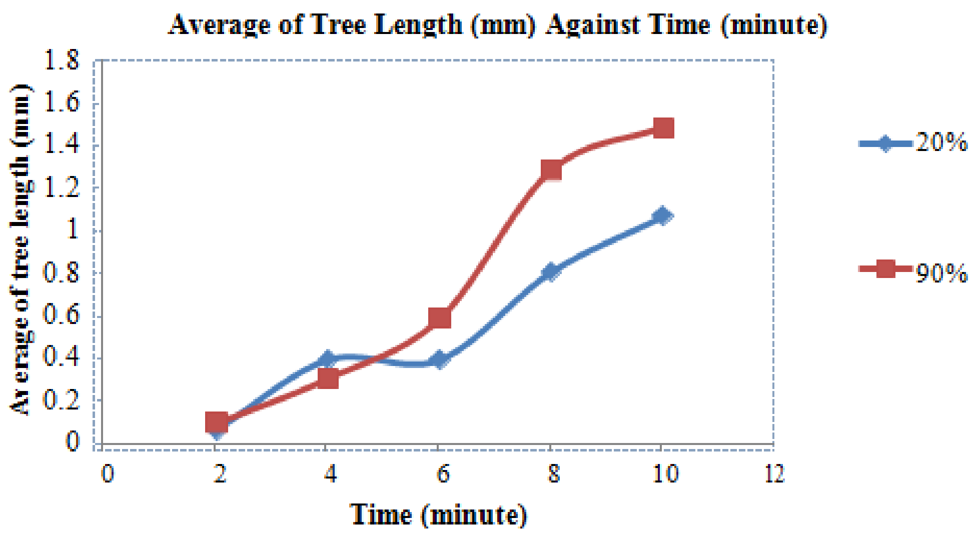


Figure 2. Grow rate of tree growth at 20% and 90% relative humidity

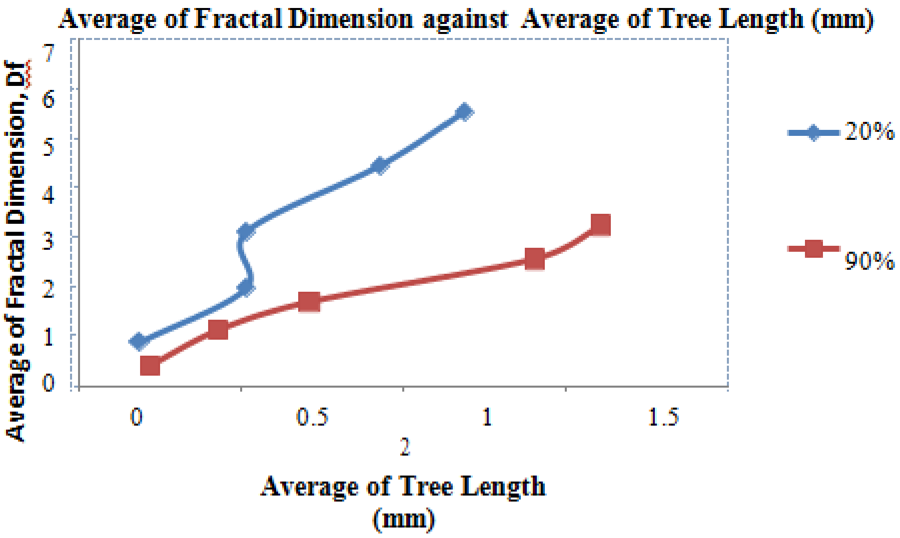


Figure 3. Tendency of fractal dimension to the function of tree length at 20% and 90% relative humidity

The analysis of this relationship was studied to classify the tree shape with lower and higher fractal dimension. Bush-type trees would lead to high fractal dimension whereas branch-type or treeing-like structure would result in low fractal dimension. At the inception voltage, the tree grows nearly linear in both conditions, while during at propagation stage the shape of electrical trees at dry condition were started to be localized. In the humid condition, the shape of electrical trees brought the faster change from treeing-like to branching-like shape and almost reached the ground electrode. Thus, the tendency of fractal dimension to the function of tree length at dry condition was greater than to that humid condition.

4. CONCLUSION

This can be summarized that the deterioration of solid insulation in dry condition is smaller than in that of moisture condition. The dry condition with 20% relative humidity is related to the country with four seasons especially in Europe. Moisture condition with 90% relative humidity is in tropical climate such as in Malaysia. Thus, the correlation between characterization of treeing patterns in RTV silicone rubber and the shapes of electrical treeing in respect of humidity influence was identified. In dry condition, the higher fractal dimension would give better performance of solid insulation. In humid condition, the lower fractal dimension would give low performance of the solid insulation.

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