J.Natn.Sci.Foundation Sri Lanka 2022 50 (4): 725 - 732
DOI: http://dx.doi.org/10.4038/jnsfsr.v50i4.10641

RESEARCH ARTICLE

High voltage engineering

Investigation of oil level and type of solid insulator on creeping discharges propagating under an AC electric field

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Submitted: 8 August 2021; Revised: 8 March 2022; Accepted: 25 March 2022

Abstract: This paper presents a study on the use of different solid insulators and oil volumes inside oil-filled high voltage equipment to minimize the effect of damage that occurs due to creeping discharge activity. A point-plane electrode arrangement-based test apparatus, energized by a high voltage supply, is used for analyzing the propagation of creeping discharges over solid/coconut oil interfaces using visual observation. In particular, the effect of oil level and the effect of the kind of solid insulators, such as glass and acrylic, are analyzed incorporating the discharge length associated with pattern propagation. The result shows that the glass and acrylic insulators do not have a significant effect on the discharge length when they are immersed in coconut oil even if the breakdown voltage of acrylic is higher than that of glass by 28%. The results also show that when the oil level inside the test cell increases, the amount of ramification and propagation of streamers decreases, reducing the discharge length. The fall of the coconut oil level under electric field-generated electrodynamics motion inside the oil-filled high voltage equipment can create an opposition force on the discharge propagation. However, such a phenomenon can initiate discharge propagation at low voltage values.

Keywords: Coconut oil, discharge length, electric field, electrodynamic motion, propagation, Oil Height,

INTRODUCTION

An efficient and reliable electrical power supply plays an important role in the quality of electricity. Failure of high voltage equipment leads to catastrophic events, resulting in economic losses and injury to humans. Therefore, power utilities are putting their maximum effort to maintain high voltage assets with a reliable operation (Beroual & Boubakeur, 1991; Kebbabi & Beroual, 2006; Ediriweera *et al.*, 2018). Solid/liquid or solid/gas interfaces can be seen in oil or gas-filled high voltage equipment such as power transformers, capacitors, bushings, and circuit breakers. These composite insulation systems are subjected to different stresses and when the tangential electric field at the interface exceeds a threshold value, discharges can be initiated and propagated over the interface (Douar *et al.*, 2015). These discharges are commonly called creeping discharges. Due to the frequent occurrence of creeping discharges, the insulation system can undergo irrecoverable damage, and finally, this may lead to flashover (Douar *et al.*, 2015).

Conventionally, petroleum-based mineral oil has been used inside oil-filled high voltage apparatus due to its better electrical and thermal properties. However, recently attention has been paid to the useability of natural ester oils such as coconut oil, soybean oil, and sunflower oil, due to several disadvantages associated with mineral oil such as future scarcity and poor biodegradability. Past research has concluded that treated ester oils can be used as an alternative oil, with improved dielectric properties (Abeysundara *et al.*, 2001; Lucas *et al.*, 2002). Coconut oil is a commercially available vegetable oil, used for

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cooking purposes in countries such as Sri Lanka, India, and Malaysia. Studies have shown that the physical, chemical, thermal, and dielectric properties of the oil have acceptable levels for it to be used as a dielectric liquid. Compared to other natural esters, coconut oil is rich in saturated fatty acids (around 90%), which increases its melting point and conductivity levels (Matharage *et al*., 2013). A lot of work has recently been devoted to the creeping discharges propagating on solid insulators immersed in mineral oil and different kinds of esters (Kebbabi & Beroual, 2006; Sitorus *et al.*, 2015; Zhou *et al.*, 2016;). Therefore, it is worthwhile to study creeping discharge formation on insulators immersed in coconut oil.

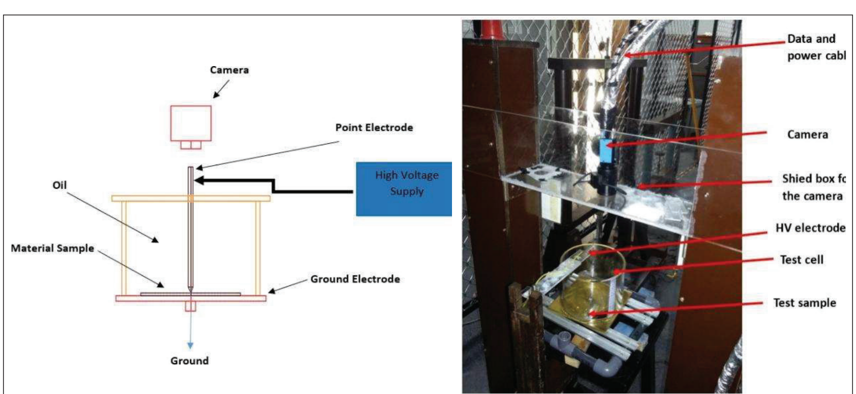
On the other hand, engineers have carried out many studies to understand the creeping discharge propagation mechanism to reduce the likelihood of a breakdown. Most of the work has focused on the formation of streamers which are low-density conductive gaseous channels that are formed in the liquid closer to the interface (FitzPatrick *et al.*, 1990; Lesaint *et al.*, 1988; Gournay & Lesaint, 1994). In our previous studies, the effect of the pressure generated by the mass of the coconut oil on the gaseous streamers and the fractal dimension of the creeping discharges have been analyzed (Ediriweera *et al.*, 2019). The electrohydrodynamic motion of the coconut oil has limited the discharge prorogation reducing the possibility of flashover. Thus, the effect of oil levels on the variation of discharge length should be studied to reduce the effect on the creeping discharge formation.

The main objective of this paper is to analyse experimental creeping discharges propagating over glass and acrylic insulating materials immersed in coconut oil, using a test apparatus. The experiential model, which is based on a point-plane electrode system, is used to carry out the experimental tests. The effect of the kind of dielectric material on the discharge prorogation, while incorporating the structure and discharge length of the patterns and the effect of oil level on creeping discharge propagation, incorporating the discharge length, are analysed.

MATERIALS AND METHODS

Experimental test setup

Figure 1 shows the schematic view of the test setup, similar to what has been used in previous studies (Ediriweera *et al*., 2020). The test cell basically consists of a cylindrical core made of clear acrylic and has a point-plane electrode arrangement inside it. The gap between the point electrode and the plane electrode can be varied and thin flat insulating material samples can be inserted for testing purposes. The samples are immersed in insulating liquid by filling the test cell with coconut oil. A CCD camera, with a high frame rate 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. If the flashover or the complete dielectric breakdown is observed, the test cell is refilled with new oil to maintain the condition of the oil.



(a)2D Model of the test setup (b) Hardware set up

Figure 1: Experimental test setup

Experimental procedure

Flat square-shaped solid material samples of a side length of 9 cm and a thickness of 3 mm are used for the study. Two kinds of pre-prepared solid materials, namely glass and acrylic are used to analyze the creeping discharge propagation over the solid/coconut oil interface. In particular, the effect of kind of the solid dielectric and oil level on the solid material sample on discharge propagation are analysed using the test setup. Commercially available copra type coconut oil is selected as the liquid dielectric medium. More details on the extraction method and chemical composition of copra-type coconut oil can be found in earlier research (Matharage *et al.*, 2013). Table 1 shows the dielectric breakdown voltage and dielectric constant of material samples. The parallel plate method is used to measure the relative permittivity of the solid material samples at 100 Hz using an LCR meter as in previous studies (Mandric *et al*., 2018; Karunarathna *et al.*, 2019). The breakdown voltages of the solid samples and coconut oil were found according to the ASTM D-149 standard and IEC 60156 standard, respectively.

The influence of hydrostatic pressure on creeping discharges has been studied (Kebbabi & Beroual, 2003; Beroual & Kebbabi, 2008; Matharage *et al.*, 2013; Beroual & Khaled, 2018), and according to these findings, low-density gaseous channels are affected by the hydrostatic pressure. In the current study, the level of copra-type coconut oil inside the test cell is changed in order to analyse the effect of the oil level over the solid sample on creeping discharge propagation, and glass material samples are used. The heights of the oil levels inside the test cell, and the corresponding calculated volumes are listed in Table 2.

Table 1: Dielectric properties of material samples

	Acrylic	Glass	Coconut oil
Breakdown voltage (kV/mm)	41	32	15
Dielectric constant	4.5	5	2.9

Table 2: Considered oil levels

	Level 1	Level 2	Level 3	Level 4
Oil height (mm)	10	20	35	50
Oil volume (mL)	154	307	548	769

Discharge length

Creeping discharges may have several mainstreamers starting from their starting point, and there may be side branches starting from mainstreamers. Discharge morphology depends on different factors such as electric field distribution. As an example, with mineral oils, negative streamers tend to propagate radially while positive streamers are more concentrated around their initiation point with more ramified branches having different discharge lengths (Kebbabi & Beroual, 2006). Therefore, each streamer may have different total discharge lengths. In this paper, two terms, final discharge length and radial discharge length, are defined for the purpose of analysis of the creeping discharges. What is defined as the final discharge length in this paper is the maximum discharge length of a particular streamer out of all the streamers that the pattern has, and it assesses the voltage required to get a discharge of a particular length. The other term is the radial discharge length which measures the maximum radial extension the pattern makes from its initiating point.

RESULTS AND DISCUSSION

Type of solid dielectric material

Creeping discharges under an alternating voltage do not always propagate radially with this point plane arrangement. An electric field distorted by space charges on the insulators is considered to be the main reason for such an orientation (Beroual *et al*., 2011). Creeping discharge characteristics such as light intensity, number of mainstreamers and branches, and amount of ramification depend on the type of solid material. Figure 2 and Figure 3 show the development of discharge patterns propagating over acrylic and glass samples respectively. The size of the discharge patterns increases when the applied voltage is increased. The thickness and the brightness of the channels reduce along with the streamers.

The shape of the discharges on the glass/oil interface is different from what was observed on the acrylic/ oil interface. It accounts for luminosity, the number of mainstreamers, the amount of ramification, and shape. On this material, it is noted that the patterns have more ramified branches and luminous points. Previous studies have shown that negative discharges propagating under vegetable oils have the same characteristics as what was observed on the glass/coconut oil interface (Dang *et al*., 2012). Therefore, patterns propagating over a glass/oil interface show the characteristics of negative streamers rather than positive ones. On the other hand, the brightness of the streamers has no high dependency on the applied voltage, compared to that on the acrylic/oil interface.

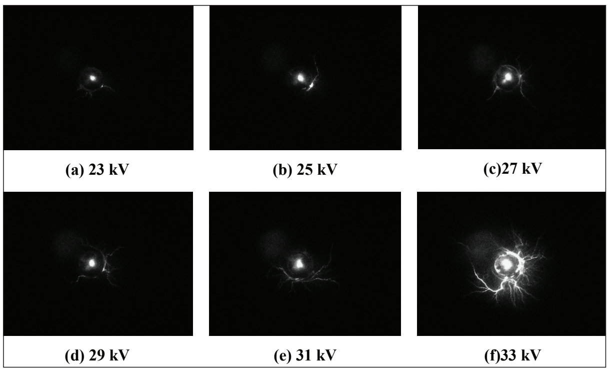


Figure 2: Development of creeping discharges on acrylic material samples

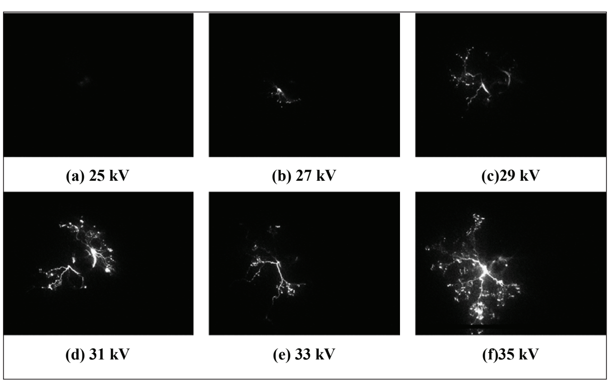


Figure 3: Development of creeping discharges on glass material samples

As the voltage increases, the brightness of the streamers propagating on both interfaces increases. The luminous points on the glass surface make the streamers less prominent so that they cannot be identified separately or defined very well just by the naked eye. Other than that, discharge patterns propagating over the glass surface tend to propagate radially compared to that on the acrylic surface, where curved streamers can be observed, as a result of the electro-hydrodynamic motion of oil in the vicinity of the point electrode. Therefore, streamers try to follow these contours. Even though the light emitted by the patterns propagating over the acrylic/oil interface is not intense at the initial stage of development compared to that of glass/oil, the amount of ionization on the glass interface increases as the voltage increases. The contours closer to the tip of the point electrode have caused the space charges to concentrate more around it, resulting in a more intensive glow around the tip of the point electrode.

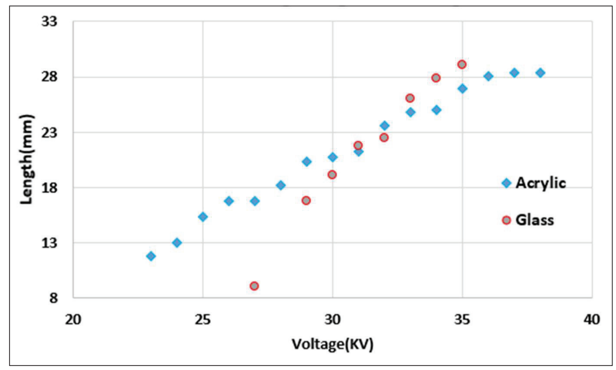


Figure 4: Variation of the final discharge length of the creeping discharges propagating over the different solid samples with the applied AC voltage

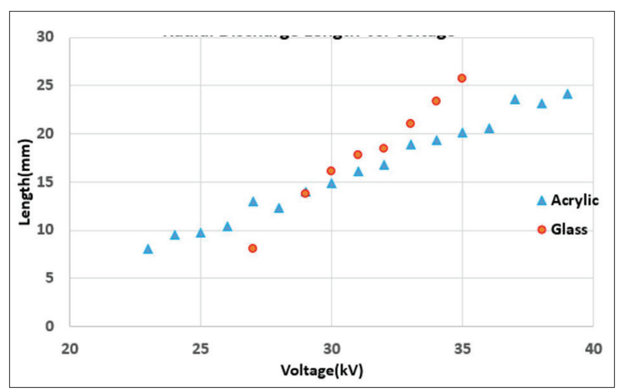


Figure 5: Variation of the radial discharge length of the creeping discharges

The final discharge length and radial discharge length increase quasi-linearly with the voltage, as shown in Figure 4 and Figure 5, respectively. It is to be noted that all the discharge length values listed in the paper are the average of four experiments conducted under the same conditions. With a high-speed CCD camera, it is possible to take the discharge patterns at their maximum extension. Even if at low voltage values, the lengths corresponding to the acrylic/oil interface is slightly higher than that of the glass/oil interface, when the voltage increases, the discharge length of patterns on glass/oil exceed that on the acrylic/oil interface. However, the discharge length cannot exactly define which interface promotes more discharges. Further, the capacitive effect of the slightly different permittivity values of the solid material samples, as shown in Table 1, on discharge prorogation, is also negligible.

Effect of oil level

Figures 6 – 8 show the development of creeping discharge patterns on the glass surface at applied voltages of 18 kV, 23 kV, and 26 kV respectively, for the different oil levels shown in Table 2.

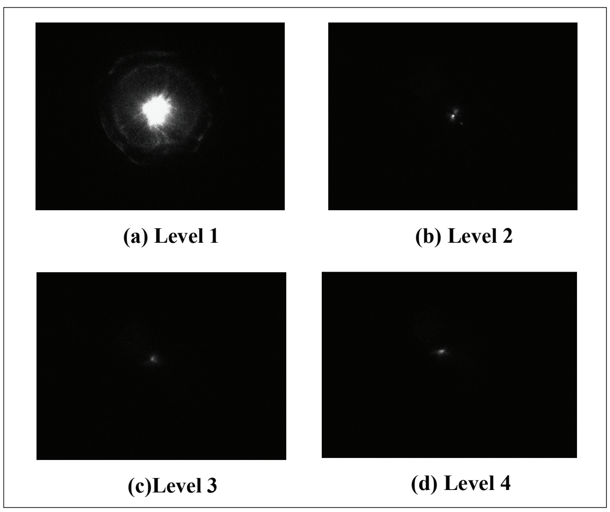


Figure 6: Oil level on creeping discharge development under 18 kV

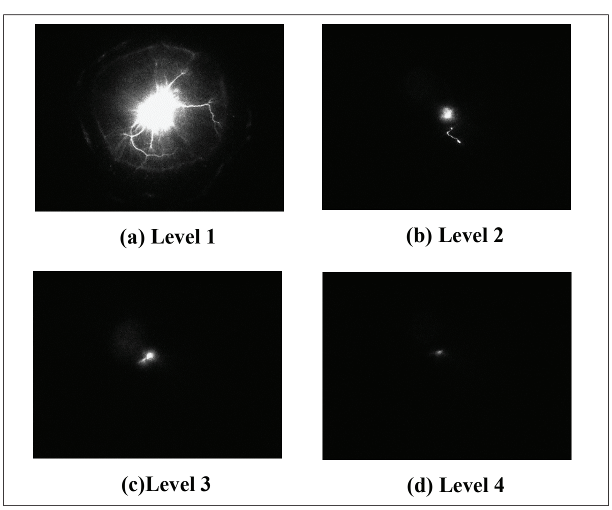


Figure 7: Oil level on creeping discharge development under 23 kV

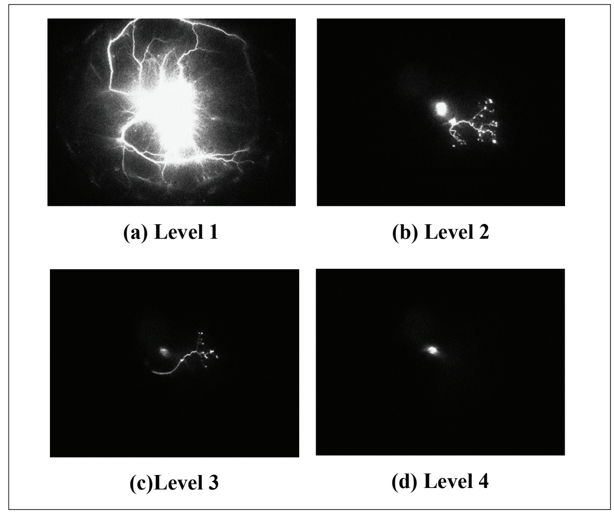


Figure 8: Oil level on creeping discharge development under 26 kV

When the oil level increases, the size of the pattern, the number of branches, and emitted light decrease due to the reduction in the tangential electric field at the tip of the point electrode. At low coconut oil levels, electrodynamic motion becomes more prominent and affects the pattern prorogation and its characteristics. More details on the electrodynamic motion associated with coconut oil and the effect of the tangential electric field at the tip of the point electrode on the pattern propagation can be found in Ediriweera *et al.* (2019).

When the oil level is increased, the final and radial discharge lengths of creeping discharges are reduced, as shown in Figure 9 and Figure 10 respectively, and the discharge length curves show a quasi-linear behaviour with the applied voltage irrespective of the oil level when the solid samples are immersed in copra-type coconut oil. Such a variation on the discharge length was observed for different hydrostatic pressure values by Beroual *et al.* in 2002, 2003, and in 2008 under AC, DC, and impulse voltages with solid samples immersed in petroleum-based mineral oil (Kebbabi & Beroual, 2003; Beroual & Kebbabi, 2008; Beroual & Khaled, 2018).

The slopes of discharge length curves and the associated R-square values, considering the quasi-linearity of discharge length curves, are listed in Tables 3 and 4. With the R square value of each curve close to 1, their quasi- linearity is confirmed. The rate of rise of discharge length with applied voltage depends on the coconut oil level. The rate of rise of each curve becomes weaker as the oil level increases, except the curve corresponding to level 1. The rate of rise of the curves corresponding to level 1 is lower than that corresponding to level 2, because the fall of the oil level at low oil levels due to electric field generated electrodynamics motion opposes the pattern propagation, and it had become more prominent at oil level 1.

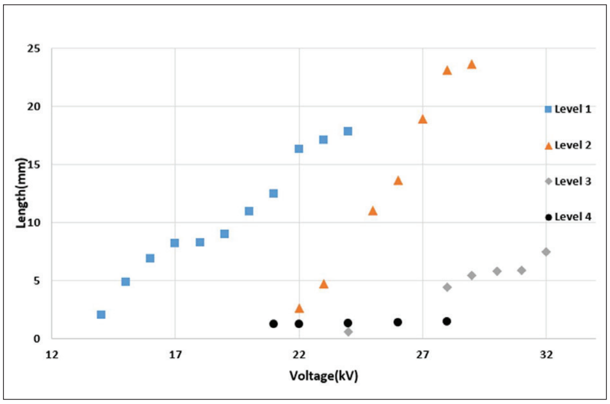


Figure 9: Variation of the final discharge length of the creeping discharges propagating over the solid samples versus the applied AC voltage for different oil levels.

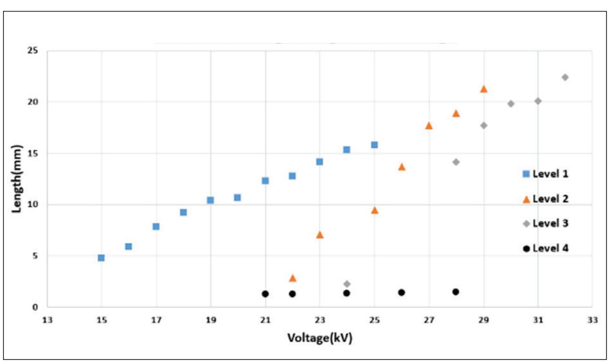


Figure 10: Variation of the radial discharge length of the creeping discharges propagating over the solid samples versus the applied AC voltage for different oil levels.

Table 3: Information of final discharge length curves

	Final discharge length with oil level			
	Level 1	Level 2	Level 3	Level 4
Slope	1.523	3.25	0.8098	0.033
R square value	0.9653	0.9825	0.9653	0.9717

Table 4: Information of radial discharge length curves

	Radial Discharge Length with oil level			
	Level 1	Level 2	Level 3	Level 4
Slope	1.1021	2.6196	2.5475	0.033
R square value	0.9856	0.9771	0.9679	0.9717

CONCLUSION

This paper presented a study of creeping discharge propagation over solid/coconut oil insulation interfaces. Experiments were carried out with a point plane electrode arrangement and a high-speed image recorder in order to investigate creeping discharges along surfaces of glass and acrylic samples immersed in coconut oil with varying oil levels under an AC divergent field. Pattern propagating on the glass surface can be more characterized by luminous, ramified streamers. Glass and acrylic material samples do not have a significant effect on the discharge length when they are immersed in coconut oil even though the breakdown voltage of acrylic is higher than that of glass by 28%. The study has shown that the final discharge length and radial discharge length increase quasi-linearly with the applied voltage even on materials immersed in coconut oil. It has been observed that size, brightness, and discharge length reduce as the oil level increases. The rate of change of the discharge length with the applied voltage decreases when the oil height over the solid dielectric increases. Electrodynamic motion has been shown to be a key factor in deciding the characteristics of discharge propagation along with the tangential electric field. Decrease in oil level due to the electric field generated electrodynamics motion can create an opposing force on the discharge prorogation, reducing the possibility of flashover as the discharges try to follow the contours created by the oil. However, discharges can get initiated at low voltage values with low oil levels. In industrial applications, the insulation systems are normally subjected to high stress levels. Thus, it can be concluded that the volume or the height of oil inside coconut oil filled high voltage equipment should be maintained to minimize the discharge initiation.

Conflict of 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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