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Fractal analysis of electrical tree grown in silicone rubber nanocomposites

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ABSTRACT

Electrical treeing is one of the main reasons for long-term degradation of high voltage insulation especially in the cable accessory which commonly made from silicone rubber due to non-uniformly structures of the cable accessories. Recently, the combination of nanofillers with the silicone rubber matrix can reduce the possibility of the electrical treeing to grow further by changing its patterns and slow-down its propagation. However, the influences of nanofillers on the tree hindrance and its patterns are not well understood. This paper explores the influence of nanofiller on tree pattern in silicon rubber. The electrical tree patterns were characterized using fractal analysis. The box-counting method was used to measure the fractal dimension and lacunarity to obtain the structure of the tree pattern during the electrical tree growth. The structure of the electrical tree in silicone rubber nanocomposites has higher fractal dimension and lacunarity. Sample with nanofiller possesses dominant fractal dimension of tree growth compared to the sample without nanofiller.

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1. INTRODUCTION

Electrical treeing is a pre-breakdown phenomenon occurs in polymeric insulating materials which usually used in high voltage insulation system [1-4]. It also can cause long-term degradation of insulation cable and may be caused by an irregular shape, void and impurities [5-7]. The electrical tree growth can be classified into three stages which are inception, propagation and runaway. Inception period is an initial stage occurred when a microvoid is produced but no electrical tree is figured. Next stage is the propagation stage. It occurs when the electrical tree starts to form and shows the variety image of electrical treeing such as branch, bush or branch-bush. Lastly, the breakdown will occur in runaway stage because of the acceleration of treeing till nearly across the tested material [8]. In high voltage apparatus, silicone rubber (SiR) is commonly used as an insulation due to the excellent in electrical properties, dielectric strength and flexibility. It is usually used as insulation for cable joint and outdoor insulation. Its advantages comprise to its properties including the silicone rubber material can give a service for a long-term, good in electrical insulation, a large range of temperature for operation and it was not affected by weather [9-11].

Recently, silicone rubber-based nanocomposites have been researched for retarding the electrical treeing growth [12-14]. By adding the nanofiller into the base material, it can produce better insulation and more excellent insulation properties of the SiR can be improved. Tanaka reported that the nanostructured polymer known as nanocomposites have the potential to improve the properties of electrical, mechanical, and thermal compared to the neat polymers [15]. In addition, various types of fillers have also been studied such as metallic oxide, magnesium oxide, zinc oxide and most of the fillers had been used is silica [16]. Previously, micro silica is used, but it is replaced by the nano-silica because of the decreasing of dielectric strength composite causes by high loading rate [17-19]. Although nano-silica studied by other researchers not many investigations combine the nano-silica with silicone rubber as a base material in the insulation.

Furthermore, it is still not well understood for characterization of electrical treeing in silicone rubber nanocomposites. To identify the structure of the electrical treeing, many researchers have been conducting studies on the fractal analysis used to measure the patterns of the electrical tree in the silicone rubber insulating material but the electrical treeing patterns when adding nanofiller into the silicone rubber is not much investigated. Fractal analysis of electrical treeing can analyze the growth pattern of electrical treeing and lifespan of the insulating material [20-22]. Therefore, this research is important to conduct a study on fractal analysis of electrical treeing in the insulation when adding nanofillers into silicone rubber insulating material.

2. EXPERIMENT

There were four types of the specimen to be used in this experiment to identify the electrical treeing structure that occurred on the specimen between the needle tip and electrode during injecting HVAC. Then, the result was analyzed using fractal analysis to measure the fractal dimension and lacunarity for each specimen.

2.1. Leaf-like specimen

To clarify the effect of filler on tree inception, propagation and breakdown, the leaf-like specimen was used as shown in Figure 1. The specimens were prepared as four types of materials; pure silicone rubber, silicone rubber with 1 weight percentage (wt%), 3 wt% and 5 wt% of nano-silica. The SiO_2 nanofiller used in this specimen was from Sigma Aldrich with the particle size of 12 nm and polymer used was sylgrad 184 SiR elastomer from Dow Corning. The nano-silica was mixed with silicone rubber in accordance with the desired ratio. If the amount of silicone rubber used is 10 g, then the weight of nano-silica will be 0.1 g, 0.3 g and 0.5 g. The process of mixing the silicone rubber with nano-silica was performed with a magnetic stirrer at a speed of 125 rpm for 60 minutes. To ensure the nano-silica dispersed completely in the SiR an ultrasonic dismembrator (Fischer, FB705BX) was used. The dispersion energy maintained more than 100 kJ, operation power range between 100-150 W and an amplitude of 70%. For pure silicone rubber specimen, this mixture will not go through the sonication process. After the sonification process there will be weight loss in the SiR/SiO_2 due to shifting from one breaker to another. Re-weighing of the SiR/SiO_2 mixture was carried out again and silicone elastomer curing agent (hardener) added to this mixture in the ratio of 1:10 with the help of magnetic stirrer at 125 rpm for 15 minutes. The further process is to remove the voids and the air bubbles formed in the mixing process. This was done by degasification process by placing the prepared solution in the vacuum oven for 25 minutes. Afterwards, the nanocomposite was cast on the electrodes gap on a microscopic glass and covered with another glass as shown in Figure 1. Then, the leaf-like specimen was cured at 100°C for 45 minutes inside a vacuum oven. The electrode used for the tree initiation was a needle with a tip radius of 3 μm and a diameter of 0.3 mm was used. A spacing of 2 mm was maintained between the needle tip and the ground electrode for the propagation of electrical tree.

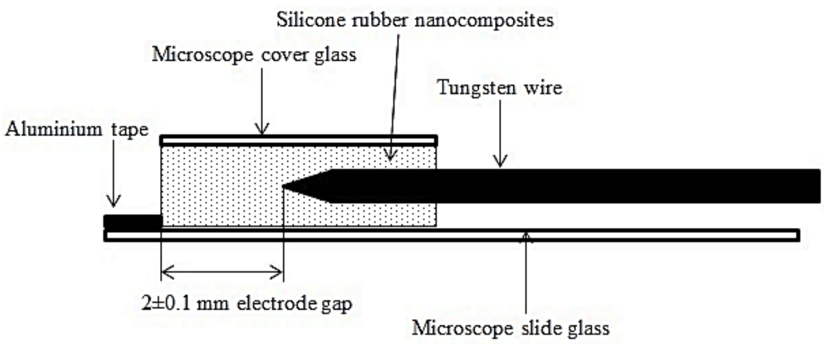

Figure 1. Leaf-like specimen configuration

2.2. Experimental procedure

Figure 2 shows the circuit diagram of the experiment set up and its connections to the Olympus SZX16 optical microscope and personal computer. The 240V/50kV step-up transformer was used to step up the voltage from the power supply to a certain level of required high voltage and the 6100 Ω protection resistor was used to protect overcurrent to the transformer. The specimens were placed in a container filled with silicone oil to prevent surface flashover. The acupuncture needle was connected to the AC voltage supply that consists of 50 Hz of 240 V/50 kV step-up transformers meanwhile counter electrode was connected to the ground. The microscope was connected to a personal computer and the microscope was adjusted until the image appears on the personal computer screen.

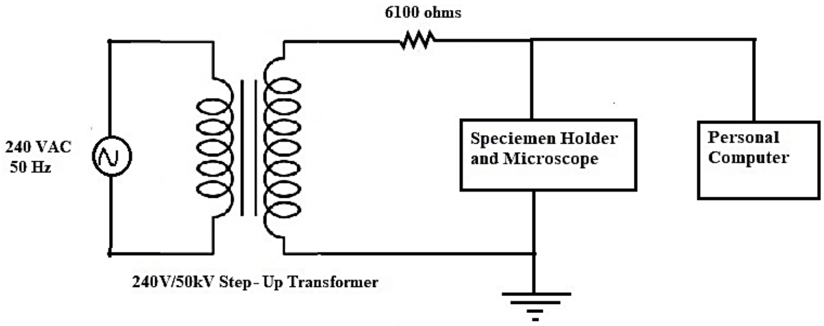

Figure 2. Circuit diagram of experiment set-up

Then, AC voltage at 11 kV was applied to the acupuncture needle to help the growth of electrical trees and the tree inception and propagation were observed on the screen. The tree inception and propagation were recorded at different time intervals by using Cell Sens Standard software through a CCD camera. The length of electrical tree growth was measured. The tests were performed three times for each percentage of nanocomposites to consider the average of electrical tree length. The experiments were conducted to all specimens with the same steps.

2.3. Analysis of the electrical treeing

The images of electrical treeing obtained from the experiments were analyzed using the ImageJ software. The ImageJ software was used to measure the fractal dimension and lacunarity using the box-counting method. Box-counting fractal was used to characterize the propagation of the electrical treeing. The analysis was tested with three samples for each percentage of nanocomposites to obtain the average value of fractal dimension and lacunarity.

2.3.1. Calculation of the fractal dimension, D_f

In order to measure the fractal dimension, the logarithm graph was plotted from the equation below which the number of boxes that covered the electrical tree image against a scaling grid [23].

$$N\,(s) = Ks^{-Df} \quad (1)$$

N(s) = Number of boxes that cover the electrical tree
K = Constant value
s = Scaling grid
D_f = Fractal dimension

The logarithm graphs of ln(N(s)) on y-axis and ln(s) on the x-axis was plotted by scanning the image. By referring to the logarithm graph, the fractal dimension was obtained from the slope of the linear graph.

2.3.2. Calculation of the lacunarity, λ

In the box-counting method, the (2) was used to define the lacunarity, λ [24].

$$\lambda = 1 + (\frac{\sigma^2}{\mu^2}) \quad (2)$$

λ = Lacunarity

σ = Variance of treeing structure in each box size
μ = Mean of treeing structure in each box size
Variance and the mean of the treeing structure were determined from the scanning of the image. The lacunarity was obtained from the slope of the linear graph of ln (lacunarity, λ) on the y-axis versus ln (grid size divided by the size of the image, k) on the x-axis.

3. RESULTS AND DISCUSSION

In this research, there were four types of materials used to investigate the performance and growth of electrical treeing in silicone rubber nanocomposite.

3.1. Analysis of relationship between propagation stages of electrical treeing with dimension, Df and lacunarity, λ

In this experiment, the electrical tree propagation was observed until the breakdown stage where the electrical tree reaches the counter electrode and causes the breakdown of the system. The fractal dimension and lacunarity were measured by the box-counting method for each stage involving all specimens. Figures 3 show the images of electrical tree propagation for pure silicone rubber, silicone rubber filled with 1 wt%, 3 wt% and 5 wt% nanofillers respectively in four stages The images of the electrical tree were covered by boxes with different scaling grids of 8, 16, 32, and 64 pixels for fractal dimension and lacunarity measurements. In Figure 3 shown only the electrical tree images with scaling grid of 8.

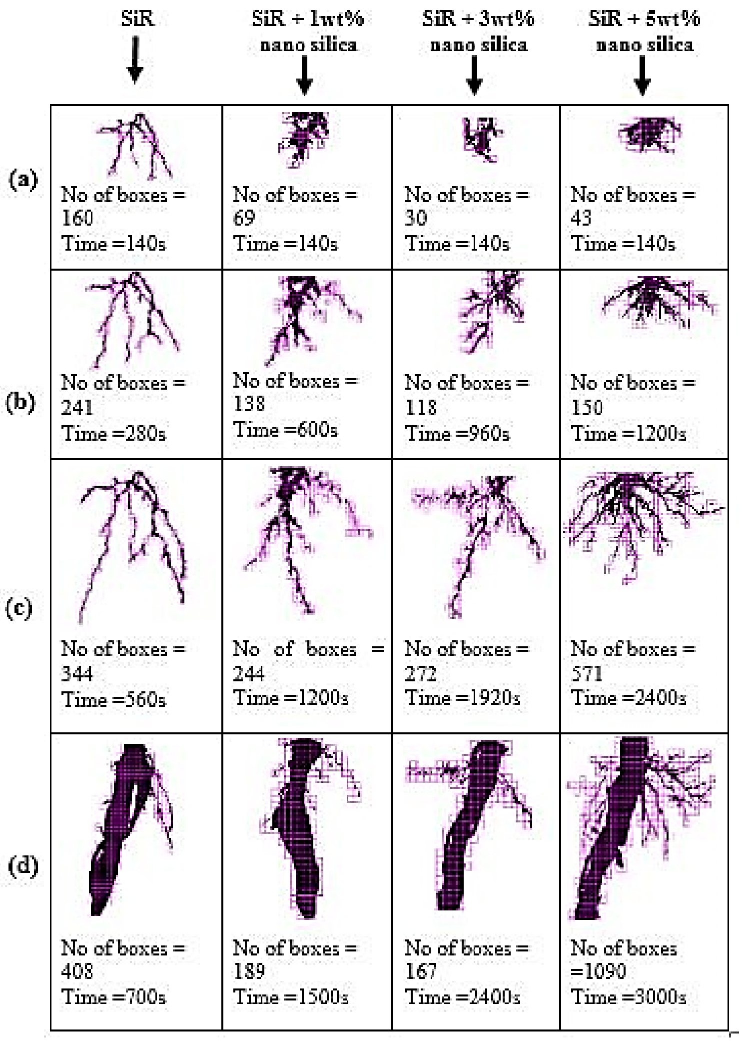

Figure 3. Images of electrical tree propagation with box-counting method in silicone rubber without and with nanocomposites; (a) inception stage, (b) propagation stage 1, (c) propagation stage 2, (d) breakdown stage

In Figure 3 at 140 seconds, was considered as inception stage for all the 4 samples. At the inception stage, the number of the branches increases as the SiO2 weight percentage (wt%) rises and reduce the tree propagation length. In Figure 3 (a) the length the tree size has reduced and the branch type turned to bush branch type of electrical tree. The number of boxes needs to cover the tree increases from the inception to the breakdown stage except in the sample with 1 wt% and 3 wt% only differs at breakdown condition. This was due to the number of interfacial branches are less and not wide for 1 wt% and 3 wt% as compared to 5 wt%. When breakdown happens, these interfacial branches are also shorted and reduces the number of the boxes need to cover them as their width is smaller. In propagation stage 2 the number of the boxes required for 1, 3 and 5 wt% increases due to the number of the branches forming increases with wt%. The measurement with different sizes of boxes resulted in logarithm function. This measurement number of boxed covered the fractal patterns were repeated with all samples for each stage in order to identify the differences of fractal dimension and lacunarity for each propagation.

Figures 4 and 5 show the graph of fractal dimension and lacunarity of fractal for silicone rubber filled with different wt% nanofiller as shown in Figure 3. The values of fractal dimension plotted in Figure 4 were obtained from the slope of graph where the x-axis was logarithm of scaling grid and y-axis was the logarithm number of boxes. From Figure 4 the fractal dimension is not linear from the inception to breakdown stage. The average value of the Df from inception to breakdown at each wt% of nanofiller is shown in Figure 4. The average value of the Df for the pure SiR was 1.445. For the remaining 1, 3 and 5 wt% were 1.5027, 1.5044, and 1.5297 respectively. The average Df value increases with the increment in the nanofiller quantity in SiR. This is due to the nanofiller restrict tree propagation in a straight path by increases the number of the branches and the type of the electrical tree propagated influence the Df.

For lacunarity, it was also calculated the same as Df and the variation was only in the axis of the graph where the logarithm of box size divided by image size on x-axis and lacunarity on the y-axis. The slope of the graph represented as the lacunarity of the fractal. The average value of the lacunarity increases with the filler concentration and its value are as follows; SIR with 0 wt% lacunarity was 0.1093, the remaining 1, 3 and 5 wt% were 0.1512,0.2078 and 0.2726 respectively as shown in Figure 5. Henceforth, the lacunarity increases with the filler concentration and without filler having the lower value of lacunarity. The electrical treeing growth was measured for each stage in order to obtain the difference between the values of fractal dimension and lacunarity during the inception until breakdown stages. Based on the values of an obtained fractal dimension, the type of electrical treeing was identified

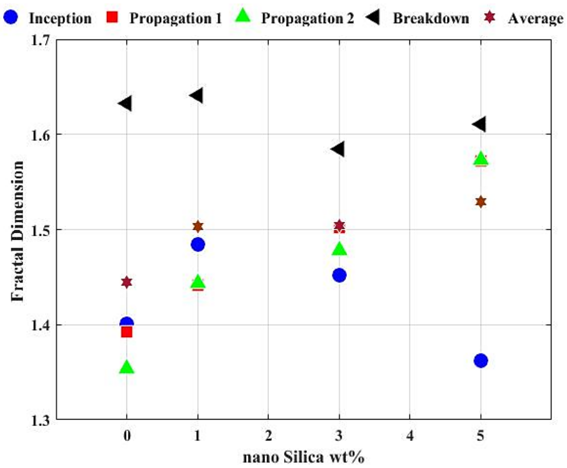

Figure 4. Graph of fractal dimension for silicone rubber with different wt% SiO_2

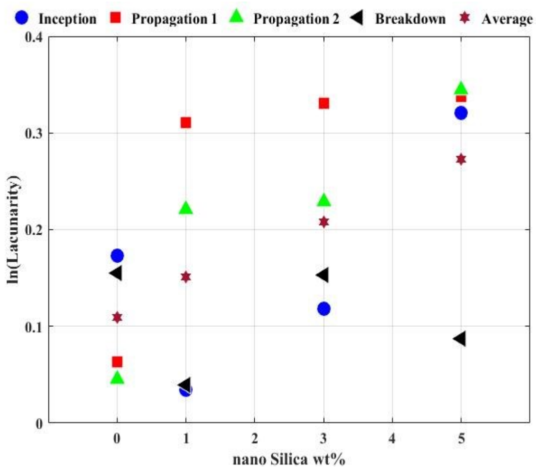

Figure 5. Graph of lacunarity for pure SiR and SiR with different SiO_2 wt% nanofiller

3.2. Analysis of relationship between types of electrical treeing with fractal dimension, Df and lacunarity, λ

The treeing patterns obtained from the experiment under dry condition were analysed. Based on the results, the shapes of electrical treeing of four different fillers were branch type and bush-branch type. Figures 6 show the sample images of the different type of electrical treeing. From Figure 6, it shows that the different percentage of nano-silica added into silicone rubber led to the different types of electrical treeing. Pure silicone rubber shows the electrical treeing of branch type. Meanwhile, the silicone rubber filled with 1 wt%, 3 wt% and 5 wt% nano-silica shows the electrical treeing with bush-branch type. The formation of electrical treeing grows to counter electrode for pure silicone rubber has only a few local branches compared with silicone rubber filled with filler have more local branches can be seen. This is because, the nanoparticles act as elementary barriers and the nanofiller gives the polymer a densely packed structure to prevent trees from growing straight towards the ground. The tree branch for silicone rubber with filler always changes the direction during propagation staging resulted in more branches formed and thereby prolonging the time for a breakdown. These results demonstrated that the growth of tree branches was a local process and dependent on the filler concentrations. Therefore, it was observed that the fillers helped to inhibit electrical treeing by producing more branches to slow down the tree propagation process.

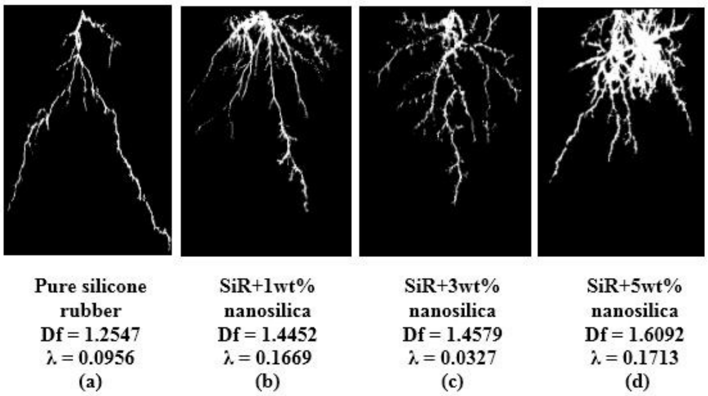

Figure 6. Sample images of different type of electrical treeing;
(a) branch type, (b) bush-branch type, (c) bush-branch type, (d) bush-branch type

In addition, the introduction of the filler may increase the value of the fractal dimension due to the increase in the number of branches. Type of electrical treeing has a linear relationship with the fractal dimension based on the complexity of electrical treeing structure that produced, the higher the fractal dimension values were obtained. Based on Figure 6, the fractal dimension of the sample pure silicone rubber was lower compared to the other sample which was 1.2547. This was due to the electrical treeing structure consists of the main branches that only produced a few branches. Meanwhile, the value of the fractal dimension of the silicone rubber with 1 wt%, 3 wt% and 5 wt% of filler were higher depending on the percentages of filler adding into silicone rubber which were equaled to 1.4452, 1.4579, and 1.6092 respectively. This was due to the structure of the electrical treeing produced is the type of bush-branch, where it has a complicated structure and consists a lot of branches. The classification of tree propagation using Df needs further investigation. This was done by using the lacunarity.

The value of lacunarity on the tree structure of silicone rubber filled with 3wt% of filler was 0.0327 in which lower compared to the treeing structure of silicone rubber without filler which was 0.0956 as shown in Figure 6. The value of the lacunarity obtained from Figure 5 shows its value increased from without filler to with filler concentration. The reason for this one is due to the bush tree has large gaps in the image of treeing structure. Lacunarity can help to the characterization of the complexity of the structure of tree growth in composite materials with describing the texture of the fractal and classifying further on the treeing structure. Thus, it can be stated that the shape of the tree is like branch type, it had lower value of a fractal dimension and low of value of lacunarity. The low value of lacunarity indicates that all the gap sizes are approximately equal and its shape was homogeneous [25]. The localized tree branches form at the interface between the nanofiller and SiR specimen. Due to large gaps, the λ value was high and gaps formed were heterogenous. These are depending on the scaling size. The homogeneous tree was observed at larger scale can be heterogeneous at smaller scale and vice-versa [26].

3.3. The comparison of average of tree length against time

The comparison of the average tree length against time was displayed in Figure 7. From the results, it shows that the propagation of electrical treeing for pure silicone rubber was the fastest. It is followed by the silicone rubber filled with 1 wt% silica, silicone rubber filled with 3 wt% silica and lastly, silicone rubber filled with 5 wt% silica. The electrical treeing propagation in pure silicone rubber was very quick at 140 seconds, the length of the electrical tree already reached 0.9147 mm and it took only 700 seconds to break down. This happened because there was no filler to slow down the treeing process. The electrical treeing grew without obstacle and the formation of the treeing has focused on the main branch and only has a few branches.

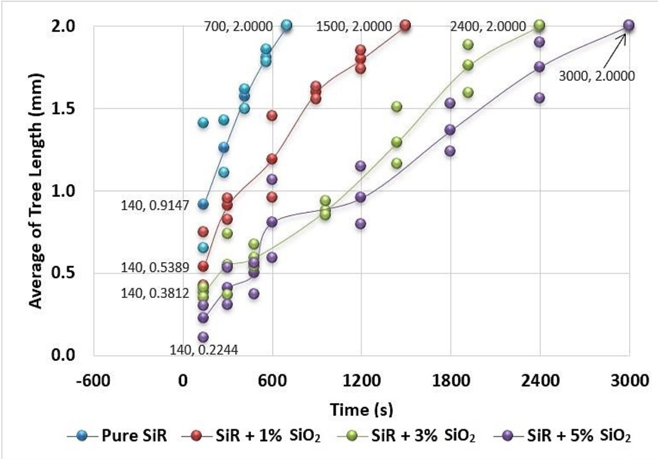

Figure 7. Comparison of average of tree length against time

Meanwhile, the tree length of 5 wt% nano-silica sample was slower than the other. At duration time 140 seconds, the average tree length was 0.2244 mm and grow slowly to the length of tree reaches 2 mm at 3000 seconds. This shows that the presence of filler in silicone rubber can produce a better result for the insulation in which it could increase in the lifespan and prevent the breakdown occurrence. It was caused by the propagation of electrical treeing became difficult when containing the fillers that inhibit from growing straight towards the ground electrode. Based on the literature, when the percentage of the filler increases, the insulating material becomes better due to the improvement of dielectric properties.

3.4. The comparison of average of fractal dimension to the function of tree length

Figure 8 represents the relationship between the fractal dimension and tree length with different filler contents. From the results, it shows that the silicone rubber added with 5wt% nanofillers leading to the higher values of fractal dimension compared to the pure silicone rubber is the lower value of the fractal dimension.

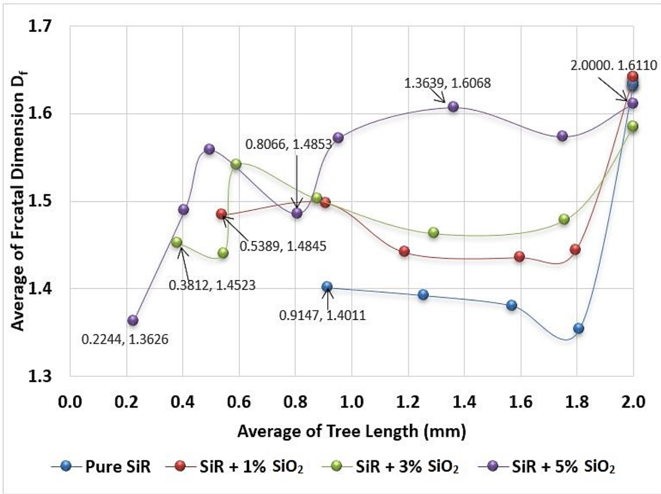

Figure 8. Comparison of average of fractal dimension against tree length

The variation value of fractal dimension was obtained starting from the inception until the breakdown stages. At the inception, the tree grows for silicone rubber with 5wt% of nanofillers is the lowest value of the fractal dimension was 1.3626. This is because, during inception, the tree grows nearly straight while at propagation stage the tree started to grow with more branches. When a greater number of branches produced the value of the fractal dimension is higher as shown in the propagation 1 and 2. The fractal dimension obtained is 1.4853 and 1.6068 respectively. This shows that the nanofillers give a strong reaction to the propagation stage where it caused the electrical trees to form more side branches which have contributed to the increment in fractal dimension and reducing the lacunarity. In contrast to pure silicone rubber, which is at the inception stages, the electrical tree grows faster to form a branch shape and lead to a higher value of the fractal dimension of 1.4011. However, at the propagation stages, the electrical trees quickly turned into the main branch and reduced the value of the fractal dimension.

The tree propagation in silicone rubber with filler was attended by more branches than in pure silicone rubber. The higher the percentage of filler contents, the larger the number of tree branches leading to a tree structure of the higher fractal dimension. Therefore, the number of branches has a very close relationship with the fractal dimension. The analysis of this relationship has been studied to classifying the tree shape with lower and higher fractal dimension. Bush types of trees would lead to higher fractal dimension and structure of branch type would causes low fractal dimension. According to the observations, the branch and bush-branch typed trees produced from this analysis from inception to propagation stages have the fractal dimension of approximately 1.2-1.5 and 1.5-1.8, respectively. Based on this analysis, the tree patterns can be correlated with the fractal dimension and lacunarity.

4. CONCLUSION

The growth of electrical treeing in silicone rubber nanocomposite with different filler concentration and the characterization of the electrical treeing structure was investigated. In this research, the pure silicone rubber has resulted in the branch type of electrical tree patterns while the sample silicone rubber added with filler, the patterns of electrical trees were the bush-branch type. The electrical tree in the bush branch type led to less destruction of insulation compared to the branch type. Based on the experiment, the tree inception time for pure silicone rubber is the shortest and the propagation time to break down is the fastest compared to the filled sample. By adding the nanofiller to the pure polymer, it can delay tree inception time and the propagation of electrical tree becomes slower. Thus, by adding the filler can lead to significant improvements and can be considered that adding the nanofillers can inhibit the growth of electrical treeing. Besides that, filler has a positive impact on insulation material because it is able to act as a barrier to slow down the growth of electrical treeing and can lengthen the lifespan of electrical insulation. Based on the analysis, the fractal dimension and lacunarity of the electrical treeing structure were investigated. The presence of filler in silicone rubber raised the fractal dimension due to the increase the number of tree branches and give a higher value of lacunarity. This is due to the different shapes of the treeing structure produced in the interface of silicone rubber that depends on the percentage of filler added in silicone rubber. According to the observations, the types of branch and bush-branch trees produced from the experiment have the fractal dimension of approximately 1.2-1.5 and 1.5-1.8 respectively from inception to propagation stages. The pure SiR average lacunarity is less than 0.125 and with filler is more than 0.125. Therefore, the higher percentage of fillers resulted in a higher value of a fractal dimension and a higher value of lacunarity.

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