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Barrier effect on electrical tree growth characteristics in silicone rubber

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ABSTRACT

Reliable power cable systems are necessary for efficient electrical power transmission over a long distance. However, electrical trees could grow in the cable systems, such as the cable insulation, joint and termination, eventually leading to insulation breakdown, therefore requiring serious attention. This paper concentrates on the effects of single-layer and double-layer barriers, which are improved techniques for suppressing electrical tree growth in silicone rubber with ethylene-vinyl acetate (EVA) as the barrier material. A simulation work using the finite element method was carried out on silicone composite with the barrier to study the influence of the barrier distance on the electrical tree propagation due to high electric field stress using a needle-plane electrode configuration. In addition, electric field distributions in silicone rubber with single-layer and double-layer barriers were investigated through experiment and simulation. The results illustrated that the electrical tree growth in the barrier region had been slowed down by the double-layer barrier, and the time to the breakdown had increased significantly.

1. Introduction

Reliable power cable systems have greatly influenced the efficiency of transferring enormous electrical power over a long distance to a substation closer to our homes and industries. Notwithstanding, cables accessories such as joint and termination are categorized as the weak point where most of the cable failures started from the accessories vicinity due to the non-uniformity of the electric field. The losses due to the failure of the cable accessories had resulted in long downtime of the transmission and distribution systems. The failures were identified majorly due to the insulation breakdown. Therefore, insulation was identified as the most crucial component for insulating the high voltage parts and preventing breakdown [1]. Nonetheless, due to some factors such as aging process, poor quality of workmanship, manufacturing flaw, water ingress, etc, these imperfections could cause the electrical trees to be initiated and propagated inside the insulation. Therefore, it was one of the major causes of insulation breakdown in the power cable systems [2,3]. The electrical trees were initiated due to defects within the insulation containing voids, impurities, defects and conducting particles, and all of these caused excessive electrical stresses within the insulation or a portion of the internal surface of the insulation [4]. When persistent stress is applied, the electrical tree growth would eventually lead to a total breakdown of the system when the trees bridge both high voltage and ground electrodes. Due to the electrical tree propagation behaviours, many kinds of research have been carried out using a single thin-layer barrier to curb its growth and delay the breakdown time [5]. Up-to-date, less attention has been paid to applying double or multiple layered barrier to suppress the growth of the electrical trees. However, there was a problem of surface incompatibility of the double-layer barrier surface and polymers at the barrier region, which was also important to consider for further research [6].

Therefore, this paper concentrates on discussing the effects of double-layer barrier interfaces on the electrical tree propagation in the silicone rubber. On top of that, the experimental and numerical simulations were carried out using the 2-dimensional (2-D) finite element method of the needle to plane electrode arrangement. In addition, this paper presents a comprehensive study involving the analysis of the electric field and charge density using 2-D finite element simulation method via Finite Element Analysis (FEA) software, sample preparation of the silicone rubber base material with EVA film as the barrier for the test of electrical tree propagation, and production of the electrical trees using leaf-like experimental method under microscopic observation. Precisely, the characteristics of the electrical trees such as tree growth rate, tree propagation time, tree length were measured and analyzed

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systematically.

2. Simulation modeling

The electric field and potential distribution in a high voltage needle to plane electrode gap with a double barrier were analytically examined using the 2-D finite element simulation method. The simulation model was run to determine the electric field in the system, especially the region with the highest electric field strength, field density and potential distribution inside the material. Fig. 1 shows the top view of the 2-D simulation arrangement. A high voltage needle to plane electrode was modeled, and a radius of 0.3 mm for the needle tip was chosen with a hyperbolic edge. The gap distance of 2.0 mm between the tip of the needle and the plane electrode was chosen with 1.0 mm between the tip of the needle, and the barrier surface distance was also chosen to study the electrical tree propagation vertically inside the gap position.

A barrier with a thickness of 200 μm was set between the electrodes in such a way that the surface of the barrier was perpendicular to the needle axis. A constant AC voltage of 10 kVrms was applied, and the relative permittivities of the silicone rubber insulating material and EVA barrier were 11.86 and 2.6, respectively. These relative permittivity values were selected to be matched with the relative permittivity values of the raw materials of silicone rubber and EVA purchased from Sigma Aldrich. The simulation model dimension of the box was ten (10) millimeter squares, which was filled with silicone rubber except for the needle and double barrier spaces. The specimen was modeled according to the specification mentioned above. In addition, the examination of the electric field condition and the results obtained were demonstrated and explained accordingly.

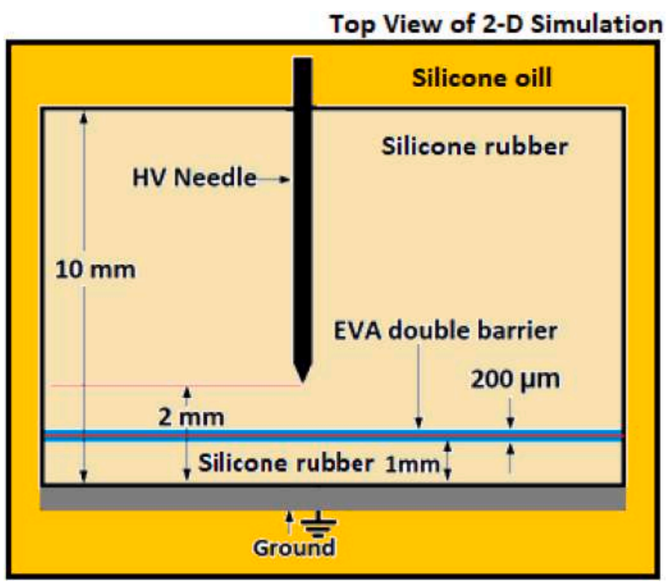

Fig. 1. Schematic drawing of the needle to plane electrode arrangement of the simulation study.

3. Experimental process

Fig. 2 shows the schematic diagram of the experimental setup. The electrical tree experiment was conducted using a digital image processing set [7], consisting of a microscope, a digital camera, and a computer to acquire the data of the electrical treeing. The prepared specimens from a silicone rubber material with EVA barrier film were stressed by an AC voltage of 10 kVrms, at a frequency of 50 Hz, through the high voltage needle and plane electrode arrangement. For facilitating the tree initiation, a needle with a tip radius of 3 μm and a diameter of 0.3 mm was used at a distance of 2 mm between the tip of the needle and the ground electrode, which provide adequate space for the tree growth [8–10]. The EVA films of 100 μm and 200 μm thicknesses with a constant length of 10 mm were placed at the centre of the gap between the two electrodes and perpendicular to the axis along the tip of the needle. The ground electrode was created using metallic foil adhered to create a proper contact. Fig. 3 shows the electrical tree test rig used for the measurement and the specimen as elaborated previously.

The prepared specimen was placed inside a clean glass vessel in the centre position of the vessel, where the needle was connected to the high voltage source, and the plain electrode was connected to the ground potential point. Silicone oil was then poured into the glass vessel until it covered the surface of the specimen to avoid surface flashover. The glass vessel was then placed under the microscopic system to visualize the electrical tree upon injection of 10 kVrms, 50 Hz AC voltage to the needle, which was maintained constant until the breakdown occurred.

The electrical tree initiation and growth videos were recorded using a charge-coupled device (CCD) camera (Olympus, DP26) with 16 frames

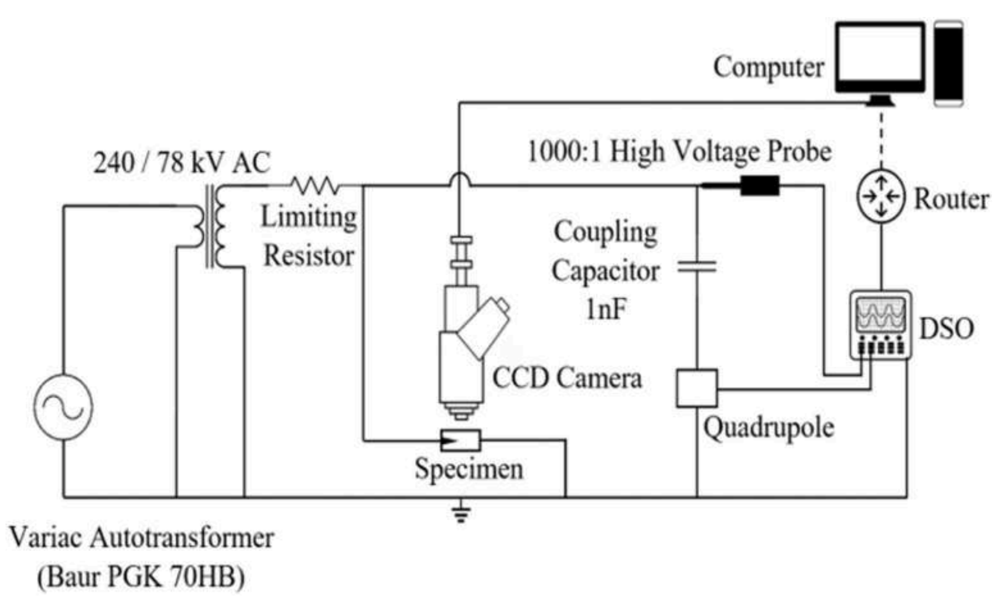

Fig. 2. Schematic diagram of the experimental setup for electrical tree measurement. [11]

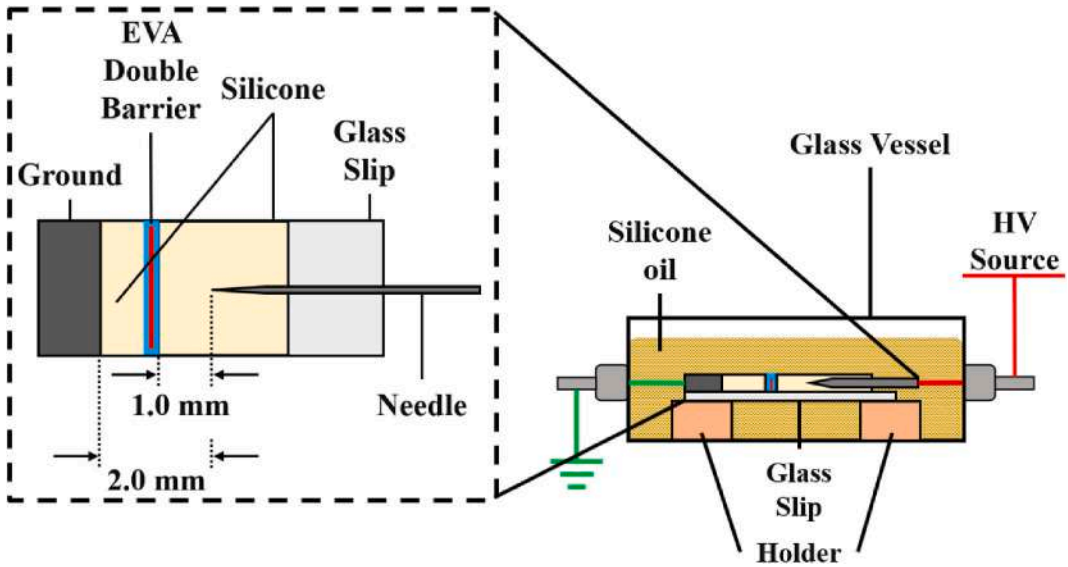

Fig. 3. The arrangement of the electrical tree test rig and the specimen configuration. .

per second of speed capturing rate and 60 μs of exposure times mounted on top of the microscopic system. The tree length was measured by the calibrated measurement system of the microscope via Cellsens software. The entire experiment was conducted at room temperature and 50-60% relative humidity. The prepared samples were tested for the electrical tree growth under AC high voltage, and the electrical trees were captured with the help of the microscopic system.

Besides, the electrical tree length would emanate from the tip of the needle due to the high electric field at the needle tip position [10,12]. The inception of the first branch would occur during the initial voltage rise to the final value within a certain tree inception time. Once the first branch was created, the tree would continue to grow in branches to the ground electrode. However, the first branch breakdown does not occur until many branches bridge the tip and the electrode gap.

4. Results and discussion

The simulation and experimental results are elaborated in the section along with the discussion.

4.1. Simulation result

The electric field distribution in the gap between the tip of the needle

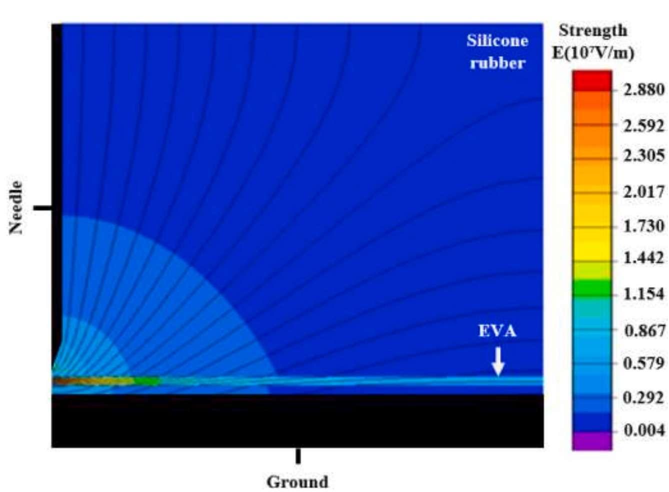

Fig. 4. Simulation result of the electric field strength.

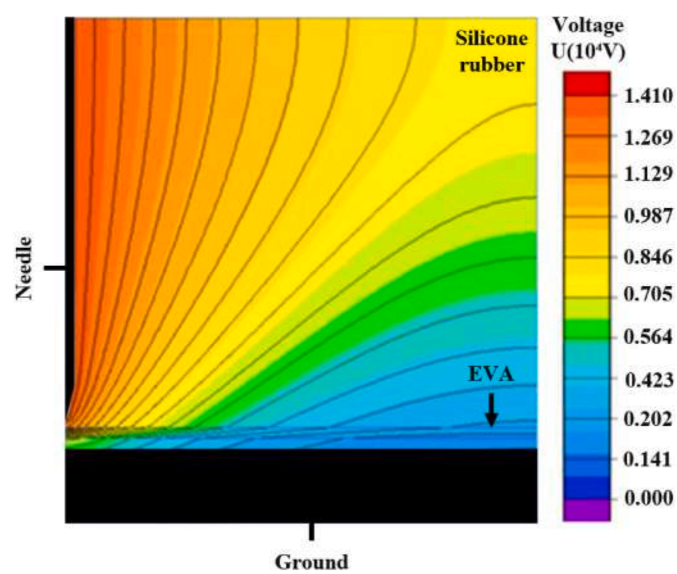

Fig. 5. Simulation result of the voltage distribution.

and the ground electrode of the silicone rubber materials and EVA barrier at 10 kVrms of the applied voltage was numerically analyzed using the finite element analysis software. The relative permittivity values of the silicone rubber and EVA materials were very important as these values need to be considered as the boundary conditions to obtain realistic results in simulating the experimental works. As a result, the simulation shows that the maximum electric field strength value is always higher at the tip of the high voltage needle and in the barrier region. The electric field in the insulation experienced a significant change, and the electric field is distributed over the whole area, where the resulting field played a significant role in the continuous growth of the electrical tree branches and bushes. The barrier has caused the electrical field strength to be higher at the barrier region, thereby preventing the trees from reaching the opposite electrode on time, but depending on the barrier type of material, the thickness of the barrier and the magnitude of the applied voltage. Fig. 4 shows the electric field strength from the simulation result.

The electric field potential varied with distance. The potential was higher at a closed distance from the needle tip and continued to reduce

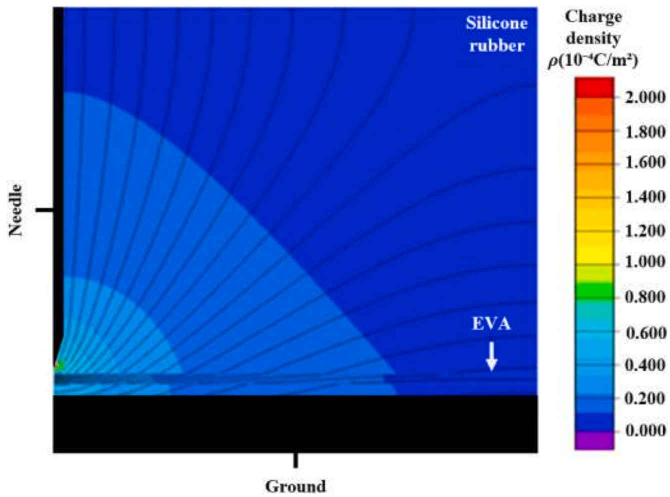

Fig. 6. Electric charge density from FEA simulation.

with increasing distance. Fig. 5 shows that the potential is higher inside the gap between the two electrodes, especially at the tip of the needle and in the barrier region. This defined the tree inception voltage and the tree breakdown voltage; the structure of the electrical treeing was reduced with increasing breakdown voltage, and the tree inception voltage decreased due to the presence of the barrier in the insulation. Fig. 6 shows that the electric charge density --concentration is more at the tip of the high voltage needle and on the surface of the barrier with about 1.6 x10^{-4} C/m^2 [13]. The charge occupied a small portion between the needle tip and the barrier region and was delayed for some time (inception time) until it was fully concentrated and started to move (initiation stage). The electrical tree initiation started from the tip of the needle, where the electric charge density was higher. The tree continued to grow due to the continuous movement of the charge inside the insulation [14,15].

4.2. Electrical treecharacteristics with a single-layer barrier

The tree inception time and tree growth were affected by the presence of a barrier in the insulation region. The inception time appeared to be very small, with 14.06 s of average initiation time and a very short

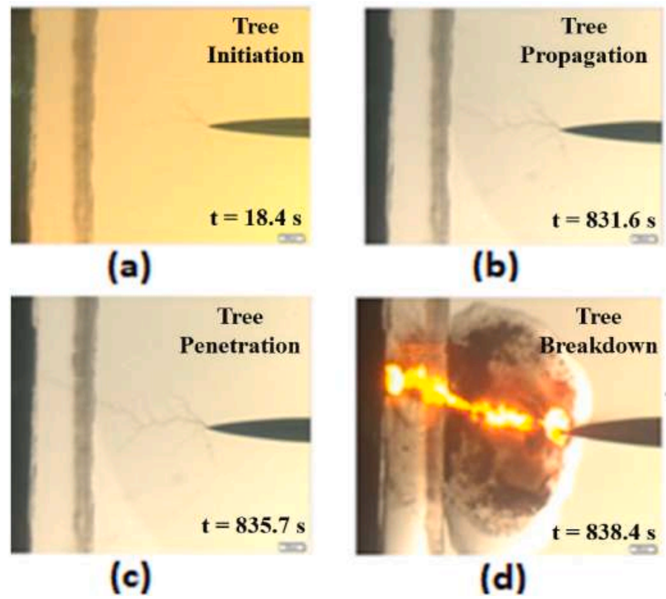

Fig. 8. The second sample with the single-layer barrier.

tree length with 34.96 μm of the tree length. The tree structure at the initiation stage was mainly a tree branch before changing to bush tree when it continued to propagate toward the barrier region. At the barrier region, the tree propagation was very slow. The effect of the barrier caused the electrical tree to be retarded at the surface of the barrier without penetrating the barrier region on time. Due to the barrier effect, different tree structures are formed, including branch-type tree, bush-type tree, and pine bush tree, which require more energy for the leading tree branch to penetrate the barrier. After the barrier was penetrated, the propagation speed was still very low, which took a 57.83 s average period to reach the bridging phase; therefore, it took some time for the trees to cause a breakdown. Figs. 7–9 shows the experimental results obtained from different samples.

Figs. 10 and 11 represent tree length as a function of time at the constant applied voltage for the silicone rubber and EVA as the single-layer barrier. Since the growth of the electrical tree is a stochastic measurement, it could be a reason why there are significant differences

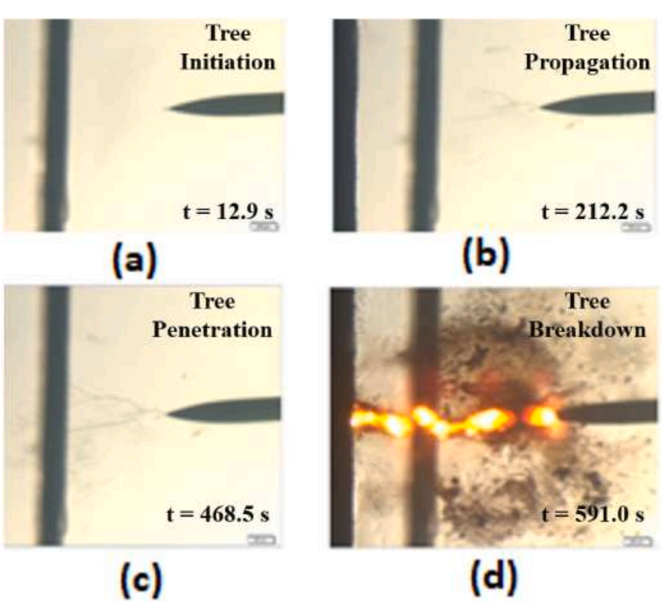

Fig. 7. The first sample with the single-layer barrier.

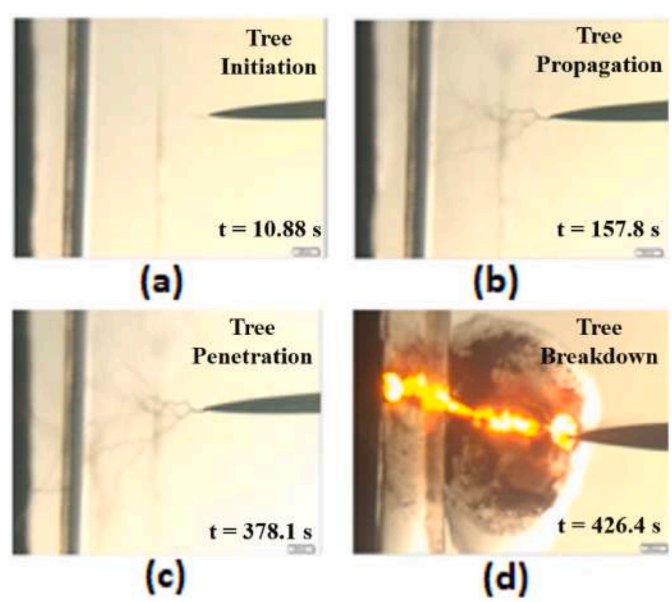

Fig. 9. The third sample with the single-layer barrier.

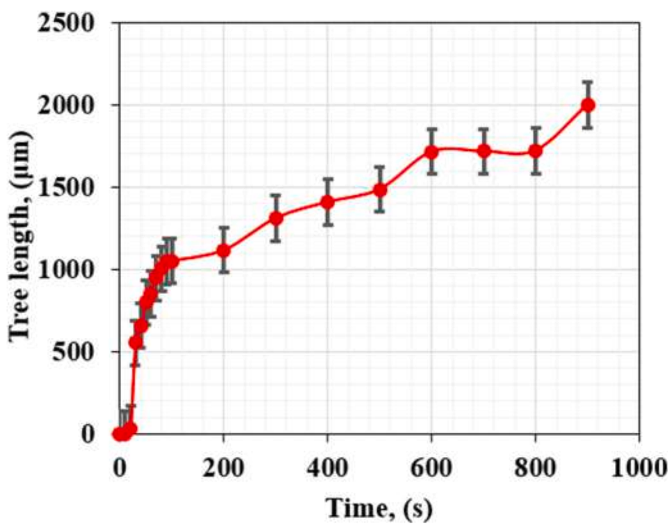

Fig. 10. Average tree length of the electrical trees from the experimental results of three samples with a single-layer barrier.

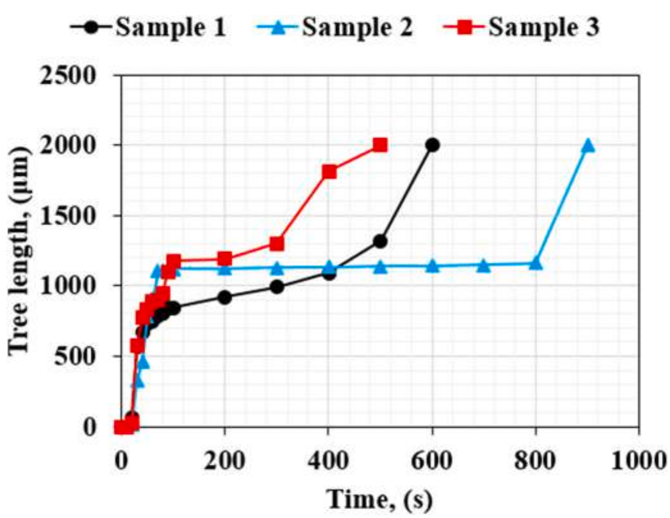

Fig. 11. The individual growth of tree length in each sample with a single-layer barrier.

between the time growth of tree phases for each tested sample. Henceforth, the measurement of tree length as a function of time was observed based on the average value obtained from three samples. The trees started to initiate within a very short period in less than 20 s upon the applied voltage; the trees were stagnant immediately after initiation at a point for some time before it then hurtled to a certain distance and continued to propagate. The electrical tree growth rate was almost the same for the different samples, with a 2.25 standard error for the initial stage.Nonetheless, the tree propagated with other structures toward the barrier surface, and the time of propagation was quite different from all the samples. All samples experienced a breakdown in less than 1000 s with an average of approximately 618 s, as shown in Table 1. The electrical trees spent most of the time during propagation because of the barrier effect. It was observed that the tree remained for some time on the barrier surface before penetrating the barrier, and the tree extended proportionally with the duration of the applied voltage. The pinhole-like puncture of the barrier caused by the tree penetration served as a kind of a point electrode that allowed the tree to propagate toward the plane electrode until breakdown occurred. Therefore, the barrier has slowed down propagation right from the tree initiation stage, not only at the barrier surface.

4.3. Electrical tree characteristics with double-layer barrier

Electrical tree inception time and growth were improved with the double barriers almost twice the single-layer barrier effect. The tree structure was observed to be quite different compared to the single-layer barrier. The tree initiation started with a pine bush treeing pattern, but it took a longer inception time to be initiated. The trees took a very long time to reach the surface of the barrier, with 919.6 s of average propagation period. Moreover, the tree was suppressed for a long time at the barrier surface without penetrating the barrier. After penetrating the barriers, the interface effect at the barrier surface facilitated the growth of the electrical tree in a reduced number of branches. The tree length was found to be increased with the presence of the double-layer barrier,

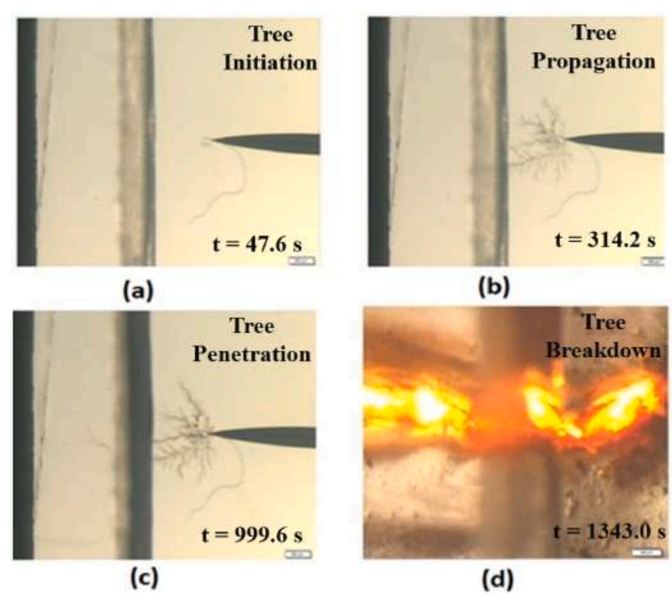

Fig. 12. The first sample with the double-layer barrier.

Table 1
Tree initiation time, tree penetration time and tree breakdown time results of samples having a single-layer barrier.

Time (s)	Sample1	Sample2	Sample3	Average	Standard error
Tree initiation time	12.90	18.40	10.88	14.06	2.25
Tree propagation time	212.20	831.60	157.80	400.53	216.10
Tree penetration time	468.5	835.7	378.1	560.77	139.92
Tree breakdown time	591.0	838.4	426.4	618.60	119.73

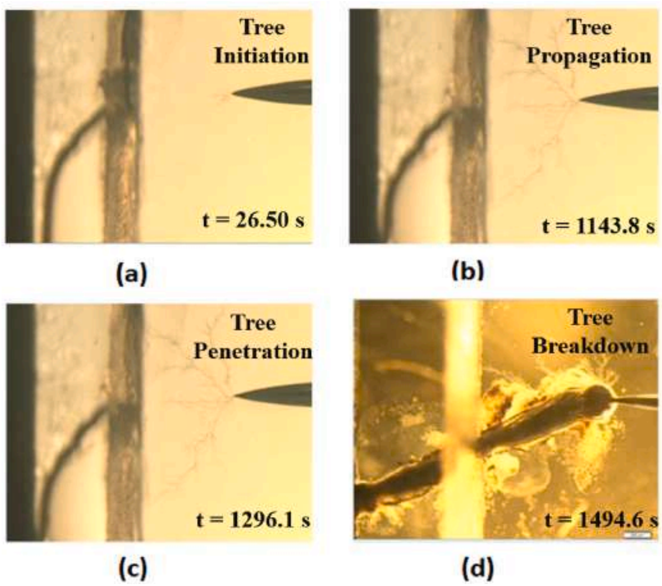

Fig. 13. The second sample with the double-layer barrier.

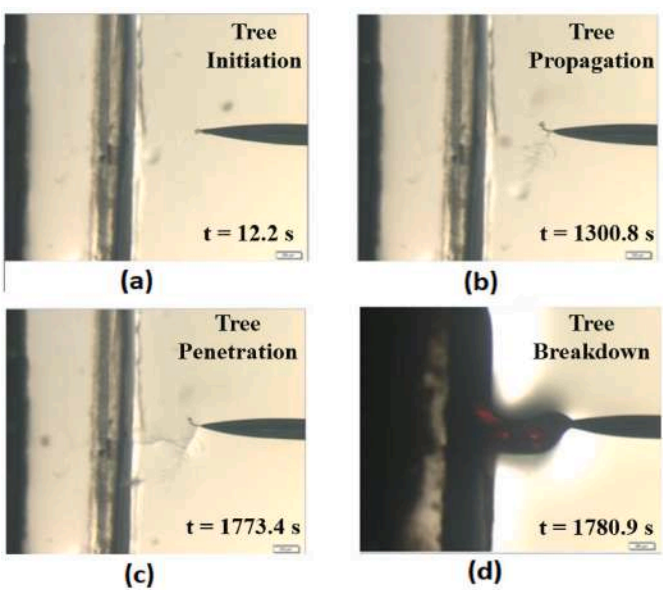

Fig. 14. The third sample with the double-layer barrier.

which corresponds to some of the research findings on the effect of barrier thickness on the electrical tree growth. With the presence of the double-layer barrier, the trees required more energy to cause an electrical breakdown [16]. Figs. 12–14 show the electrical tree characteristic results of the sample containing double-layer barrier interfaces.

Figs. 15 and 16 represent tree length as a function of time at the constant applied voltage for the silicone rubber and EVA films as the double-layer barriers. The double-layer barrier prolonged the initiation time of the electrical tree growth. It was found that the trees took some time before appearing after the voltage was applied. The electrical trees took a long time to propagate and penetrate the barrier because of the double barrier effect, such that the breakdown occurred after about 1500 s on average, as shown in Table 2. It shows that the tree was retarded much longer than the single barrier. The pinhole-like puncture of the barrier due to the tree penetration served as a kind of opening path for the trees to pass through and propagate towards the plane electrode until the breakdown occurred. The double-layer barrier has slowed down the trees more effectively. The trees have propagated right after

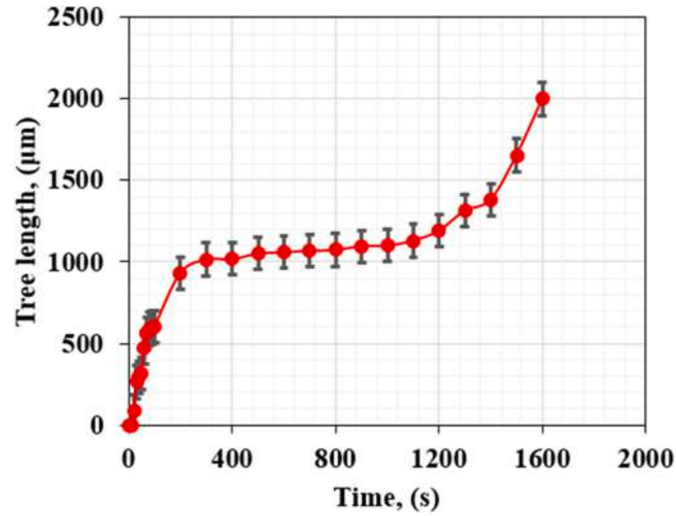

Fig. 15. Average tree length of the electrical trees from the experimental results of three samples with double-layer barrier.

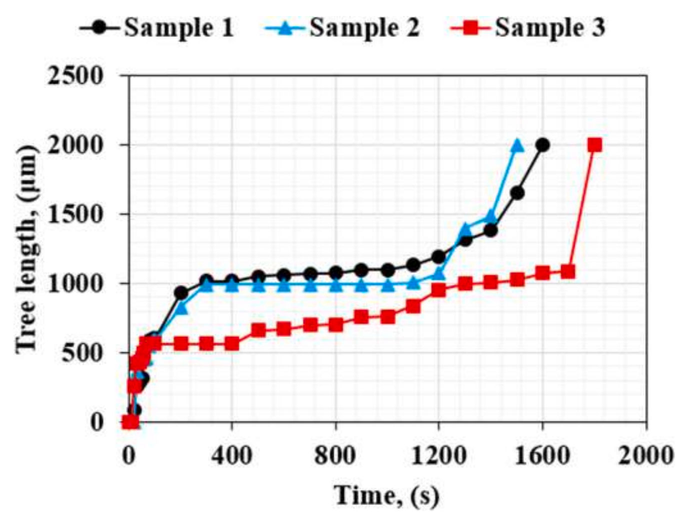

Fig. 16. The individual growth of tree length in each sample with double-layer barrier.

Table 2
Tree initiation time, tree penetration time and tree breakdown time results of samples having double-layer barrier.

Time (s)	Sample1	Sample2	Sample3	Average	Standard error
Tree initiation time	47.60	26.50	12.20	28.80	10.28
Tree propagation time	314.20	1143.80	1300.80	919.60	306.07
Tree penetration time	999.60	1296.10	1773.40	1356.40	225.40
Tree breakdown time	1343.00	1494.60	1780.90	1539.50	128.39

the tree initiation stage, not only at the barrier surface.

4.4. Comparison between the single-layer barrier and double-layer barrier

The analysis of the two results discovered that the double-layer barrier has positively suppressed the electrical tree growth in the silicone rubber composite insulation better than the single-layer barrier.

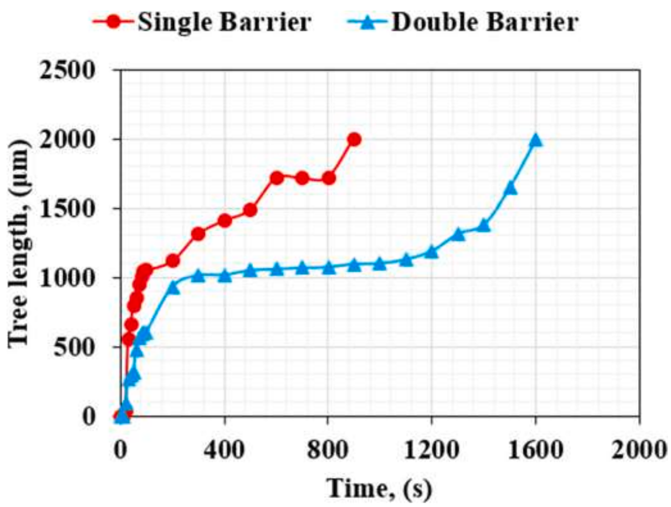

Fig. 17. Comparison of the average tree lengths of both barrier configurations.

Table 3
Comparison between the single-layer barrier and the double-layer barrier (average value).

Time (s)	Single-layer barrier	Double-layer barrier
Tree initiation time	14.06	28.8
Tree propagation time	400.53	919.6
Tree penetration time	560.77	1356.4
Tree breakdown time	618.60	1539.5

The tree initiation time, propagation time and breakdown time have been delayed longer with the double-layer barrier almost double from the single-layer barrier. The average time of 1500 s was taken for the double-layer barrier samples to break down, while the single-layer barrier samples broke down in just 618.60 s on averagely, as shown in Fig. 17. The penetration times of the trees were prolonged with the double-layer barrier on the surface of the barrier region, whereas in the case of the single-layer barrier, the tree penetrated the barrier shortly after reaching the barrier surface without much delay. Table 3 shows an analysis of the difference in the characteristics of the two barriers.

4.5. Discussion

The silicone rubber has excellent electrical and mechanical properties and is capable of withstanding high voltage stress. The conductivity of pure silicone rubber is very poor to the electrical tree growth when subjected to high voltage, making it necessary for filler treatment as composite materials [17]. The main cause of the tree initiation in the composite dielectric material sample is the presence of the high value of the electric field at the tip of the high voltage needle. The first significant change occurs in the region with the highest electric field. Hence, the position where the first electrical tree branch appears together with several tree branches extensively grow in different directions, forming the tree-like structure. In all cases, the electrical tree developed toward the ground electrode, but a significant difference in the structure of the early tree branches was observed from different samples, especially with the double-layer barrier some time the pine branch trees or tree branches started to grow, as shown in Figs. 7–9. However, it was observed that all kinds of electrical trees grew rapidly in the first instant of propagation, and the process lasted for a very short period. The trees continued to grow at a different rate in the silicone rubber insulation material, and the branches were scattered and nonuniformly distributed; they were of different dimensions in different directions. Some trees were vertically propagated while others were horizontal, and others were diagonal.

It was observed that the vertical trees stopped growing along the line while the horizontal tree grew faster than the diagonal tree. However, the vertical tree always reached the barrier first before other branches. The differences in the growth rate of the electrical trees and the time to breakdown of the insulation are because of the presence of the barrier in-between the two electrodes. When the electrical tree approached the barrier, the leading tree branches were delayed at the barrier region. The tree growth was suppressed on the surface of the barrier for some time, depending on the strength of the barrier and the permittivity value. In this experiment, solid material with high electric strength and permittivity was used as a barrier, which was then difficult for the tree to penetrate easily, unlike other barriers which happened to be liquid. The distance between the ground and the barrier has determined how much the electrical tree's spreading on the surface of the barrier, and the edge of the vertical tree has been retarded by the barrier preventing it from reaching the ground electrode on time. The horizontal and diagonal branches of the tree growth were higher than the vertically directed branch; therefore, the ability for these electrical tree branches to penetrate the barrier was higher for the vertically directed branches than the horizontal directed branches. Also, the more the thickness of the barrier, the wider the spreading of the electrical trees on the surface of the barrier, and the longer delay time of the trees at the barrier surface without penetrating the barrier.

5. Conclusion

The simulation results deduced that the electric field was higher at the tip of the needle and the barrier junction. The electrical tree propagation started from a region where the critical value of the electric energy density was exceeded. Experimental results testified that the impact of the barrier was dependent upon the interface condition between the polymeric composite materials and their properties. Other factors such as barrier thickness, the material used, and the position of the barrier could also play a significant impact. The barrier effect caused the electrical trees to be retarded at the barrier's surface without penetrating the barrier zone on time. When the electrical trees approached the barrier zone, the growth of the main tree branches were delayed. Compared to a single-layer barrier, the double-layer barrier has a greater impact in suppressing the growth of the electrical trees in silicone rubber. The tree propagation delay has extended the lifetime of the insulation, but proper distance and thickness ought to be considered for an effective lifetime of the insulation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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