Finite Element Modelling of Electric Field and Voltage Distribution on a Silicone Insulating Surface Covered with Water Droplets

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ABSTRACT

The main objective of this work is to study the behaviour of water droplets placed on a silicone surface in the presence of an electric field. We observed the effect of the water droplets on the distribution of the electric field and the voltage generated. A geometric model of the insulator was designed and studied using the finite element method as implemented in COMSOL Multiphysics. The results of the simulations showed that numerous parameters, such as the volume, number, and conductivity of the droplets, as well as their position with respect to the electrodes, affected the potential and electric field distribution. Furthermore, the simulations show that discharges caused by water droplets on the surface of polymeric insulators affect the long-term reliability of the component by lowering the surface hydrophobicity, boosting surface discharges.

Index Terms — **Electric field, high voltage, silicone insulating, water droplets, COMSOL Multiphysics, FEM.**

1 INTRODUCTION

HIGH voltage lines are an important component of electric power transportation networks because of the role they play in conveying energy from power plants to consumption centres through distances exceeding thousands of kilometres. These electric lines also include elements called insulators, which are factors of significant importance because of their reliability in transporting energy. These insulators must support conductors, insulate them from pylons, and maintain a sufficient air gap between the cable and the pylon, such that electric current does not pass through the pylon.

In the last 25 years, polymeric materials have emerged as a viable option for outdoor insulation. Insulators of this kind are increasingly used in outdoor applications because of their improved characteristics and efficiency over those of porcelain and glass. They also have better contamination performance because of their hydrophobic surfaces [1-2].

In this context, a number of investigations have been conducted in order to show the effects of coating a hydrophobic silicone surface with water droplets, on the performance of an insulator [3-12].

Of these investigations, the results of Karady's [5] experimental inquiry offer a good comprehension of phenomena leading to flashover. This inquiry showed that the flashover mechanism of a silicone surface is different to that of a porcelain insulator, and that in polluted conditions, the flashover voltage of a silicone surface is superior to that of a porcelain insulator.

Krivda and Birtwhistle [13] note that partial discharges on the surface of polymeric insulators are considered one of the aging mechanisms responsible for the failure of an insulator. According to tests dealing with this phenomenon, Karoulidas et al showed in [14] that droplet volume and conductivity are conditions that affect the value and the duration of breakdown voltage.

Mizuno et al [15] also performed tests on a silicone rubber specimen, and found that the breakdown voltage of a sample filled with droplets of contaminated water becomes inferior just after contamination. They noted that the duration and magnitude of the breakdown voltage depends on the duration of contamination. They also discovered that after five days of contamination, the breakdown voltage was almost the same as that obtained with clean silicone rubber.

Jianwu et al [16] carried out experimental tests and simulations with water droplets of different volumes to observe their effect on electrical distribution. They note that

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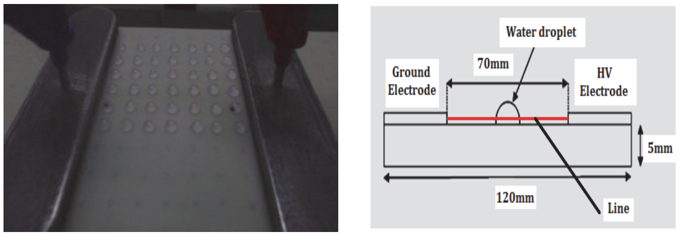
with the increase in the volume of the droplets, the electric field also increases, and a corona discharge is produced at the triple point (the position where the water droplets, the insulating surface, and air coincide). As a result, the electric potential is lower at the location of the electric voltage drop.

A triple junction is essentially a contact between three materials: vacuum, dielectric and metal. The electric field behaviour at the zero-angle contact point (triple junction) has been extensively studied. High intensity electric fields have been observed at the vicinity of metal and vacuum contacts and can be magnified significantly with increasing the dielectric constant of the dielectric solid [17–18]. Research has shown that this field enhancement occurs due to the presence of dielectrics at the interface, creating a region of triple junctions [19].

This work presents the results of 3D and 2D simulations of the behaviour of droplets in an electric field, performed in the COMSOL Multiphysics 5.0 software package.

2 METHODOLOGY OF RESEARCH

Tests were conducted with a high alternating voltage, using the experimental model presented in Figure 1. The model consisted of a rectangular silicone rubber sheet, 12 cm in length, 8 cm in width, and 5 mm in thickness. Iron electrodes arranged in a plane–plane configuration were used in this system. The electrodes had round edges, with a parallelepiped form, 1 cm in thickness, 2 cm in width, and 8 cm in length. An adjustable pipette was used to distribute water drops with a defined volume of 45 µl, and a conductivity of 180 µS/cm, on the surface of the sample.



a) **b)**

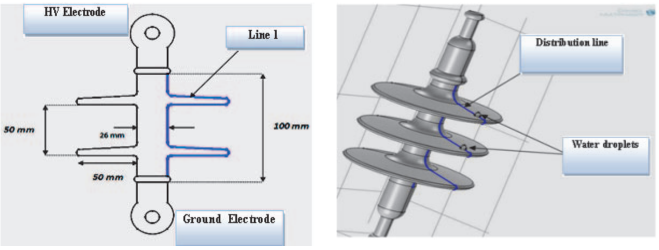
Figure 1. Electrodes arranged in a plane–plane configuration. a) Photograph of electrodes. b) Diagram of electrodes.

There is a risk of thermal energy radiating in the area of the electrode, created by electric flashover, because of the temporary degradation of the surface properties of silicone rubber. Samples were allowed to regenerate for 24 h between successive tests to enable the recovery of their surface properties [20].

Changes in the shapes of water droplets were visualized using a fast camera with a variable shutter speed (Auto mode: 1/4 s to 1/1800 s, all other modes: 8 s to 1/1800 s). Selected pictures were used to simulate the normalized electric field on the surface of the sample in COMSOL Multiphysics.

3 SIMULATION PROCEDURES

In the simulations presented, two cases were considered: the first concerns the plane-plane electrode system (Figure 1), and the second concerns a real insulator (Figure 2).



a) 2D b) 3D

Figure 2. Models of insulator used in simulation.

3.1 EQUATIONS FOR ELECTRIC FIELD AND POTENTIAL

Our experiments aim to study the distribution of voltage on the chains of the insulators. Maxwell's equations were used to calculate the potential and electric field. Using these, the electric potential created by an electric field is written as follows:

$$\vec{E} = -\nabla V \tag{1}$$

By using Maxwell's theorem defined as:

$$\nabla E = \frac{\rho}{\varepsilon} \tag{2}$$

Where ρ is the charge density, ε is the permittivity of dielectric material ($\varepsilon = \varepsilon_0\varepsilon_r$), ε_0 is the permittivity of vacuum (8.854×10^{-12}F/m), and ε_r is the relative permittivity of the dielectric material.

The **Poisson** equation can be obtained by substituting equation (1) into (2) as

$$\nabla^2 V = -\frac{\rho}{\varepsilon} \tag{3}$$

The Laplace equation can be obtained by making the space charge, ρ = 0.

$$\nabla^2 V = 0 \tag{4}$$

In the field of electrostatics, the electrical conductivity, σ, is 0 for ideal insulating regions, and σ = ∞ for ideal conducting regions.

3.1. CHARACTERISTICS OF AN INSULATOR IN COMSOL MULTIPHYSICS

We defined the different regions of the insulator studied in COMSOL Multiphysics by introducing their respective relative permittivities, ε_r, and electrical conductivities, σ. The characteristics of the materials used in the insulator are defined in Table 1. A 36-kV voltage was applied to the high-voltage electrode.

Table 1. Summary of components in COMSOL simulation.

Material	**Relative Permittivity, ε_r**	**Conductivity, σ (S/m)**
Silicone	**3.9**	**1×10^{-12}**
Glass Fibre	4.2	1×10^{-12}
Forged steel	1	5.9×10^{7}
Water droplets	**81**	**180×10^{-6}**

4 RESULTS AND DISCUSSIONS

4.1 PLANE-PLANE SYSTEM

A. EFFECT OF WATER DROPS

The principal objective of this simulation is to determine the effect of water droplets on the distribution of the electrical field along the creepage line (labelled in Figure 1b as line) on the surface of the silicone insulator. Illustrations of the insulator were drawn in Auto-CAD (Figures 1 and 2).

Figures 3 and 5 show the results of experiments and simulations analysing the behaviour of water droplets in an electric field and their effect on electric field distribution. The simulations were performed with a varying distribution of water droplets in the interelectrode area.

Figure 3 presents a selection of pictures depicting the changes in the form of the water droplets that were distributed symmetrically in the interelectrode area.

In this part, experiments were performed in order to understand the influence of water drops under AC electric field stress to the discharge inception phenomena. His volume conductivity is maintained constant at about 180µS/cm. The obtained results are shown in Figure 3. The observations with the video camera system have shown that the flashover process from the inception to full flashover is described essentially as follows:

a) First, the group of water droplets deposited on the sample surface, before its energisation, is shown in Figure 3a.

b) In the second phase, When an electric field is applied, It is observed that the water droplets shape change along the electrode axis leading to the decrease of the ignition distance (Figures 3b and 3c) and the sharp edge of the water droplets at the triple line together with the opposite electrode form a no homogeneous field configuration which is the basic cause to have the streamer inception on the sample surface.

c) Next, for the reason that the electric-field strength near the HV electrode is strong enough, electrical discharge is established along the electrode axis

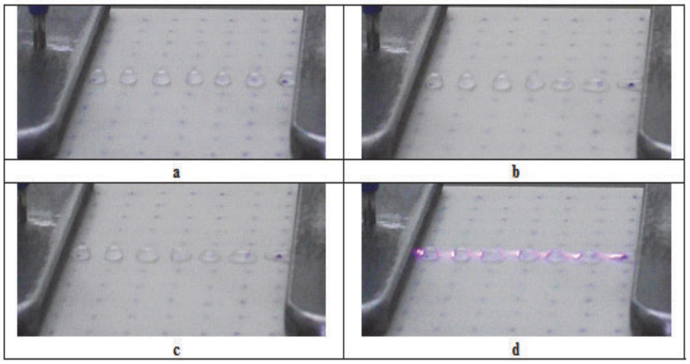


Figure 3. Behaviour of many water drops.

Figure 4 shows the distribution of the electric field intensity on the line of the leak for drops that were not deformed and for drops deformed prior to flashover. We observe a more than twofold increase in the intensity of the local electric field between the results measured with drops in their original state, and those that were deformed prior to flashover. This increase is caused by stretching and shape changes of the droplets. The maximum values of the electric field are at the extremities of the drops at the triple point because of the existence of discharges in this zone, as shown in Figure 5.

We also conclude that the increase in the electric field intensity is caused by the increase in the number of deformed water droplets on the surface.

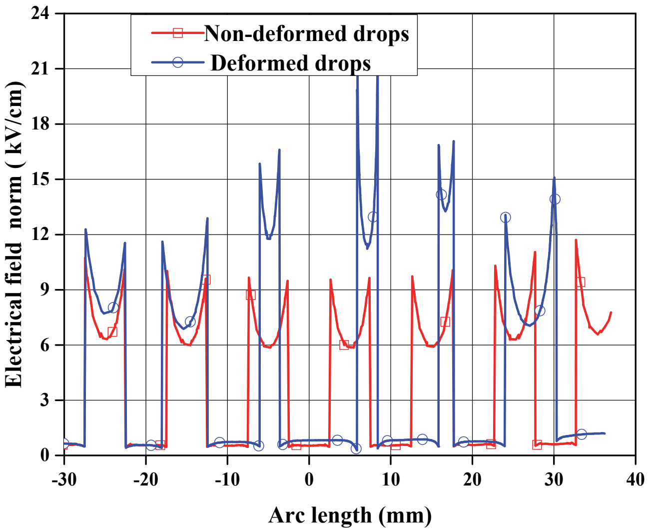


Figure 4. Electric field stresses on a line of water droplets with no deformation and on water droplets deformed prior to flashover.

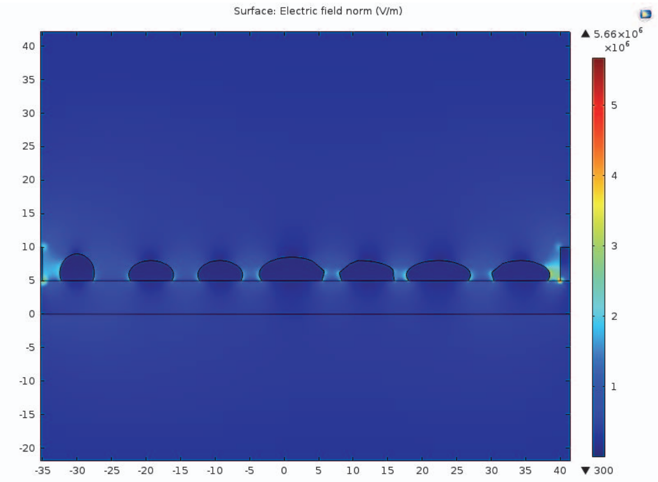


Figure 5. Simulated electric field distribution in the inter-electrode region, prior to flashover.

B. POSITION OF WATER DROPLETS WITH RESPECT TO ELECTRODES

The photographs presented in Figure 6 illustrate the various flashover phases of the insulator. The water droplets gradually increase in length because of the electric field, a distortion that increases considerably with the increase in the magnitude of the electric field. The photographs in Figure 6b show that the shape of the water droplets changed before flashover in the first case (ground side). The shape of the water droplets and their position with respect to the electrodes constitute important parameters affecting the behaviour of droplets under the influence of an electric field.

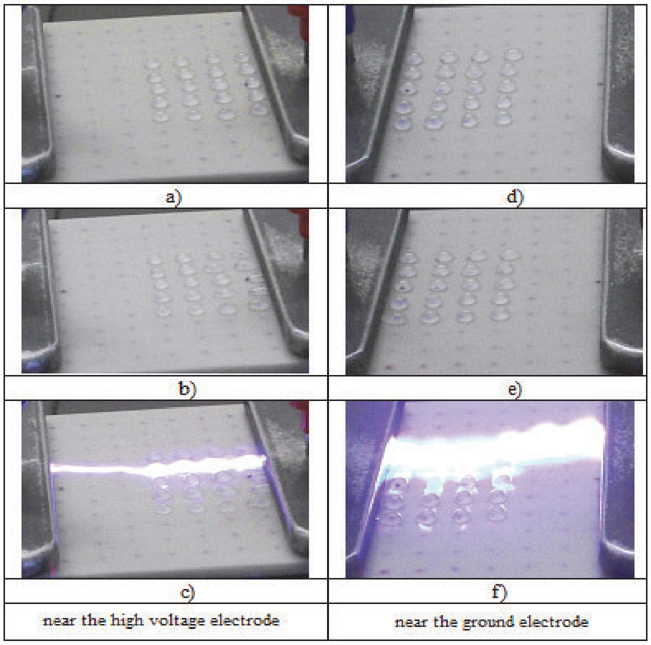


Figure 6. Response of an array of water droplets to an applied electric field.

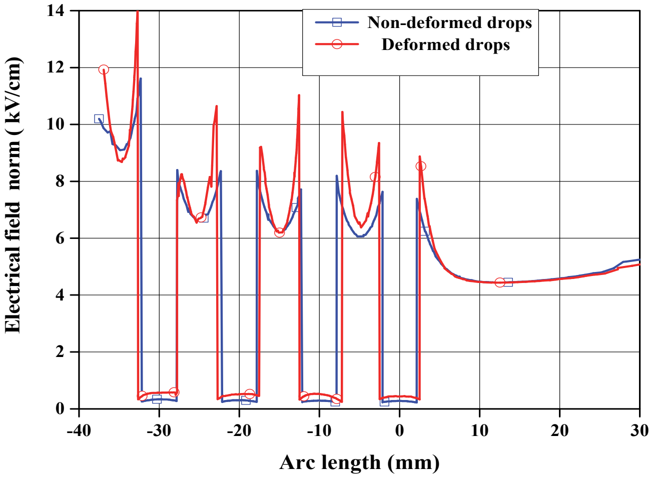
Figure 7 shows the distribution of the electric field along a hydrophobic surface coated with drops that are not deformed and drops that are deformed. Two cases were considered; in the first, the water droplets were positioned close to the ground electrode, and in the second, the water droplets were placed close to the high-voltage electrode. According to the calculated result, the following can be observed:

- The maximum electric field intensity appears at the water-gas-solid triple point. With a value of 20 kV/cm, the maximum electric field intensity is greater in the second case than in the first case. The magnitude of the electric field is weakest on the surface of the water droplet, where it is about 0.25 kV/cm.
- The increase in the local electric field, caused by droplet deformation before flashover, depends on the position of the droplets with respect to the electrodes.

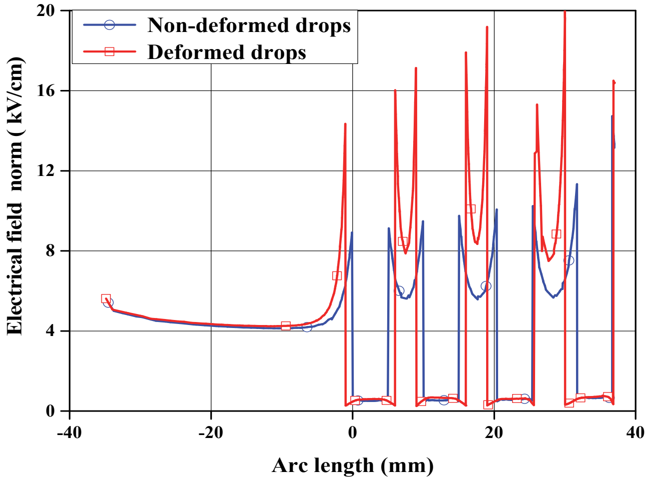
4.1. ELECTRIC FIELD AND VOLTAGE CALCULATION OF A COMPOSITE INSULATOR

A. EFFECT OF WATER DROPLET FORM ON ELECTRICAL DISTRIBUTION

To analyse the effect of droplet form on electric field distribution and voltage, we studied three cases: without droplets, with uniform droplets, and with non-uniform water droplets on the surface of the insulator. A 15 kV voltage was applied to the high-voltage electrode. Figures 8–11 illustrate the obtained results. We note a small drop in voltage in Figure 9. In comparison to the first case, the magnitude of the drop levels in both cases where there were water droplets on the surface of the insulator. The water droplets induce a low voltage because their permittivities are $\varepsilon_r = 81$. No major differences were noted between the last two cases.



a) Close to the ground electrode.



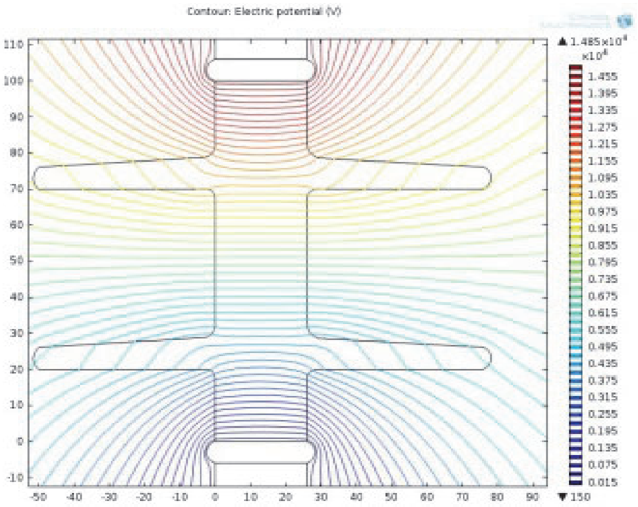
b) Near the high voltage electrode

Figure 7. Electric field stresses on an array of water droplets with no deformation and on deformed water droplets.

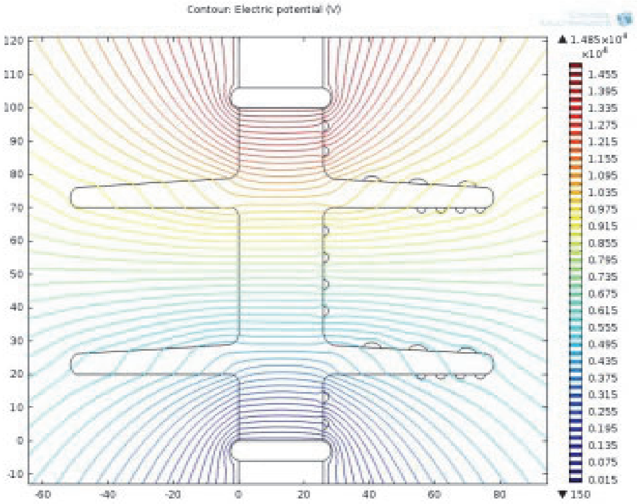
The conclusion is that the drops have no remarkable effect on the distribution of voltage along the surface of the insulator [21].

Figure 11 presents the variation in the distribution of the electrical field for the different cases considered. From these figures, we note that the shapes of the electric field differ in all three cases; the magnitude of the electric field is high in the second as well as in the third case. Non-uniform water droplets (third case) cause a larger increase to the magnitude of the electric field than uniform droplets (second case). In the last two cases, the maximum values of the field were located at the extremities of the drops at the triple point (air, insulator surface, and the water droplets) because of the existence of discharges in this zone.

Thus, we conclude that uniform and non-uniform drops have a noticeable effect on the distribution of the electric field along the surface of the insulator. We also conclude that the increase in the intensity of the electric field is caused by the increase in the number of water droplets on the surface of the insulator.



a) Without droplets.



b) With droplets.

Figure 8. Simulated equipotential lines at a cross-section of an insulator.

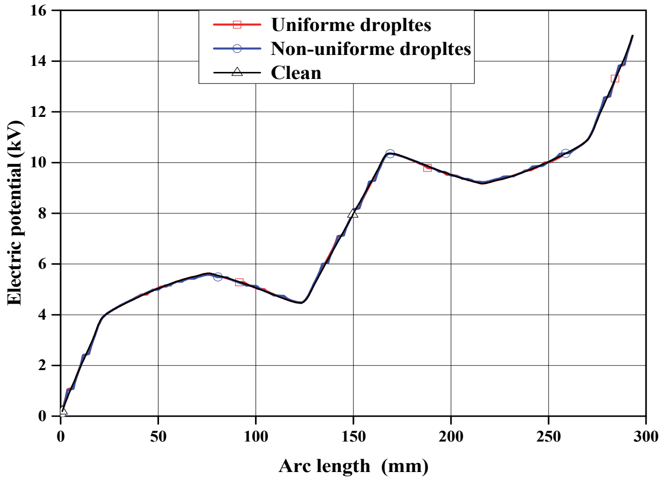
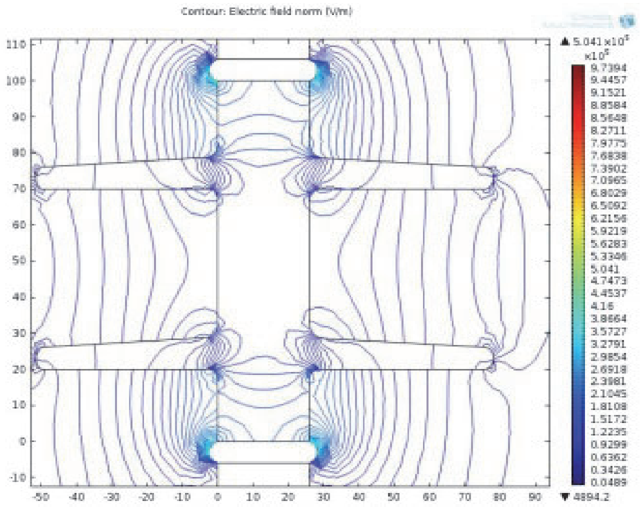
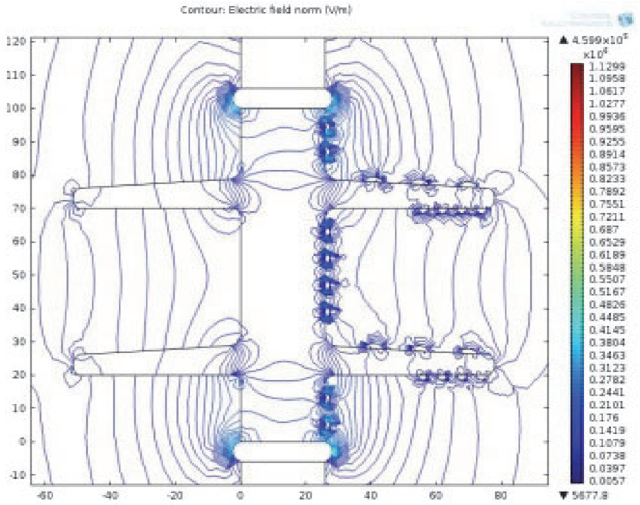


Figure 9. Comparison of the distribution of the electric potential along the surface of an insulator, with droplets and without droplets.



a) Without droplets.



b) With droplets.

Figure 10. Simulated electric field lines at a cross-section of an insulator.

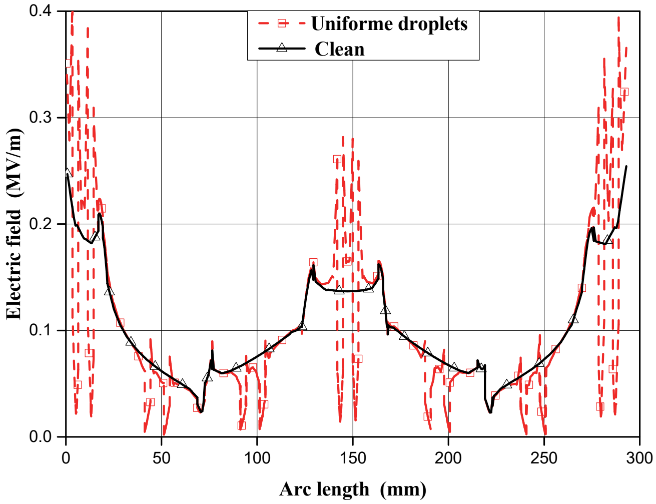
B. EFFECT OF A PAIR OF DROPLETS ON ELECTRICAL DISTRIBUTION

We created a model to simulate the behaviour of a real insulator in 3D (Figure 2b). Two scenarios were considered in this simulation. The first concerns a clean surface (no droplets on the surface), and the second concerns the case when there are a pair of drops on the surface of the insulator. These scenarios were designed to observe the effects of these drops on the distribution of the electric field and the electric potential.

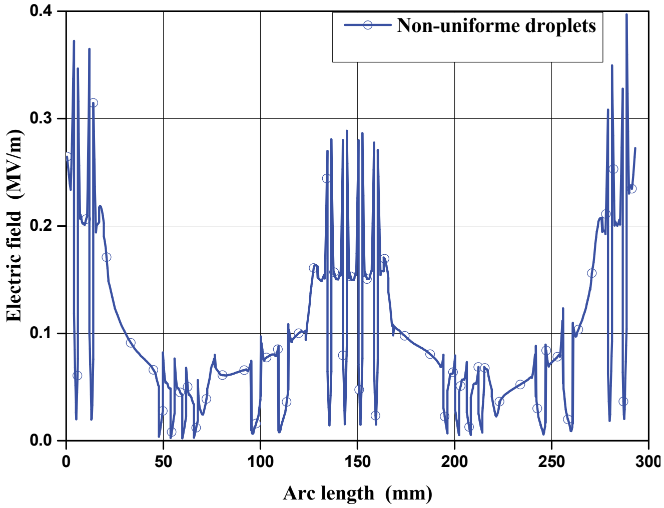
A comparison of the results of the two scenarios simulated is illustrated in Figures 12 and 13. In Figure 12, we note that there is no evident difference in the electrical potential at a distance of 175 mm on the distribution line (Figure 14b). In contrast, a voltage drop is observed at a distance of 275 mm on the same line because of the presence of the water drops on the surface of the insulator. This reduction in voltage confirms the effect of the droplets on the distribution of electric potential.

The electric field on the distribution line is different in both cases considered. In the second case, the magnitude of the electric field increases to 1.0 × 10^5 V/m at the first distance

(175 mm), and to 2.0 × 10^5 V/m at the second (275 mm) since this point is close to the high-voltage electrode.



a) With uniform droplets and without droplets



b) With non-uniform droplets

Figure 11. Comparison of electric field distribution along the surface of an insulator, with droplets and without droplets.

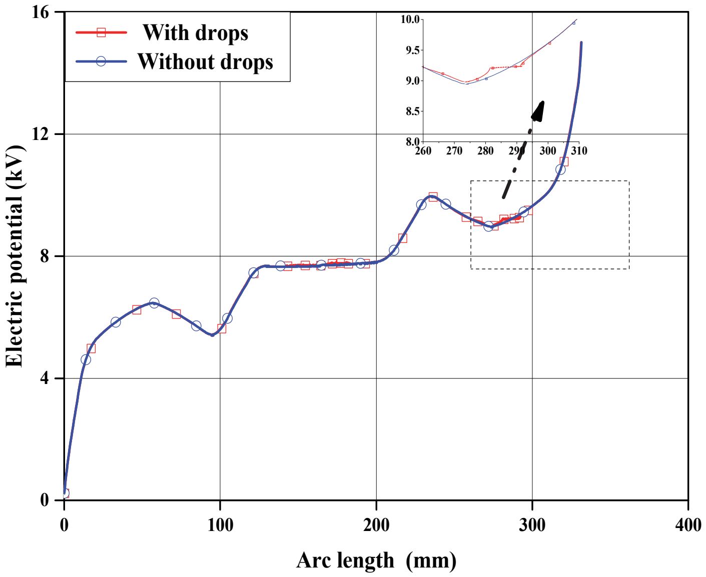


Figure 12. Distribution of electrical potential on the line of the leak, with and without water droplets.

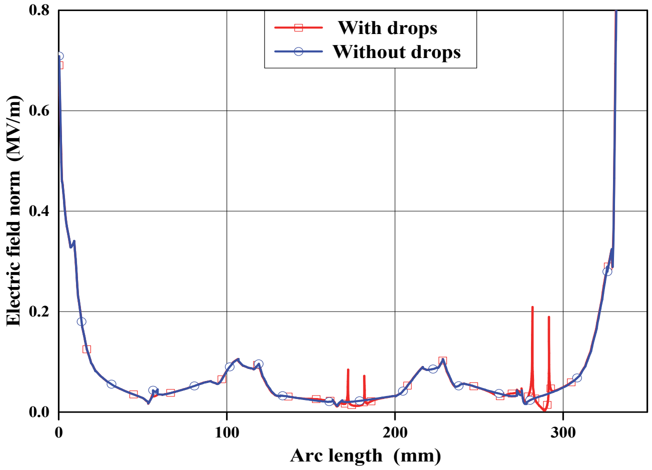


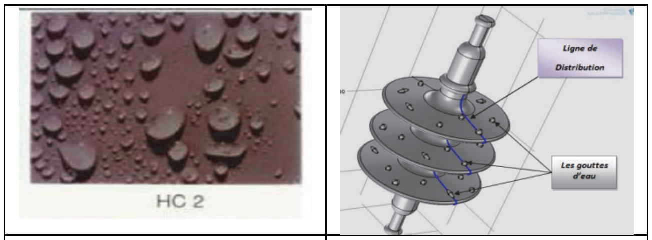
Figure 13. Electric field distribution on the line of the leak, with and without water droplets.

The discrepancy between the two cases is caused by the presence of droplets on the surface of the insulator, which exemplifies the effects of contamination on the distribution of a real electric field, such as electric discharges at the extremities of these droplets.

C. EFFECT OF MULTIPLE DROPLETS ON ELECTRICAL DISTRIBUTION

We created a model using the hydrophobic material HC 2, as seen in Figure 14a, to simulate the behaviour of the 3D insulator shown in Figure 14b to see the influence of multiple droplets with different volumes and shapes on the distribution of the electric field as well as electric potential.

Figures 15, 16, and 17 show the resulting electric potential and electric field distributions. The electric field distribution is non-uniform, particularly at the extremities of the copper electrodes. This is due to the difference between the air around the insulator and the dielectric material.



a. Hydrophobicity class | b. *Simulation of HC2*

Figure 14. Diagram of a real insulator in 3D, including an illustration of a hydrophobic material.

Figure 17 presents different plots in 2D for visualising the electric field and electric potential calculated with this model.

Figure 18 shows the distribution of the electric potential along the surface of the silicone insulator. We observe that this distribution is non-linear.

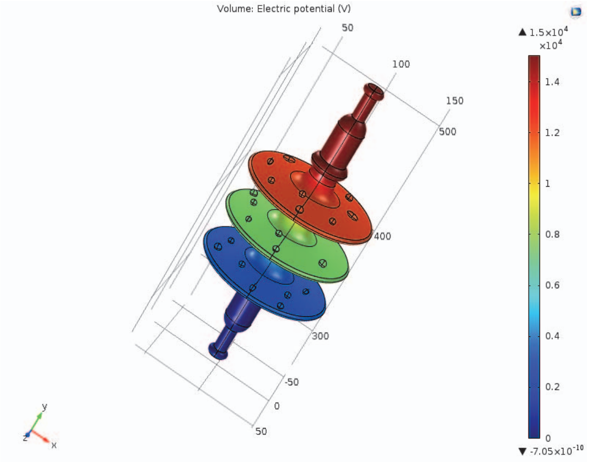


Figure 15. Three-dimensional voltage distribution in the insulator.

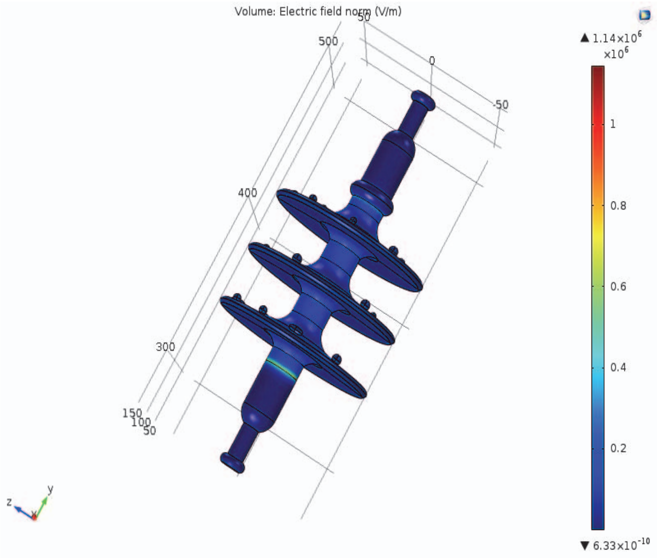
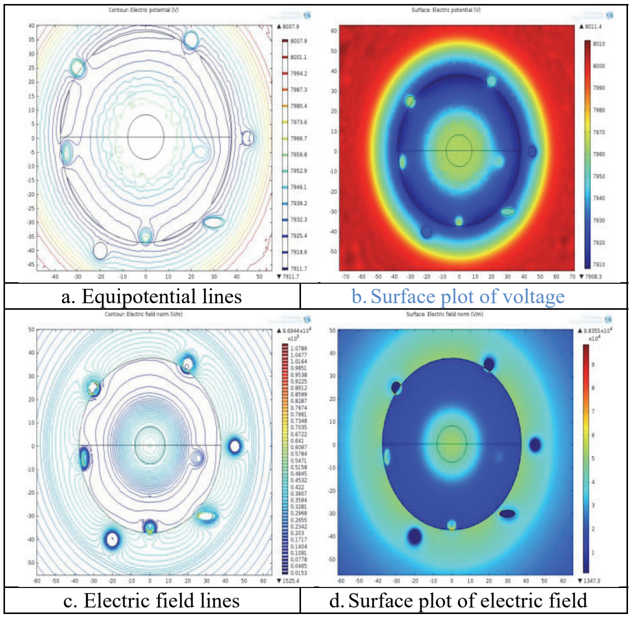


Figure 16. Three-dimensional electric field distribution in the insulator.



a. Equipotential lines
b. Surface plot of voltage
c. Electric field lines
d. Surface plot of electric field

Figure 17. 2D plots of electrical properties of the insulator in the x-z plane.

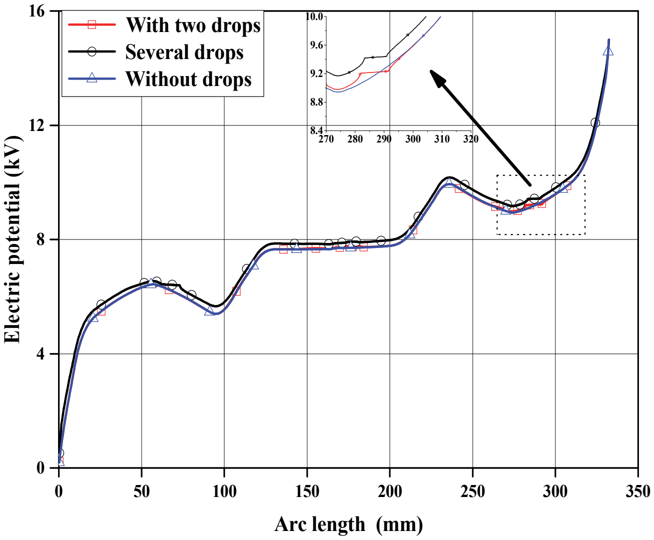


Figure 18. Distribution of voltage on the surface of the insulator.

The amplitude of electric field intensity along the insulator is presented in Figure 19. We can see that the electric field intensity is much higher (E=1.03 MV/m) in the junction area between the electrode and the small wings.

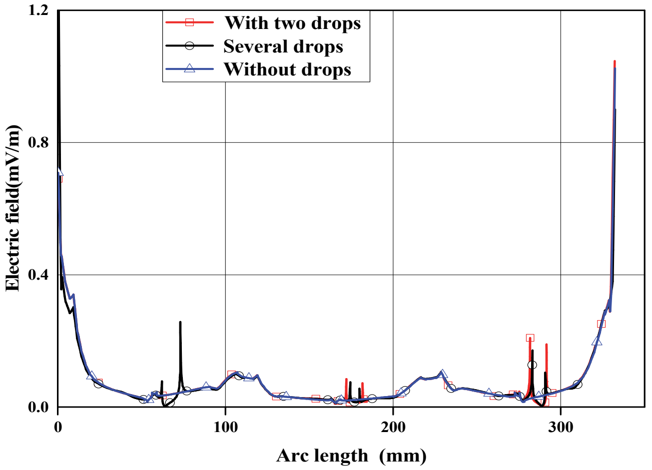


Figure 19. Distribution of electric field on the surface of the insulator.

5 CONCLUSION

In this study, we simulated a real insulator in 2D and 3D, using COMSOL Multiphysics 5.0. This software uses the finite element method to calculate the electric field and electric potential along the silicone insulator.

We have shown that several properties of water droplets on a dielectric surface, such as their volume, number, and shape, can influence the distribution of both electric field and electric potential.

We also conclude that the existence of these drops on the surface of an insulator increases the field intensity at the triple point (the location where air, water droplets, and the surface of the insulator coincide). The increase in the local value of the electric field caused by droplet deformation before flashover depends on the position of the droplets with respect to the electrodes.

Finally we consider the water droplets will be deformed and elongated along the direction of the electric field lines. The deformations will cause local electric field intensifications; the critical point will be the triple point between the water drop, air and the insulating material. This will be a starting point for partial discharges, finally leading to material deterioration.

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REFERENCES

[1] R. Hackam, “Outdoor HV Composite polymeric Insulators”, IEEE Trans. on Dielectr. Electr. Insul., vol. 6, pp. 557-585, 1999.

[2] E. A. Cherney and R.S. Gorur, “RTV Silicone Rubber Coatings for outdoor Insulators”, IEEE Trans. Dielectr. Electr. Insul., vol. 6, pp. 605-611, 1999.

[3] D.A. Swift, “Flashover of an Insulator Surface in Air Due to polluted Water Droplets”, in *Proceedings of the IEEE International Conference on Properties and Applications of Dielectric Materials,* 1994, pp. 550-553.

[4] C. Yuan, G. Zhichang and L. Xidong, “Analysis of Flashover on the contaminated Silicone Rubber Composite Insulator”, in *Proceedings of the IEEE Conference on Properties and Applications of Dielectric Materials*, 1997, pp. 914-917.

[5] G. G. Karady, “Flashover mechanism of Non-ceramic Insulators”, IEEE Trans. Dielectr. Electr. Insul., vol. 6, pp.718-723, 1999.

[6] M. G. Danikas, R. Sarathi, P. Ramnalis and S. L. Nalmpantis, “Analysis of Polymer Surface Modifications due to Discharges Initiated by water Droplets under High Electric Fields”, Int’l. J. Electr. Electronics Eng., vol. 4-5, pp. 329-334, 2010.

[7] W. Shaowu, L. Xidong and H. Lengceng, “Experimental Study on the Pollution Flashover Mechanism of Polymer Insulators” in *Proceedings of the IEEE Power Engineering Society Winter Meeting*, 2000, pp. 2830 - 2833.

[8] I. J. S. Lopes, S.H. Jayaram and E. A. Cherney, “A Study of Partial Discharges from Water”, IEEE Trans. Dielectr. Electr. Insul., vol. 6, pp. 262-267, 2001.

[9] Y. Zhu, K. Haji, M. Otsubo, C. Honda and N. Hayashi, “Electrohydrodynamic behaviour of water droplet on an electrically stressed hydrophobic surface”, J. Appl. Phys., vol. 39, pp. 1970-1975, 2006.

[10] A. J. Phillips, D. J. Childs and H. M. Schneider, “Aging of non–ceramic Insulator due to corona from water drops”, IEEE Trans. Power Delivery, vol. 14, pp. 258-263, 1999.

[11] S. M. Rowland and F. C. Lin, “Stability of alternating current discharges between water drops on insulation surfaces”, J. Appl. Phys., vol. 39, pp. 3067-3076, 2006.

[12] D. A. Swift, C. Spellman and A. Haddad, “Hydrophobicity Transfer from Silicone Rubber to Adhering Pollutants and its Effect on Insulator Performance”, IEEE Trans. Dielectr. Electr. Insul., vol. 13, pp. 820-829, 2006.

[13] A. Krivda and D. Birtwhistle, “Breakdown between water drops on wet polymer surfaces”, in *IEEE Conferemce on Electrical Insulation and Dielectric Phenomena Annual Report*, 2001, pp. 572-580.

[14] K. Karakoulidis, M. Danikas and P. Rakitzis, '”Deterioration phenomena on polymeric insulating surfaces due to water droplets”, J. Electr. Eng., vol. 56, pp.169–175, 2005.

[15] Y. Mizuno, M. Iwatani, M. Nagata K. Naito, K. Kondo and S. Ito, “Behavior of Water Droplets on Silicone Rubber Sheet under AC Voltage Application”, in *IEEE Conference on Electrical Insulation and Dielectric Phenomena Annual Report*, 1998, pp. 96-99.

[16] W. Jianwu, W. Xishan, L. Lei and L. Haiyan, “Study of Discharge Process and Characteristics of Discrete Water Droplets on the RTV Hydrophobic Surface in the Non-uniform Electric Field”, in *Proceedings of the IEEE Conference on Power System Technology*, 2006, pp. 1-6.

[17] T. Takuma, “Field behavior at a triple junction in composite dielectric arrangements,” IEEE Trans. Electr. Insul., vol. 26, pp. 500–509, 1991.

[18] T. Takuma and B. Techaumnat, *Electric Field in Composite Dielectrics*, Springer, 2010.

[19] T. Takuma, T. Kawamoto, “Field intensification near various points of contact with a zero contact angle between a solid dielectric and an electrode”, IEEE Trans. Pwr Appar. Syst., vol 103, pp. 2486-2494, 1984.

[20] B. Marungsri, W. Onchantuek, A. Oonsivilai and T. Kulworawanichpong, “Analysis of Electric Field and Potential Distributions along Surface of Silicone Rubber Insulators under Various Contamination Conditions Using Finite Element Method”, World Academy Sci., Eng. Technology, vol. 53, pp.1055-1060. 2009.

[21] W Bretuj and A Pelesz, “The behaviour of water droplets on the silicone rubber surface in an electric field”, IOP Conf. Series: Materials Sci. Eng., vol. 113, 012005, 2016.

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