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RESEARCH ARTICLE

High Voltage Engineering

Fractal characteristics of creeping discharges propagating on nano-epoxy composite insulators immersed in coconut oil

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Abstract : A solid/liquid dielectric interface is considered to be one of the weakest points in a composite insulation system, as it facilitates creeping discharges on the interface when the electric field strength exceeds a threshold value. This paper presents a study on the use of nano epoxy composite to minimize the effect of damage which occurs due to creeping discharge activity, when it was immersed in coconut oil. A point-plane electrode arrangement-based test apparatus, energized by a high voltage supply, was used for analysing the propagation of creeping discharges over solid/liquid interfaces using visual observation. An algorithm was used to determine the fractal dimension of creeping discharges propagating over various solid/liquid insulating interfaces. In particular, it focused on the variation in creeping discharge patterns with the use of pure epoxy and nano-composite epoxy samples. The results showed that the use of nanofillers can increase the dielectric breakdown strength of epoxy by 7%. The results also showed nanofillers of 20 nm with 1% concentration do not affect the tortuosity of the creeping discharge pattern on the solid material immersed in coconut oil. However, it can increase the possibility of flashover due to creeping discharge propagation over epoxy insulating material immersed in coconut oil by around 12%.

Keywords: Coconut oil, creeping discharges, final discharge length, fractals, nanotechnology, propagation.

INTRODUCTION

A quality electricity supply has become one of the basic necessities in modern society, demanding an efficient and uninterrupted power supply. The failure of critical oil-filled high voltage (HV) equipment such as cables, transformers, capacitors, and circuit breakers with many solid/liquid interfaces may lead to catastrophic events, resulting in economic losses and injury to humans. Therefore, it is important for the power utilities to reliably operate and maintain their high voltage equipment (Kebbabi & Beroual, 2006; Ediriweera *et al.*, 2018a). Dielectric liquids are used in the power industry together with solid insulating material to serve as an insulation, impregnation, and cooling medium. In some cases, the solid barrier materials are used to improve the dielectric strength of gas and oil gaps (Liu *et al.*, 2016; Ediriweera *et al.*, 2018b). Dielectric liquid and solid barriers can increase the dielectric strength of oil-filled HV equipment. However, the arrangement of the composite insulation system is also one of the key points that has to be considered. When the electric field strength exceeds a threshold value, the tangential electric field over the solid/liquid interface initiates surface discharges (Yi, 2012). These discharges are commonly called creeping discharges. This discharge can cause irrecoverable damage to the insulation system and cause flashover which undermines the use of a composite insulation system (Yi, 2012).

A lot of work has recently been devoted to improving the dielectric properties of insulating materials by adding specific nano-fillers to polymer-based materials, changing the dielectric and mechanical properties. Nano-

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composite polymer materials show better performance when it comes to the dielectric properties of the materials (Yanashima *et al.*, 2017; Hornak *et al.*, 2020). In addition to the electrical characteristics, they also show higher tensile strength, thermal stability, and improved chemical properties over conventional insulating materials (Liang & Wong, 2017).

Petroleum-based mineral oil has been used as the dielectric liquid in high voltage equipment for more than seven decades due to its better performance. However, due to some of its disadvantages such as low fire point, limited biodegradability, and high toxicity, attention has been paid to use alternative vegetable oils such as soya bean oil, coconut oil (Abeysundara *et al.*, 2001; Lucas *et al.*, 2002), and sunflower oil, even though their properties such as viscosity, conductivity, acidity, and water solubility are still to be improved. Coconut oil is produced on a commercial scale in Sri Lanka and it is rich in saturated fat with medium and short chains. Most of its physical, chemical, and dielectric properties are at satisfactory levels as an alternative for the conventional mineral oil for high voltage equipment (Abeysundara *et al.*, 2001; Matharage *et al.*, 2013), and it offers better oxidation stability compared to other vegetable oil due to the higher percentage of saturated fatty acids. However, the studies have not progressed to the analysis of creeping discharge over nanocomposite insulating materials immersed in coconut oil, which can affect the performance of the nanocomposite insulation system. Fractal analysis of creeping discharges can be used to compare the amount of discharge branch formation on the advanced solid dielectric materials with that of conventional materials.

The main objective of this study was to perform a fractal analysis of creeping discharges propagating over nanocomposite polymer insulating materials immersed in coconut oil. In particular, the discharge length and the fractal dimension are determined using a test apparatus based on a point-plane electrode arrangement. An experimental setup based on a point-plane electrode system is used to initiate the discharges in a laboratory environment. Pure epoxy and nanocomposite samples are synthesized for testing purposes and a statistical method is used to analyse the breakdown of prepared solid material samples.

METHODOLOGY

Experimental test setup

In the current study, a point-plane electrode system based test apparatus was adopted in order to initiate creeping discharges and compare their propagating characteristics on solid/liquid interfaces. Needle plane electrode systems are usually selected to experimentally investigate the creeping discharge development (Kebbabi & Beroual, 2006; Dang *et al.*, 2012). The tangential field component of the divergent electric field drives the propagation of creeping discharge as observed inside actual high voltage apparatus (Ediriweera *et al.*, 2018a).

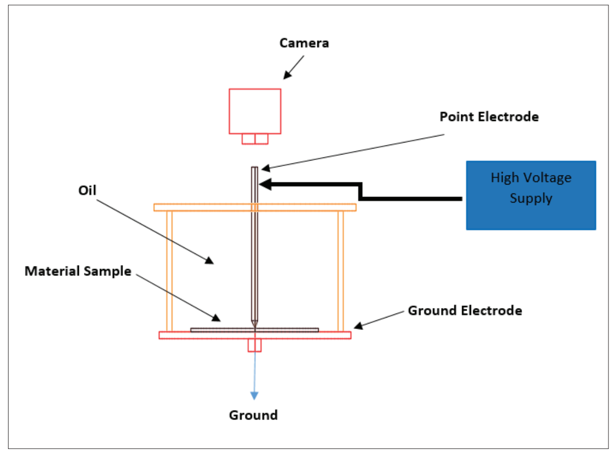


Figure 1: Schematic of the test setup

Figure. 1 shows the schematic view of the test cell and this is similar to what other researchers adopted in their studies (Kebbabi & Beroual, 2006). The test cell consists of a cylindrical core with a height of 100 mm and 130 mm inner diameter, made of clear acrylic to visualize the discharge, and a square-shaped brass plate as its lower cover. The test cell is mounted on a structure made of wood. The test cell has a point-plane electrode arrangement, where the vertical point electrode is held using a movable bearing system to permit vertical movement. The point electrode, made of tungsten, has a diameter of 1 mm and the tip of the point is hemispherical so that the field between the two electrodes would be divergent (Ediriweera *et al.*, 2018a). The gap between the two electrodes can be varied from zero to 20 mm. Thin flat insulating material samples can be maintained horizontally between the two electrodes and the point electrode is configured in such a way that the tip of the point electrode nearly touches the solid material sample. The samples are immersed in an insulating liquid by filling the test cell with oil. A CCD camera, connected to a high-performance video card is mounted over the test cell and the integrated images taken by it are used for the optical observation of the discharge. The plane electrode is grounded and the point electrode is energized by a partial discharge (PD) free HVAC test transformer.

Sample preparation

There are various types of epoxy resins that are used for many engineering applications. Bisphenol - A type epoxy resins do not fall in to the category of cycloaliphatic epoxy resins. The epoxy used consists of diglycidyl ether of bisphenol-A (DGEBA) type Epon@Resin 828. The curing agent is Modified Cyclo-aliphatic Amine Adduct type 3388. The chemical structure of the epoxy resin is shown in Figure. 2. The considered epoxy type has a lower viscosity compared to other types and is commonly used in the high voltage industry. SiO_2 with a particle size of 20 nm is chosen as the filler material of the epoxy-based nano-composite. Both pure epoxy and nano-composite material samples are synthesized and a block diagram representing the synthetic procedure for the nano-composite material is shown in Figure 3 (Kochetov, 2012).

Dielectric samples having silicon dioxide nanoparticle compositions (weight to weight) of 1 % are prepared in this study for testing purposes. The synthetic procedure is similar to what other researchers adopted in their studies (Kochetov, 2012; Karunarathna *et al.*, 2019). As the first step, required volumes of epoxy and curing agents are measured using a pipette and measuring cylinders. Sonication is a process used to disperse the agglomerate filler particles in an ethanol medium. The mechanical mixing process mixes the epoxy and the filler medium making the fillers transfer into the epoxy. The evaporation process removes the ethanol remaining in the mixture. Finally, in the mechanical process, it mixes the medium after the curing agent is added to the mixture. The fabrication process of pure epoxy consists of simple mechanical mixing of the measured volumes of epoxy and curing agents.

Breakdown voltage of solid samples

The chemical and physical properties of dielectric insulators can affect their breakdown voltage, and breakdown voltage becomes a statistically distributed

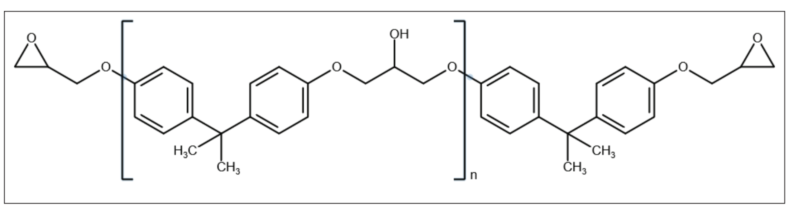


Figure 2: Chemical structure of bisphenol-A type epoxy resin

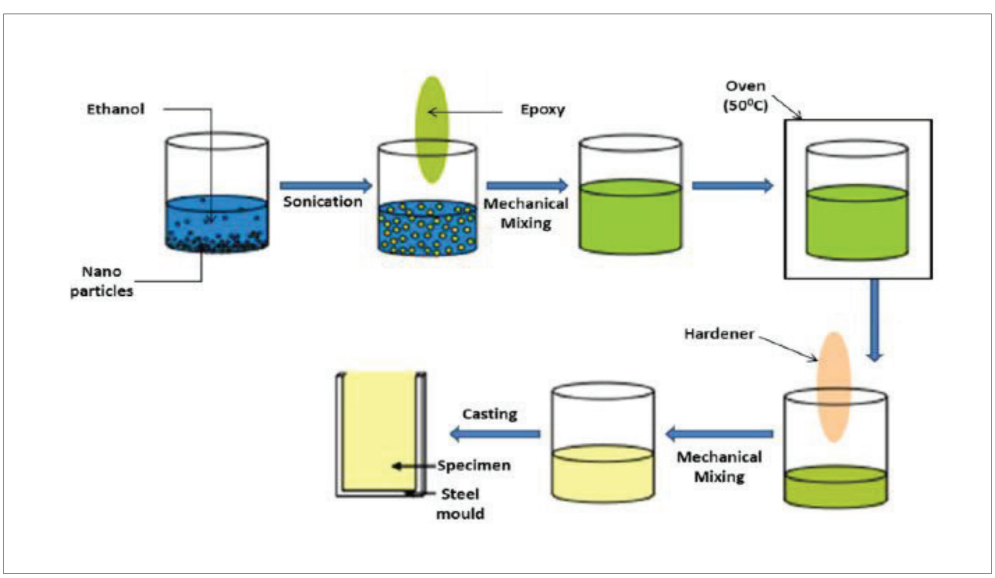


Figure 3: Fabrication process of nano-composite material

quantity. Therefore, statistics are being considered to analyse the breakdown voltage (Gupta & Das, 2017). In the current study, a two-parameter Weibull distribution was used to model and analyse the distribution of the breakdown voltage of the prepared solid insulating samples. The probability density function (PDF) and the cumulative distribution functions are given by equation 1 and equation 2, respectively (Gupta & Das, 2017; Yuan *et al.*, 2017).

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x}{\alpha}\right)^{\beta-1} \exp\left\{-\left(\frac{x}{\alpha}\right)^{\beta}\right\} \quad \ldots(1)$$

$$f(x) = 1 - \exp\left\{-\left(\frac{x}{\alpha}\right)^{\beta}\right\} \quad \ldots(2)$$

where β and α are the shape and scale parameters of the experimental data respectively.

The shape parameter is a measure of the range of experimental data and the scale parameter is a characteristic breakdown voltage at which the probability of failure is 63 %.

Skewness can be used to identify the symmetric or asymmetric nature of breakdown voltage values using equation 3 (Gupta & Das, 2017).

$$skw = \frac{E(x-\mu)^3}{\sigma^3} \quad \ldots(3)$$

Experimental procedure

Flat square shaped solid materials of prepared pure epoxy and silica/epoxy nano-composite of side length 9 cm and thickness 3 mm were used to analyse the creeping discharge propagation over the solid/liquid interface. A type of commercially available copra coconut oil with a relative permittivity of 2.9 was selected as the insulating oil in the study, as it is an emerging alternative liquid insulating material (Matharage *et al.*, 2013). The electric field in the experimental setup used in this study was not uniform. In actual power system assets, a uniform electric field cannot be expected due to the electrodes and dielectric configurations in the equipment. Therefore, tests were carried out to make a comparison between propagation patterns on different interfaces that were subjected to the same electrode arrangement. According to the IEC 60156 standard, a test cell with 2 spherical electrodes separated by a gap of 2.5 mm was used to measure the breakdown voltage of coconut oil samples at the University of Moratuwa, Sri Lanka. The mean value of the breakdown voltage given for five oil samples under ambient conditions was considered as the average breakdown voltage. The average breakdown voltage of 'as received' oil samples was measured at 20 kV.

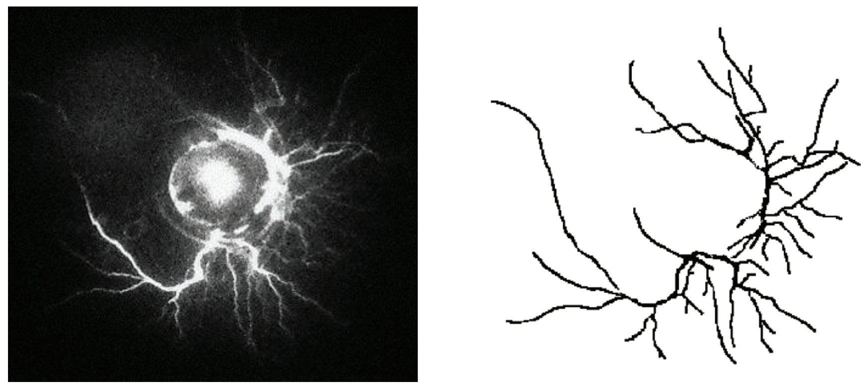
The test cell was filled with coconut oil and solid materials prepared in square shape were inserted between the two electrodes, such that the point electrode touches the surface of the sample. If the flashover is observed, the test cell was refilled with new oil from the same test oil sample. The samples were kept in the laboratory in a darkened place without any UV exposure in order to avoid contamination. Therefore, the material and electrical properties of the test volumes were assumed to be the same in all the samples in the experiments. The height of the oil volume was kept at 5 cm throughout the testing procedure.

Dielectric strength tests were performed according to the ASTM-D149 standard at the University of Moratuwa, Sri Lanka, and five samples of epoxy and nanocomposite were tested. Parameters of Weibull distribution were estimated using Minitab software.

Fractal dimension

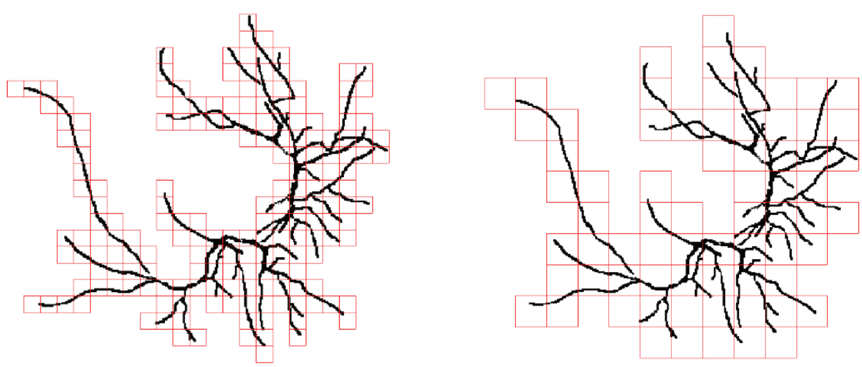
Dimension identifies the way the object fills the space. Dimensions of a point, a line, a square, and a cube are 0, 1, 2, and 3 respectively. Such dimensions are called the Euclidian dimensions. Likewise, fractal patterns have fractal dimensions. As a parameter of characterization of a complex degree of natural phenomena, a fractal dimension is used to describe the surface topography of a fracture and to give a quantitative value to each pattern (Zhou *et al.*, 2014). Several methods can be adapted to calculate the fractal dimension of creeping discharges (Beroual *et al.*, 2014; Ediriweera *et al.*, 2018a). In the current study, the box-counting method was used. Researchers have used this method for purposes of analysis of surface discharges in their findings (Kebbabi & Beroual, 2005). A greater fractal dimension means a more tortuous fracture surface.

One of the common methods called box-counting had been adopted to calculate the dimension of fractal patterns in our previous studies (Kebbabi & Beroual, 2005; Ediriweera *et al.*, 2019). The same method was used in the current study and basic steps were recalled. The original image shown in Figure 4a, obtained in a creeping discharge, was converted into a binary image as shown in Figure 4b. Before the conversion process, all the important traces of the discharge were extracted using photo editing software. The camera did not depict the entire discharge, since the needle was in the centre of the image. However, the pattern in the middle has the least amount of unclear information due to the point electrode, when compared to the visible area as the pattern was recorded to its full extent.



(a) Original image (b) Binary image

Figure 4: Application of the box-counting method



(a) Square of side l =32 pixels (b) Square of side length l = 64 pixels

Figure 5: Application of the box-counting method

However, with the glow around the tip of the point electrode and thick streamers in the centre, individual streamers cannot be distinguished because of the noise captured by the camera. So, information in the middle was ignored in any case, and the box-counting algorithm is applied considering that the morphological variation of the pattern has the same self-similarity throughout the pattern. Fractals reflect the self-similarity of the morphological variation of the pattern. Therefore self-similarity can be regarded as implying that at all scales or in all areas of the pattern, it should show the same relative variation of morphology or the fractal dimension. Then a code was applied to the binary image which generates a grid of square boxes over the image.

While changing the side length of the boxes at each step, the number of boxes having any parts of the discharge pattern was counted. Figures 5a and 5b show the binary images covered by squares of side l = 32 pixels and l = 64 pixels, respectively. The slope of the log-log plot of the number of boxes vs. box size gives the fractal dimension as shown in Figure 6.

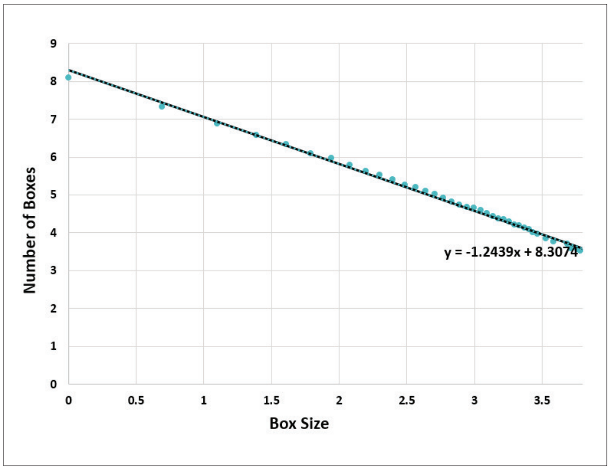


Figure 6: Total number of boxes N versus the side length l of the boxes obtained from the analysis of an example of a discharge

Discharge length

When it comes to creeping discharges, the discharge may have several mainstreamers starting from its starting point. There also can be side branches starting from mainstreamers. Therefore, each streamer may have different total discharge lengths. What is defined as the final discharge length is the maximum discharge length out of all the streamers of the discharge pattern, and the voltage required to get a streamer of a particular length is assessed. In the study, the camera setup provides the images of the propagating pattern continuously and an algorithm was used to identify the image with maximum extension to measure the final discharge length. It should be noted that each discharge length value presented in the study is an average value measurement taken from four solid dielectric samples

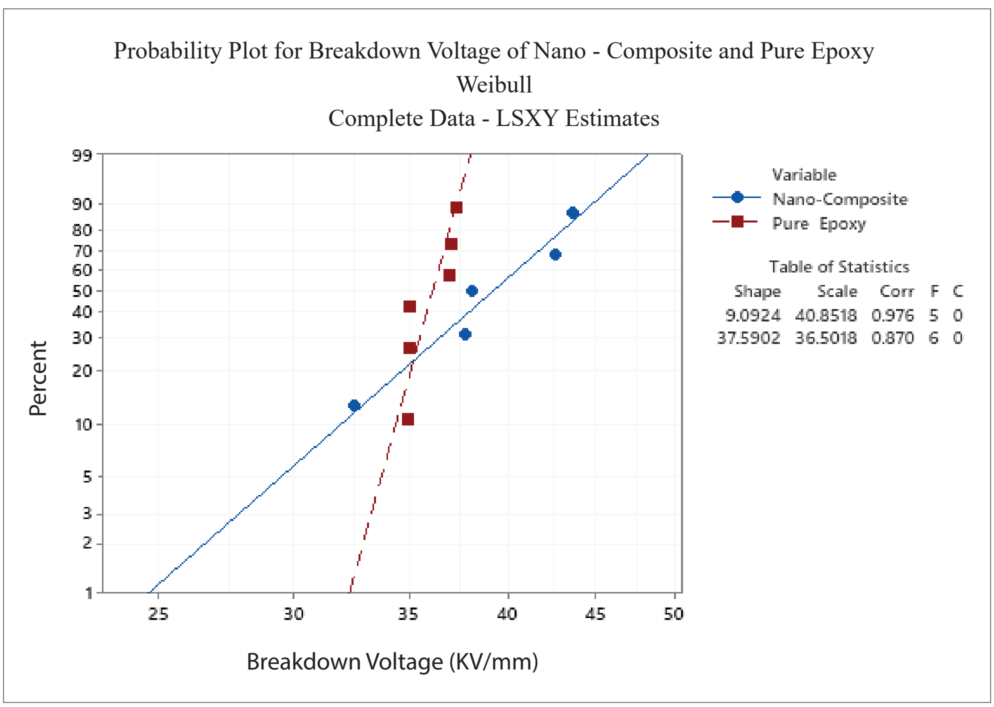


Figure 7: Probability plot for breakdown strength of nano - composite and pure epoxy

Table 1: Parameters of Weibull distribution

Material	Shape parameter	Scale parameter (kV/mm)	Mean (kV/mm)	Skewness
Pure epoxy	40.061	36.551	36.046	0.03
Nano-composite	12.034	40.667	38.975	-0.53

RESULTS AND DISCUSSION

The maximum likelihood estimator is used to estimate the parameters of the distribution of breakdown voltages. Figure 7 shows the probability plot for the breakdown voltages of the material samples.

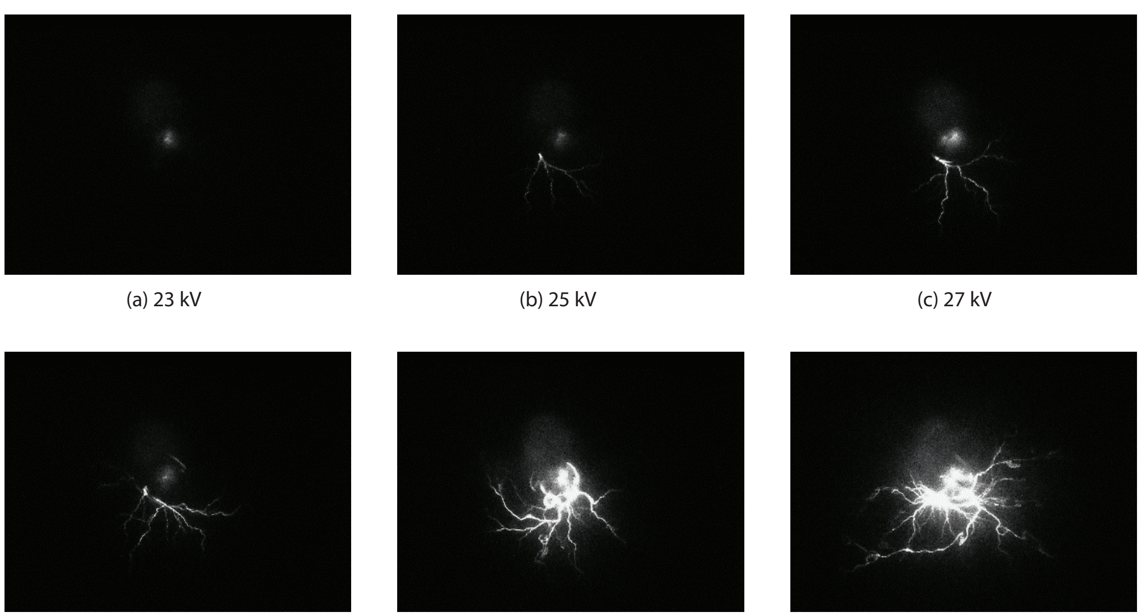
The shape, scale, mean, and skewness of the distribution are listed in Table 1. The shape parameters are 40 and 12 for pure epoxy and nanocomposite respectively. The shape parameter gives an idea about the failure. A shape parameter lower than one means early failure and when it equal one, then it represents a constant failure rate after commissioning (Gupta & Das, 2017). The skewness of the nanocomposite is a little bit higher than that of epoxy material and the asymmetrical nature of the data points can be seen with non-zero screw values for both of the material samples.

The mean breakdown voltage of epoxy materials has been increased slightly by nano-particles as shown in Table 1. It accounts for around a 7% increment. The behavior of nano-fillers is somewhat different even though microparticles decrease the breakdown strength, acting as centres of charge concentration. The interfacial area of nano-particles is considerably higher and their interparticle distance is quite small. Therefore, they act as barriers to the flow of current through the composite increasing the breakdown strength.

Figure 8 shows the development of discharge patterns propagating over epoxy samples and Figure 9 on nano-composite samples. The basic characteristics of the propagating patterns are similar to the studies with patterns propagating on the solid/mineral oil interface (Kebbabi & Beroual, 2006). Discharge patterns propagating on the interfaces have curved streamers as a result of the electro-hydrodynamic motion of oil in the vicinity of the point electrode and the electric field distorted by space charges on the insulators under AC voltage.

Therefore, streamers try to follow these contours. Observation shows that the discharges propagating on epoxy/coconut oil and nano-composite/coconut oil interfaces have similar tortuous behavior, and, however, with longer discharges on a nano-composite/glass interface. The kind of the solid material can have a significant effect on the amount of surface discharge.

The most likely reasons for the promotion effect on discharges of the solid insulation materials considered would be the influence of hetero-charges, the permittivity of the material (Yi & Wang, 2015), and nanoparticles (Jang, 2017). Once the surface of a solid material is charged with space charges, it takes some time for charges to dissipate. The dissipation time depends on the characteristics of the material such as surface



(a) 23 kV (b) 25 kV (c) 27 kV

(d) 29 kV (e) 31 kV (f) 33 kV

Figure 8: Stages of creeping discharge development on an epoxy surface

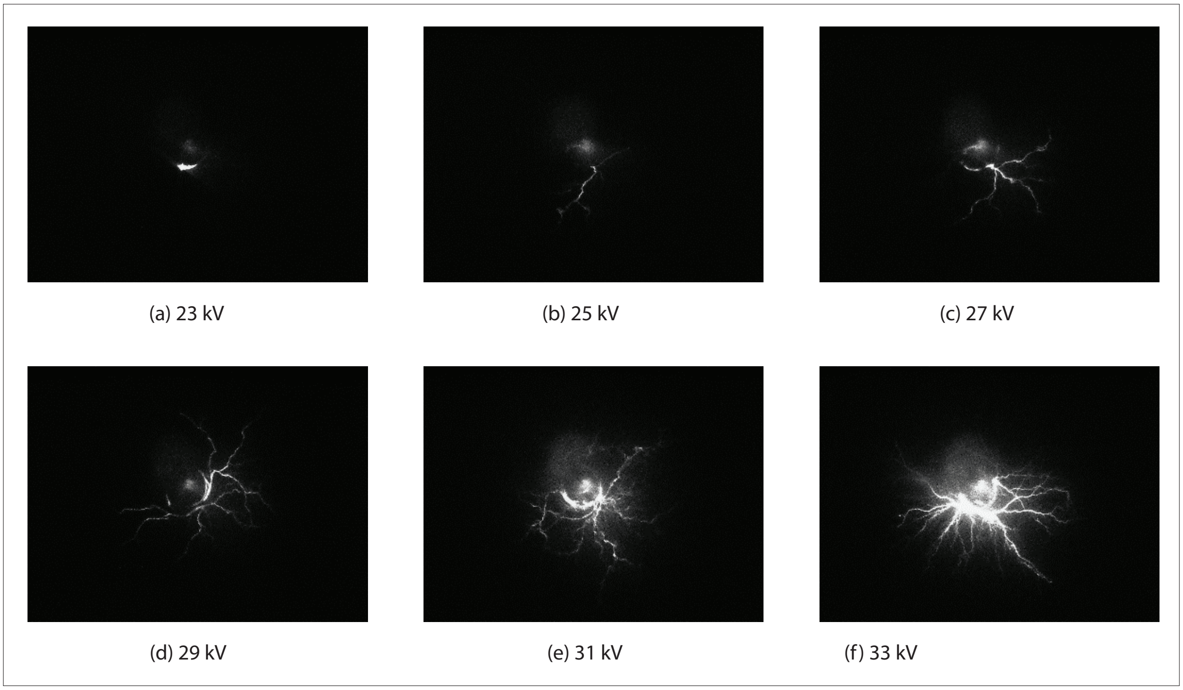


Figure 9: Stages of creeping discharge development on a nano-composite surface.

conductivity. The effect of both homo-space charges and hetero-space charges, which promote the development of subsequent discharge, should be considered in this scenario, because deposited space charges can last until the negative cycle of the supply voltage (Yi, 2012). The capacitance of the solid insulation affects the discharge inception voltage (Jang *et al.*, 2016). When a flat solid material sample is modeled as a capacitor, its value depends on the permittivity of the material. The increase in the capacitance of the solid material sample enhances the capacitive charges. Also, the permittivity mismatch between the liquid and solid affects the electric field at the tip of the point electrode, which has a direct impact on the ionization probability due to the added effect of change in total polarizability and interfacial polarization, which in turn will affect the propagation of the creeping discharge. The enhanced electric field and charges make the discharge propagate more on the surface of the material. Therefore, as the relative permittivity of the solid material increases, it increases the tendency of creeping discharges to propagate. The dielectric constants of pure epoxy and nano-composite samples are 4.89 and 5.25, respectively. The parallel plate method is used to measure the relative permittivity of the material samples at 100 Hz using a LCR meter, as in previous studies (Mandric *et al.*, 2018; Karunarathna *et al.*, 2019). Therefore, the promotional effect on the nano-composite /glass interface can be expected.

The final discharge length holds the quasi-linearity with the voltage similar to the previous experiments with mineral oil, as shown in Figure 10. It increases with the dielectric constant of the solid dielectric material. For a given value of the voltage, discharge lengths are higher with nano-composite than with pure epoxy samples. The capacitive effect is more significant over the pattern propagation on the nano-composite material samples immersed in coconut oil.

Nanoparticles have increased the final discharge length corresponding to the nano-composite samples by 4% to 17%, while having a 7.3 % increment in the dielectric constant. So there is a positive correlation between the dielectric constant and corresponding discharge length curves, with coconut oil being the dielectric liquid. Therefore, more damage on the nano-epoxy solid insulator can be expected due to the traces of the discharges.

Table 2: Fractal dimension of creeping discharges

	Epoxy	**Nano-composite**
Fractal dimension	1.26	1.26

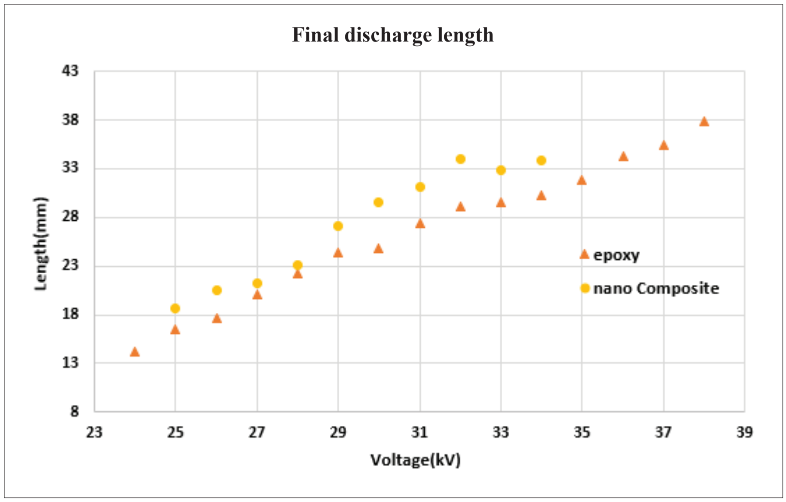


Figure 10: Variation of the final discharge length of the creeping discharges

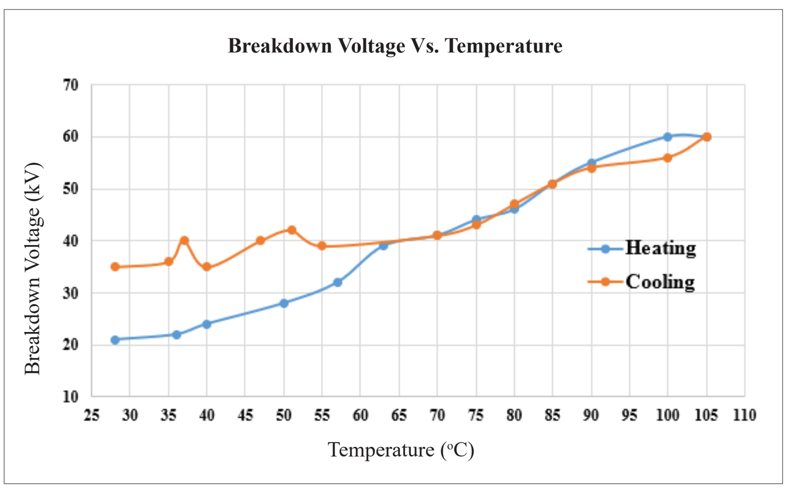


Figure 11: Variation of the breakdown voltage of coconut oil with the temperature.

Fractal dimension is more related to the amount of the divergence of the streamers and branches of a discharge pattern into smaller ones. Previous studies have shown that when the relative permittivity increases, dimension increases (Beroual *et al*., 2014). However, according to Table. 2 it can be seen that the nanoparticles considered do not have a significant effect on the amount of ramification on the epoxy/coconut oil interface, as the fractal dimension of patterns propagating on nanocomposite and epoxy material samples have the same values. Therefore, the same amount of tortuousness is found in both cases.

According to previous studies (Abeysundara *et al*., 2001; Matharage *et al*., 2013), moisture absorption can reduce the breakdown characteristics of coconut oil. Therefore, a domestic heater was used to heat the oil samples, and at different temperature values, samples are taken and the dielectric breakdown voltage is measured. After the oil is heated up to 100 ^{0}C, it was then allowed to cool down back to room temperature. While the sample was cooling, its dielectric breakdown voltage was measured at several intermediate temperatures. An improvement of dielectric strength was observed after heating the oil sample to over 100°C.

Figure 11 shows that the breakdown voltage increases gradually up to 60kV when the oil is heated. The water content in the sample affects the dielectric strength of the oil. Heating evaporates water in the oil sample. When the temperature of the sample is near to the boiling point of water (100°C) the water content is very low, hence it shows a higher dielectric strength. When the oil sample is kept open to the air and allowed to cool back, a reduction in dielectric strength was observed as a result of moisture absorption as shown in Figure 11. Therefore, poor dielectric properties can affect the discharge propagation and hence the accuracy of the results. Therefore, the condition of the dielectric liquid on the creeping discharge propagation is an under-researched topic that requires further investigation.

CONCLUSION

This paper presented a study of creeping discharge propagation over epoxy/coconut oil and nanocomposite/coconut oil insulation interfaces. Experiments were carried out with a point plane electrode arrangement and an image recorder in order to investigate creeping discharges along surfaces of pure epoxy and nano-composite epoxy samples under an AC divergent field. Results on discharge length, breakdown strength, and fractal dimension have shown that the propagation of creeping discharges depends on the properties of the solid insulator such as dielectric constant and properties of fillers.

Silicon dioxide nanoparticles with 1% concentration were used to increase the dielectric properties of the epoxy material. According to the experimental results, it was evident that it increases the dielectric breakdown voltage of epoxy by 7%. The relative permittivity of the nanocomposite was higher than that of pure epoxy. Therefore, further studies should be carried out with different filler sizes to increase the dielectric properties, especially creeping discharge performance significantly. It was shown that there is a positive correlation between the dielectric constant and corresponding discharge length curves, with coconut oil as the dielectric liquid. Final discharge length increases quasi-linearly with the applied voltage even on materials immersed in coconut oil. According to the discharge length results corresponding to the nano-composite material, it can be concluded that even though nanoparticles can increase the dielectric strength of the epoxy insulators, the capacitive effect is more significant in discharge propagation, and final discharge length has been increased by around 12 %. However, the considered nanoparticle concentration of 1% does not have a significant effect on the amount of ramification of the creeping discharges, because the fractal dimension of 1.26 was observed in creeping discharges propagating on both nanocomposite and epoxy material samples. Overall, it can be concluded that the concentration and the particle size of silicon dioxide can affect the nano dielectric properties of nano-epoxy composite, such as an increase in breakdown strength and dielectric constant by 7%. A nanocomposite with high breakdown strength is not always satisfactory when it is immersed in coconut oil as the electric field at the tip of the point electrode depends on the permittivity mismatch. The research had shown the fabricated material samples enhance the breakdown strength by 7 % while increasing the possibility of damage to the solid insulator due to creeping discharges by 4% to 17%. Therefore, the materials should be fabricated to minimize the creeping discharge propagation while keeping the dielectric properties within an acceptable level.

Conflict of interest statement

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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