A Comparative Electrostatic Analysis of Water Droplet-Induced Electric Field Distortion in Air and Oil Insulation

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ABSTRACT

Moisture reduces insulation strength, but its localized influence on electric field distribution is not always fully understood. This study examines how a single water droplet affects the electric field between two rod electrodes operating under high voltage. A two-dimensional (2D) finite element model is used to evaluate droplet behavior in both air and insulating oil under the same geometric and electrical conditions. The analysis considers how droplet position and size influence field concentration along the gap. The results indicate that the presence of a droplet alters the local electric stress, particularly in regions already experiencing elevated field intensity. The degree of distortion depends on the droplet's location and on the surrounding medium. A clear difference is observed between air and oil in terms of the magnitude of local field enhancement. While droplet size does affect the response, the trend shows that geometric interaction and positioning play a more dominant role than scale alone, with the Field Enhancement Factor (FEF) in air being approximately 7% higher than in oil under comparable conditions. These findings underline the need to account for localized moisture effects when evaluating insulation reliability. Even a single droplet can generate concentrated electric stress that may promote discharge activity and gradual material degradation. The study offers a consistent electrostatic basis for assessing moisture-related risks in both air- and oil-insulated high-voltage systems.

Keywords-water droplet; air; oil; electric field; insulation

I. INTRODUCTION

The reliability of electrical insulation systems remains a significant concern in the design and operation of high-voltage power equipment [1]. In both outdoor and enclosed electrical environments, insulation performance is often compromised by the unavoidable presence of moisture in the form of discrete water droplets [2-5]. Such droplets may arise from rainfall, condensation, contamination, or aging-related degradation and are frequently encountered in air-insulated gaps, on exposed outdoor insulator surfaces, and within oil-insulated apparatus such as transformers, bushings, and switchgear. Although the bulk dielectric properties of air and insulating oil are well understood, the localized interactions between electric fields and water droplets embedded within these media are complex, highly nonuniform phenomena that can critically influence the electric stress distribution [6]. When a water droplet enters a nonuniform electric field, particularly between electrodes operating at high potential differences, it does not behave as a passive inclusion. Due to its high permittivity relative to common insulating media and its finite electrical conductivity, the droplet strongly polarizes under the applied field. This polarization leads to pronounced distortion of the surrounding electric field, characterized by local intensification at the droplet-medium interface and, in many cases, strong asymmetry depending on droplet position relative to the electrodes. The resulting field enhancement can significantly exceed that present in the undisturbed gap, thereby increasing the likelihood of partial discharge inception, streamer initiation, or complete dielectric breakdown [5, 7, 8]. In practical systems, such mechanisms are closely associated with rain-induced flashovers on overhead line insulators, premature aging of external insulation, and localized failure points within oil-filled equipment.

Water droplets can markedly reduce breakdown voltage in short air gaps and alter discharge paths in both air and liquid dielectrics [9-11]. Many studies focus on macroscopic observations such as breakdown voltage reduction, discharge patterns, or droplet motion under electric stress [9, 11-13]. While these experimental approaches have been invaluable, they often provide limited insights into the underlying spatial distribution of electric field enhancement, particularly near the droplet surface and at electrode interfaces. Moreover, direct measurements of local electric field intensity at millimeter or submillimeter scales remain challenging, especially in transient or confined environments. Thus, numerical simulation and Finite Element Method (FEM)-based electric field analysis play an essential role in advancing the understanding of droplet-induced insulation stress. Electrostatic simulations allow controlled, repeatable evaluation of field redistribution caused by variations in droplet size, location, and surrounding medium, independent of experimental uncertainties. Such simulations are especially valuable for isolating the intrinsic influence of the insulating medium itself, air versus oil, on electric field enhancement mechanisms, a comparison that is difficult to achieve experimentally under identical geometric and electrical conditions.

Despite the recognized importance of water droplet effects, most previous numerical studies have investigated air- and oil-insulated systems independently, often under different geometrical configurations, voltage levels, and evaluation methodologies. Consequently, a direct and consistent comparison of droplet-induced electric field distortion in these two insulating media under identical conditions has not yet been clearly established. Furthermore, many existing studies, including advanced Multiphysics droplet models, have primarily focused on breakdown phenomena by coupling electrostatic analysis with fluid dynamics, charge transport, or droplet motion. In contrast, comparatively limited attention has been given to systematically quantifying how the surrounding dielectric medium itself affects the magnitude and spatial distribution of electric field enhancement around the droplet interface. As a result, the specific influence of the insulating medium on localized electric stress remains insufficiently understood. To address this gap, the present work provides a structured comparative electrostatic analysis of water droplet effects in air and insulating oil under identical geometric and electrical conditions. The study evaluates the electric Field Enhancement Factor (FEF) as a function of droplet size, droplet position along the electrode gap, and proximity to the high-voltage and grounded electrodes, thereby enabling a direct assessment of how the surrounding medium governs local electric field distortion.

II. SIMULATION METHOD

To investigate the influence of water droplets on electric field distribution in different insulating environments, a finite-element-based electrostatic simulation framework was developed, as the current study focuses on field redistribution arising from permittivity differences under steady-state conditions. The study concentrates on a simplified but electrically representative high-voltage gap in which a single water droplet is introduced between two opposing electrodes. The objective is to quantify how the surrounding medium, air or insulating oil, modifies droplet-induced electric field enhancement under identical geometric and electrical conditions.

In this work, the droplet is modeled as a purely dielectric material with constant permittivity. Conductive and electrohydrodynamic effects, including charge transport, interfacial charge accumulation, and droplet deformation or motion under electric stress, are intentionally neglected. This simplification is adopted to isolate the significant electrostatic influence of the insulating medium and to enable a direct and consistent comparison between air and oil without additional coupled physical effects. While these factors may affect the absolute magnitude and temporal behavior of the electric field, they are not expected to alter the primary comparative trends identified in this study. The simulated configuration consists of two vertically aligned rod electrodes facing each other along a common axis. Each electrode has a cylindrical body with a diameter of 2 mm and terminates in a hemispherical tip of 1 mm diameter, thereby forming a non-uniform electric field in the gap, as in [14]. The electrode geometry adopted in this study follows the configuration reported in [14] to ensure methodological consistency and result comparability. One electrode is energized at high voltage with 10 kV, while another electrode is connected to the ground. This arrangement produces a highly non-uniform electric field, representative of stressed regions in practical high-voltage equipment such as bushings, clearances near terminations, and local electrode protrusions. The electrodes are enclosed within a rectangular computational domain that represents the surrounding insulating medium. Two cases are considered: air and oil insulation. A spherical water droplet is introduced within the inter-electrode space. The droplet is modeled as a homogeneous dielectric inclusion whose location and size can be systematically varied. The simulation was carried out in two-dimensional (2D) axisymmetric mode in FEA software. Since the model is symmetric about its central axis, the 2D section can be rotated to represent the actual three-dimensional (3D) structure. The 2D model is shown in Figure 1(a), while the reconstructed 3D view is provided in Figure 1(b).

The simulations are based on the permittivity contrast between materials, which is the primary driver of electric field redistribution in the electrostatic regime. Constant relative permittivity values are assigned as follows: Water droplet: ε_r = 81, Insulating oil: ε_r = 4, and Air: ε_r = 1 [15, 16]. All materials are assumed to be linear, isotropic, and homogeneous. The droplet is treated as a stationary inclusion with a sharp interface and no deformation.

The field under stationary charges can be described as the negative gradient of the electric potential [6]:

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

where E denotes the electric field, and V represents the electric potential.

From Maxwell's equations, the relationship between the electric field and space charge density is given by:

$$\nabla \cdot D = \rho \tag{2}$$

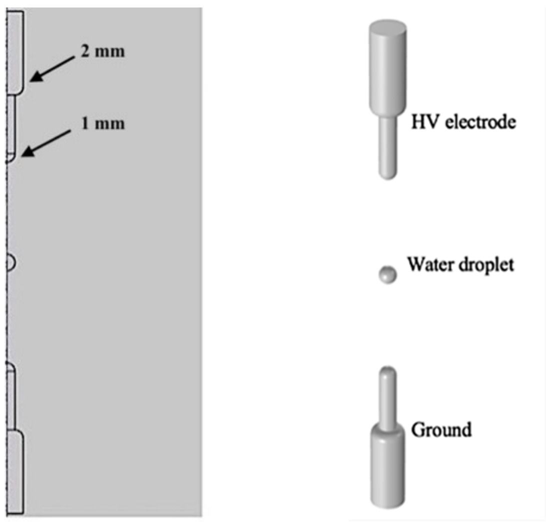
where ρ is the space charge density, and $D = \varepsilon E$ is the electric displacement field. Here, $\varepsilon = \varepsilon_0 \varepsilon_r$ denotes the permittivity of the medium, where ε_0 is the permittivity of free space, and ε_r is the relative permittivity of the material.

By substituting (1) into (2), the governing equation can be expressed in the form of Poisson's equation:

$$\nabla \cdot (\varepsilon \nabla V) = -\rho \quad (3)$$

Accordingly, the electric potential distribution is obtained by solving (3), after which the electric field is evaluated from (1).

The domain is discretized using triangular elements generated by the automatic meshing algorithm in the program, with an extra fine setting. Local refinement is applied near the droplet interface and electrode tips to accurately resolve steep electric field gradients. The minimum element size in these regions is approximately 2 μm–5 μm, while a coarser mesh is used elsewhere to reduce computational cost. Mesh independence was verified by comparing extremely fine and extra fine meshes, with the resulting variation in peak electric field remaining below 1.5%, confirming mesh convergence. Also, the simulation model files are available from the corresponding author upon reasonable request. A series of simulations was performed to examine the influence of droplet position, size, and surrounding medium. Baseline cases without a droplet were first evaluated in both air and oil to establish reference electric field distributions. A single water droplet was then introduced at different locations within the gap. Its diameter was varied from 0.2 mm to 1 mm to investigate the effect of size on field behavior.



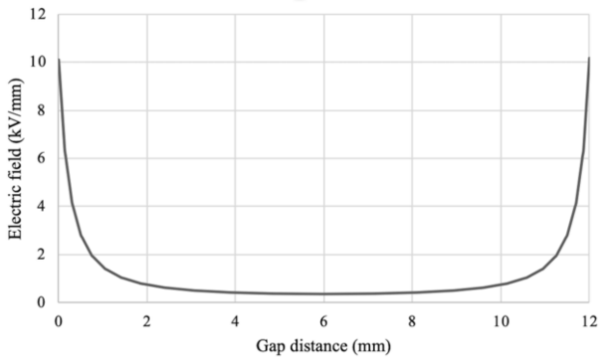
(a) (b)

Fig. 1. A gap and electrode modeling. (a) 2D modeling, (b) 3D modeling.

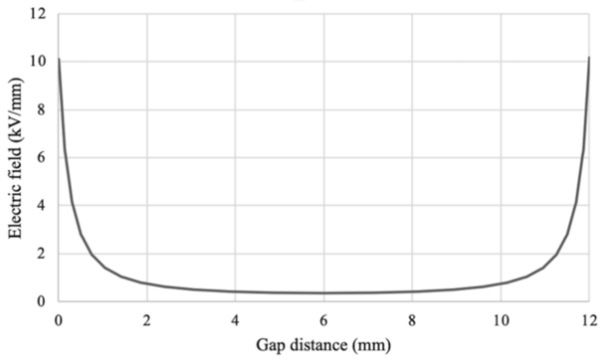
III. RESULTS AND DISCUSSION

A. *Electric Field Characteristics of Air and Oil Gaps*

The electric field distribution along the electrode gap under two insulating media: air and oil, was examined. The electrode configuration consists of a 12 mm gap without the presence of a water droplet, and the resulting electric field distributions are presented in Figure 2. As shown in Figure 2, the electric field along the arc length exhibits a distinct U-shaped profile. The field intensity reaches its maximum value at both electrode tips, approximately 10 kV/mm, and gradually decreases toward the center of the gap, where the minimum value is about 0.34 kV/mm. A similar trend is observed in both air and oil, with nearly identical distribution profiles in the two media. This baseline result indicates strong electric field concentration near the electrode tips, which is characteristic of non-uniform electric fields produced by rod-type electrode geometries. Similar field patterns have also been reported in previous FEM-based studies, supporting the validity of the present simulation model [17]. The results further suggest that, under droplet-free conditions, the electric stress distribution is governed primarily by electrode geometry and tip curvature rather than by the surrounding insulating medium itself.



(a)



(b)

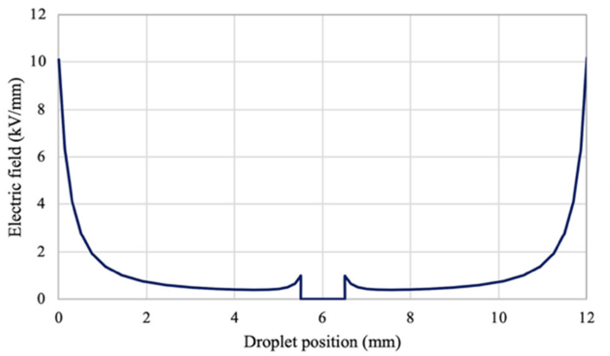
Fig. 2. Electric field distribution between two electrodes surrounding medium (a) air and (b) oil.

B. *Effect of a Water Droplet*

In this case, a single spherical water droplet with a diameter of 1 mm was introduced at the center of the gap between the two electrodes, as illustrated in Figure 1(b). The analysis was carried out for both air- and oil-insulated media under identical conditions. The resulting electric field profiles are presented in Figure 3. As shown in Figure 3, the presence of the water droplet significantly distorts the electric field distribution, producing localized field intensification near the droplet interface. Compared with the droplet-free condition, the electric field exhibits pronounced spikes, indicating strong local electric stress concentration caused by the droplet polarization effect. To quantify the degree of electric field distortion introduced by the droplet, the FEF is employed, which is defined as the ratio of the maximum electric field in the presence of the droplet, $E_{\text{drop,max}}$, to the corresponding local electric field under the reference no-droplet condition, $E_{\text{ref,local}}$. The FEF can therefore be expressed as:

$$\text{FEF} = \frac{\text{E}_{\text{drop,max}}}{\text{E}_{\text{ref,local}}} \quad (4)$$

In this study, $\text{E}_{\text{drop,max}}$ is taken as the average value of the left and right electric field peaks formed around the droplet interface. An FEF value equal to 1 indicates that the droplet does not influence the electric field distribution. In contrast, an FEF greater than 1 signifies local electric field intensification caused by the presence of the droplet. Higher FEF values correspond to stronger field distortion and greater localized electrical stress. Using the reference electric field values obtained in the previous section, the FEF was calculated for both air and oil insulation systems. In air, the calculated FEF is approximately 2.867, whereas in oil it is about 2.679. These values correspond to an increase of approximately 187% and 168%, respectively, compared with the no-droplet condition. The results indicate that the water droplet produces stronger local electric field enhancement in air than in oil. This suggests that the electric field distortion induced by the droplet is more severe in air-insulated systems, primarily due to the larger permittivity contrast between water and the surrounding medium.



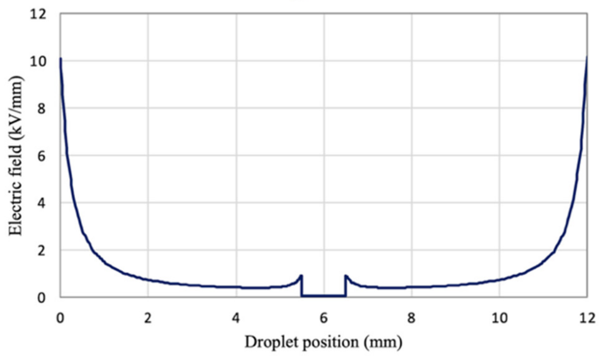


Fig. 3. Electric field distribution between two electrodes with a single droplet present, surrounding medium (a) air and (b) oil.

C. Effect of Water Droplet Position

To investigate the influence of droplet position on electric field distortion characteristics, a single water droplet with a diameter of 1 mm was placed at various gaps between the two electrodes, as illustrated in Figure 4. The results outlined in Table I show how the droplet location affects the electric field in both oil and air insulating. The results demonstrate a clear dependence of electric field enhancement on droplet position along the gap. When the droplet is located close to the electrodes (2 mm and 10 mm), $\text{E}_{\text{drop,max}}$ reaches the highest values in both media. In these regions, $\text{E}_{\text{ref,local}}$ is also higher, and the presence of the droplet further intensifies the local electric stress. The calculated FEF approaches about 2.8 in oil and 3 in air, indicating strong local enhancement. As the droplet moves toward the center of the gap (4 mm–8 mm), both $\text{E}_{\text{drop,max}}$ and $\text{E}_{\text{ref,local}}$ decrease. The FEF remains slightly lower than at the electrode regions but is still substantial, around 2.7 in oil and 2.9 in air. This corresponds to an increase of about 170%–180% in oil and 190%–200% in air relative to the no-droplet condition. The most important finding is that air is more sensitive to the presence of the droplet. Although the geometric effect of droplet position is similar in both media, the field enhancement is significantly stronger in air. The percentage difference between the FEF of oil and air is around 7%, compared to oil-based fuels. The stronger field distortion in air is attributed to the larger permittivity contrast between water and air, compared to oil. This suggests that insulation systems operating in air are more vulnerable to local field distortion caused by water droplets.

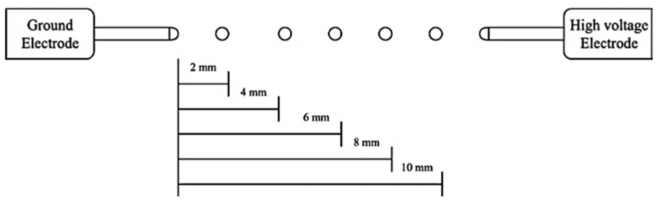


Fig. 4. Water droplet position in the modeling programme.

TABLE I. FEF UNDER VARIATION OF DROPLET LOCATION

Droplet location (mm)	$\text{E}_{\text{drop,max}}$		$\text{E}_{\text{ref,local}}$	FEF	
	oil	air	oil=air	oil	air
2	2.0535	2.197	0.736	2.7901	2.9851
4	1.0815	1.1575	0.4028	2.6850	2.8736
6	0.92	0.9845	0.3434	2.6791	2.8669
8	1.081	1.1575	0.4024	2.6864	2.8765
10	2.051	2.194	0.7358	2.7874	2.9818

D. Effect of Water Droplet Size

To investigate the influence of droplet size on electric field enhancement, the water droplet was positioned at 6 mm, corresponding to the center of the electrode gap. This location was selected because it represents the lowest electric stress region in the reference no-droplet condition, allowing the effect of droplet size to be examined with minimal influence from the strong field concentration near the electrode tips. Five droplet diameters were considered in the analysis: 0.2 mm, 0.4 mm, 0.6 mm, 0.8 mm, and 1 mm. By fixing the droplet position and varying only its diameter, the influence of size on the electric field distribution could be evaluated systematically. The corresponding results are summarized in Table II, which presents the calculated FEF values for each droplet diameter d. As shown in Table II, droplet diameter has only a minor effect on electric field enhancement when the droplet is located at the center of the gap. Across the entire range of investigated diameters, the maximum electric field remains nearly unchanged in both air and oil insulation. The variation between the smallest and largest droplets is minimal, indicating relatively stable electric field behavior with respect to droplet size under this configuration. The reference electric field, $E_{\mathrm{ref,local}}$, remains constant because the droplet location is fixed at the same geometric position in the no-droplet case. Consequently, the calculated FEF values also remain nearly constant throughout the investigated size range. In oil, the FEF remains slightly above 2.6 for all droplet diameters, whereas in air it stays close to 2.9. The overall variation in FEF from the smallest to the largest droplet is therefore very small.

These results suggest that, at the middle-gap position, electric field concentration is not highly sensitive to droplet diameter within the studied limits. Once a droplet is present, the local polarization effect appears to reach a stable enhancement level. Increasing the size beyond a certain small threshold does not significantly alter the peak electric stress. A clear and consistent difference remains between the two media. Air produces higher enhancement values than oil for every droplet size. This indicates that air allows stronger local distortion of electric field lines, while oil moderates the enhancement to some degree. Figure 5 portrays the FEF at droplet positions near the electrodes (2 mm and 10 mm) and at a mid-gap (6 mm). Comparing these 3 graphs, droplet size causes only a small variation in the FEF compared to droplet position. Therefore, under these conditions, the presence of a droplet and its position along the gap are more critical factors than droplet size. From a practical perspective, this suggests that moisture control is essential regardless of droplet scale, particularly in air-insulated systems, where electric-field enhancement tends to be higher.

TABLE II. FEF UNDER VARIATION OF DROPLET SIZE

Drop size (d:mm)	$E_{\mathrm{drop,max}}$		$E_{\mathrm{ref,local}}$	FEF	
	oil	air	oil=air	oil	air
0.2	0.914	0.979	0.3434	2.6616	2.8509
0.4	0.9135	0.978	0.3434	2.6602	2.848
0.6	0.9165	0.981	0.3434	2.6689	2.8567
0.8	0.917	0.982	0.3434	2.6704	2.8596
1	0.92	0.9845	0.3434	2.6791	2.8669

E. Discussion

This work addresses an important gap by presenting a structured and direct comparison of water droplet effects in air and oil under the same electrode geometry and applied voltage. By keeping all conditions identical and varying only droplet size and position, the electric-field enhancement can be attributed to the presence of moisture rather than to geometric differences. The use of FEF allows the influence of the droplet to be quantified consistently. The numerical results demonstrate that not only does the droplet distort the field, but also how strongly and under what conditions this distortion becomes critical. The presence of a water droplet in both air and oil gaps changes the electric field distribution. In the air, this kind of distortion agrees with previous studies, which reported that moisture can increase local electric stress [6].

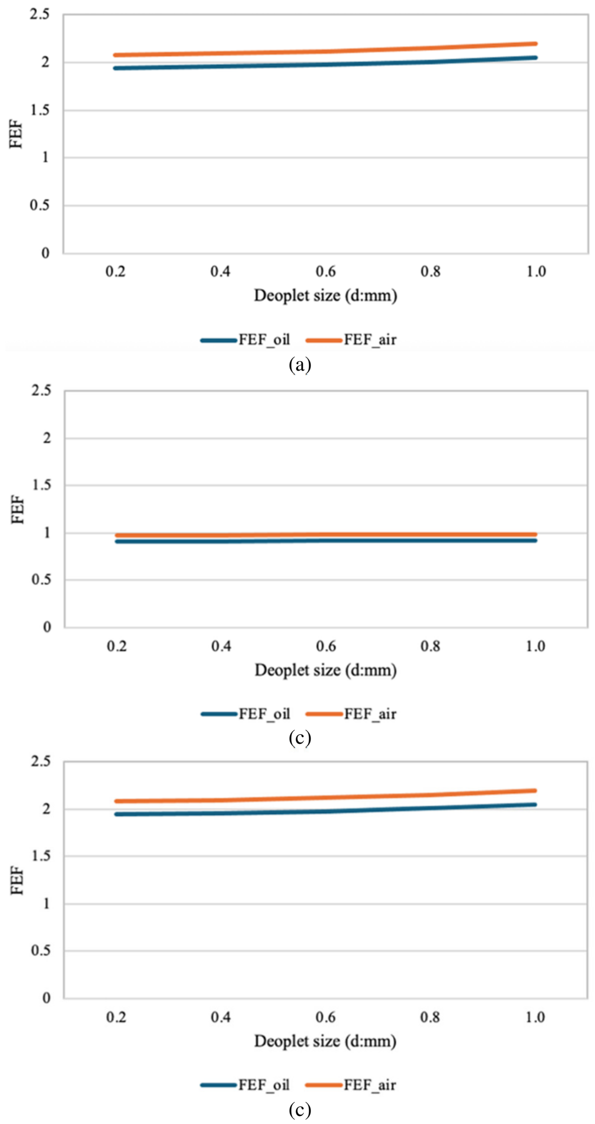


Fig. 5. FEF at variation in droplet position. (a) Droplet placed at a 2 mm gap, (b) droplet placed at a 6 mm gap, (c) droplet placed at a 10 mm gap.

However, for oil-insulated gaps, relatively few studies have provided a detailed description of how a single water droplet affects the local electric field distribution. In the present study, the field enhancement reaches nearly three times the reference electric field, demonstrating the significant influence of even a single droplet on local electric stress. The results further show that droplet position is a significant factor governing electric field enhancement. When the droplet is located near either the high-voltage or grounded electrode, the local electric field becomes substantially higher than when the droplet is positioned at the center of the gap. This behavior occurs because the electrode tips already experience strong electric stress due to geometric field concentration. The introduction of a droplet in these regions further intensifies the electric field, thereby increasing the likelihood of partial discharge initiation or dielectric breakdown. Authors in [14] showed that the breakdown voltage of air gaps decreases when a water droplet is located closer to the electrode region. This observation is consistent with the numerical results obtained in the present study, where the strongest local electric field enhancement occurs near the electrode tips. In contrast, when the droplet is positioned at the center of the gap, where the reference electric field is relatively low, electric field distortion still occurs but with lower absolute stress levels. The influence of droplet size on the electric field behavior is comparatively less significant than the influence of droplet position. In oil insulation, a slight increase in field enhancement is observed as the droplet diameter increases; however, the variation remains gradual and limited across the investigated range. No sharp increase or pronounced peak in enhancement is observed. This suggests that once a droplet is present, the polarization effect reaches a relatively stable condition, making the local electric field response less sensitive to further increases in droplet size. A similar trend is noted in air insulation, where the FEF remains nearly constant for all investigated droplet diameters. This indicates that, in air gaps, the dominant factor is the existence of the droplet itself rather than its precise size. Small variations in droplet diameter do not significantly alter the level of local electric field enhancement.

A significant finding of this study is that the surrounding medium plays a dominant role in determining the magnitude of field enhancement. Under identical geometric and electrical conditions, air consistently exhibits stronger local enhancement than oil, approximately 7% higher. Although the difference is not extreme, the trend remains uniform across all examined cases. In air, the large permittivity contrast between air ($\varepsilon_r = 1$) and water ($\varepsilon_r = 81$) creates a strong discontinuity in the electric field at the interface. This causes the field lines to become highly distorted and concentrated near the droplet surface, especially in regions of high curvature. This results in significant local electric field enhancement. Such enhancement can increase the likelihood of interfacial phenomena, such as electrical stress concentration or breakdown initiation. In contrast, when the droplet is surrounded by oil ($\varepsilon_r \approx 4$), the smaller permittivity difference allows the electric field to transition more smoothly across the interface. As a result, the field lines are less distorted and more evenly distributed, leading to weaker localization of the electric field around the droplet and reduced field enhancement effects. It could be suggested that the permittivity contrast between water and air leads to a more pronounced polarization mismatch than in oil, where the surrounding medium already partially mitigates the discontinuity. Therefore, this confirms that air is more responsive to moisture-induced field distortion, while oil provides partial moderation of local stress concentration. From an engineering perspective, these observations emphasize that droplet presence itself is the primary concern, rather than droplet scale within the studied limits. Even relatively small droplets can generate substantial localized electric stress, especially near high-field regions. Such localized intensification can contribute to long-term insulation degradation and increase the risk of discharge activity. Therefore, effective moisture management remains essential for maintaining dielectric reliability in both air- and oil-based insulation systems.

IV. CONCLUSIONS

This study presents a direct, controlled comparison of the influence of a single water droplet on the electric field distribution in air and oil under identical geometric and electrical conditions. By maintaining the same modeling configuration throughout the analysis, the study isolates the effect of the insulating medium itself, an aspect that has not been systematically clarified in previous research. The results confirm that the presence of a water droplet is sufficient to disturb the local electric field and generate additional electric stress in the surrounding region. The degree of enhancement is strongly dependent on droplet position, whereas the influence of droplet size within the investigated range is comparatively limited. When the droplet is located near high-stress regions, particularly close to the electrode tips, the local electric field increases significantly compared with the droplet-free condition. In lower-stress regions, such as the center of the gap, field distortion still occurs but with lower absolute stress levels. The comparison between air and oil further demonstrates that air experiences stronger local electric field enhancement, while oil partially moderates the distortion effect. This difference is primarily associated with the larger permittivity contrast between water and air compared with water and oil. An important outcome of this work is that the presence of moisture itself is more crucial than the exact droplet size. Even relatively small droplets can produce substantial localized electric stress, particularly when located in regions of naturally high electric field intensity. Over prolonged operating periods, such localized stress concentration may contribute to insulation degradation, partial discharge activity, and reduced dielectric reliability. Overall, these findings emphasize the importance of effective moisture control and careful insulation design in both air- and oil-insulated electrical systems to minimize localized electric field enhancement and improve long-term insulation performance.

DECLARATION OF COMPETING INTERESTS

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

ACKNOWLEDGMENT

Not applicable to this work.

DATA AVAILABILITY

The data that support the findings of this research study are available from the corresponding author upon reasonable request along with the simulation model files.

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