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Impact of the Grading Ring Size and Hydrophobicity on the High-Voltage Insulator Performance

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ABSTRACT

A high-voltage insulator is an electrical power device that is usually used in the transmission and distribution system. The insulator is normally attached to the other instrument as a protection in case any breakdown or fault happens. Each high-voltage insulator has its own properties. Meanwhile, a grading ring, one of the components connected to the insulator, to improve the distribution of the electric field on the insulator's surface. This study, it involves the hydrophobic property of the insulator's surface since it is a primary issue that influences the electric field distribution. The distribution of the electric field in a high voltage insulation system is important because it can affect the performance, reliability and safety of the insulator. The electric field needs proper management to prevent electrical breakdown, extend the lifespan of insulation materials, and reduce power losses. Consequently, this study is mainly about the effect of the grading ring's design parameters and the presence of water droplets towards the electric field distribution on high-voltage insulators by using FEA software, which is COMSOL Multiphysics, to conduct the analysis that includes evaluating the electric field distribution across the high-voltage insulators.

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The grading ring's diameter, thickness, distance from the end of the insulator, and the water droplet parameters, which are size and location, are varied to observe how the electric field distribution is affected. The results from the simulation show that increasing the grading ring's diameter and thickness, the maximum electric field (Emax) observed on the insulator surface will increase by 25 %. Besides that, the performance increases by 20% after placing a grading ring along the high-voltage insulator, while higher positions of the grading ring from the end reduce this performance by 15%. Water droplets at curved surfaces showed a higher electric field, and larger droplets concentrated the electric field more. The grading ring with the lowest electric field was chosen based on these findings, and the electric field along the insulator surface was then simulated. A proper grading ring design is essential for even electric field distribution that mitigates localised surface stress and supports optimal steady state power transmission and distribution performance.

Keywords: Corona discharge, distribution, electric field, FEA software, high-voltage, hydrophobicity, insulator, polymer, transmission

INTRODUCTION

There are two categories of insulators. It can be a high-voltage or a low-voltage insulator. In a transmission system, a high-voltage insulator is an important component that is widely used in electrical infrastructure that is commonly found on overhead transmission lines, which serve as key assets for power delivery across all countries (Mohamad Nasir et al., 2021). Additionally, high-voltage insulators are parts of grid equipment such as transformer bushings for both low- and high-voltage terminals. The insulator is a safety element in transmission that can directly impact the safety of electrical power transmission (Belhouchet et al., 2024; Illias et al., 2021). There are many factors that can affect the electric field distribution and high-voltage insulator performance in the grid system (Ahsan, 2024). The electric field distribution is uniform on the surface of a high-voltage insulator if it is in good and optimum performance. It is crucial for ensuring the reliability and efficiency of the insulation system because it can help in preventing localised overstressing of the material, thereby minimising the risk of electrical breakdowns and enhancing the overall durability and operational stability of the high-voltage equipment (Darmiani et al., 2023; Mao et al., 2022).

Pollution flashovers are a significant problem today, especially in big cities (Salem et al., 2022). However, the high-voltage insulator's performance can be disturbed by nature's conditions and environment: humidity, the surrounding temperature, environmental conditions, ultraviolet radiation or exposure, electrical stress, and the load carried. These issues must be studied thoroughly to better understand the behaviour of the high-voltage insulator for a better distribution of the electric field and to increase the lifespan of the insulator (Rao et al., 2023). The lack of understanding and research will limit the ability of the insulator manufacturer to design the insulator to its optimum performance. High-voltage insulator sizes can differ depending on the insulation location and position of the high-voltage transmission tower. Observation can be seen from the transmission tower, which is usually divided into 3 phases: upper, medium, and lower. Each load has its parameters and size to support the insulator in ensuring the conductor does not easily break down due to any fault or surge during the transmission of electrical energy (Ndoumbe et al., 2023).

Hydrophobicity is recognised to be one of the significant issues that have been faced in the electrical transmission system. There are numerous studies and research conducted in previous years to improve the characteristics of the high-voltage insulator. An insulator with a strong hydrophobicity characteristic will increase the electrical transmission quality and efficiency. The polymer-based insulator has become one of the widely used materials in recent years in the electrical transmission system (Huo et al., 2019). However, limited studies and research have been performed to evaluate the importance of the hydrophobicity property of the high-voltage insulator. The hydrophobic characteristic could minimise the adhesion of water droplets on the surface of the high-voltage insulator. It will give impact on the electric field distribution on the surface of the high-voltage insulator. The degradation of the hydrophobic coating that coats the high-voltage surface can lead to flashover or create a conductivity layer for the electricity flowing through the high-voltage insulator (Haque et al., 2021; Jin et al., 2014). A conductivity surface will cause the high-voltage insulator to break down faster if any surge or fault happens in the transmission line.

Flashover pollution occurs when excessively high-voltage discharges occur around the insulator and lead to breakdown of the insulator, allowing the insulator to become a conductor, and any surge or fault can pass through (Salem et al., 2022). The risk of potential leakage currents forming on its surfaces when high-voltage insulators are exposed to different pollution conditions. It can lead to an insulator flashover phenomenon. This phenomenon occurs when the accumulated contaminants on the surface of the insulator, such as dust, salt, and other pollutants, combined with moisture, create a conductive layer that allows current to bypass the insulator.

Consequently, this can result in a sudden and severe discharge and cause a flashover that ruins the integrity and reliability of the high-voltage insulation system. It is important to address and mitigate this issue to maintain the efficiency and safety of electrical power systems and prevent damage to equipment and potential power outages (Bi et al., 2020). Thus, the electric field distribution is important to implement the use of a grading ring in the grid asset that is connected at the end of the insulator, and it also functions as a connector to connect the conductor to the insulator and the insulator to the grid transmission tower. The effects of grading ring size, diameter, thickness, and distance from the end of the insulator to observe its impact on electric field distribution via the simulation are the focus of this study (Ahsan et al., 2024). Additionally, beyond the parameters of the grading ring, this study also aims to conduct simulations to enhance the understanding of the hydrophobic characteristics of the high-voltage insulator in terms of water droplet sizes and their various locations on the surface of the high-voltage insulator.

This research paper consists of four main sections. The first section, Section I, introduces the project, problem statements, objectives, scope of work, and limitations. Section II explains the simulation model and equations. This section is divided into five sub-sections based on the specific parameters being varied, which are 2.1 Diameter of the grading ring, 2.2 Thickness of the grading ring, 2.3 Distance of the grading ring from the end, 2.4 Location of the water droplet, and 2.5 Size of the water droplet. Section III subsequently presents the computational results and detailed discussions for each of these five parameters to evaluate the overall insulator performance. Section III, the study will compute all the results. Each data point and graph will be discussed in five parts to allow a more uniform discussion and allow the reader to understand the simulation result.

This study contributes to the enhancement of electrical transmission reliability by analysing the geometric and environmental factors that can affect the insulator performance. The main contribution of this research is the quantification of how specific grading ring diameter, thickness, and distance from the termination end directly impact the reduction of maximum electric field (Emax) stress. Furthermore, this paper provides information about the role of hydrophobicity by simulating the impact of various water droplet sizes and locations to demonstrate its significant effect on localised electric field intensity. According to the analysis, an optimised grading ring configuration can improve electric field distribution by 20%, this study offers actionable guidelines for the design of more durable and safer high-voltage insulation systems.

Simulation Model

FEA software is used in this study to analyse the electric field distribution across the surface of high-voltage insulators used in overhead lines and power transmission systems. This software utilises the finite element method. It is an effective computational technique that allows precise modelling and analysis of the electric field behaviour under various conditions. This method aims to represent the electric field distribution accurately to evaluate the performance and functionality of high-voltage insulators in real-world applications. A 3D simulation has been designed to understand the effects of environmental and operational factors on insulator performance. It will contribute to improving design strategies and maintenance methods for enhanced system efficiency and safety (Meetiyagoda et al., 2023). A static condition in which the electric field, Voltage, V, and the constitutive relation are defined in the system as referred to in Equation 1. Equation 2 shows the relationship between the electric displacement distance, D, and the electrical potential, E.

$$E = -\nabla V \qquad [1]$$

$$D = \varepsilon_r \varepsilon_0 E \quad [2]$$

V is the overvoltage set in the setting section, ε_r is the material's relative permittivity; this study will use water, with a value of 81. ε_0 is the relative permittivity of the vacuum, and E is the electric field. In this study, the free space charge density is set to zero and reformulates Gauss' Law to derive a variant of Poisson's equation, accordingly, as shown in Equation 3.

$$-\nabla \cdot \varepsilon_r \varepsilon_0 \nabla V = 0 \quad [3]$$

The applied voltage is set to 500 kV to represent the overvoltage amplitude, with the ground voltage set to zero. In the general depiction of the high-voltage system, the metallic components are modelled as equipotential bodies where the internal electric field is zero. The selection of the 500 kV applied voltage, along with the specific material properties (detailed in Table 1) and boundary conditions (detailed in Table 2) were adapted from the validated COMSOL AC/DC module tutorials (COMSOL, 2022). The physical dimensions of the insulator string and the corresponding parameter settings are visually illustrated in Figure 1. These parameters were deliberately chosen to establish a simplified and standardised baseline model. By utilising these established baseline values rather than simulating a highly specific and complex commercial transmission tower environment, this study minimises external electrical and environmental variables. This standardised modelling approach allows the simulation to strictly isolate and accurately quantify the precise impact of geometric variations, specifically the grading ring dimensions and water droplet characteristics, on the electric field distribution.

Table 1
Relative permittivity of different materials used in the simulation

Material	**Relative Permittivity**	**Conductivity**
Core rod	5	10^{-5} S/m
Weather shed	3	10^{-12} S/m
Water	8	1 S/m
Air	1	10^{-14} S/m

Table 2
The parameter setting for the simulation

Name	**Value and Unit**	**Description**
Vi	500[kV]	Overvoltage amplitude
H	30[mm]	Thickness of the grading ring
D	350[mm]	Diameter of the grading ring
d	150[mm]	Distance of the grading ring from the end

After applying all the following data to the parameters set, the 3D high-voltage insulator was built, and a simulation was performed based on the desired values of three different observed parameters. In this study, the thickness, H, the diameter, D, and the location of the grading ring from the end of the insulator that connects the grading ring, d, are varied to observe the effect of different values applied to the high-voltage insulator and how the electric field produced by the simulation is distributed.

After completing the first part of the simulation, an additional ellipse drawing is added to the drawing to perform the second and third parts of the simulation to simulate a water droplet and analyse the effects of the hydrophobicity towards the insulator. Figure 2 provides a detailed flowchart outlining the methods used to perform the simulation. Figure 3 shows an example of the designed and simulated 3D model of the grading ring with the high-voltage insulator.

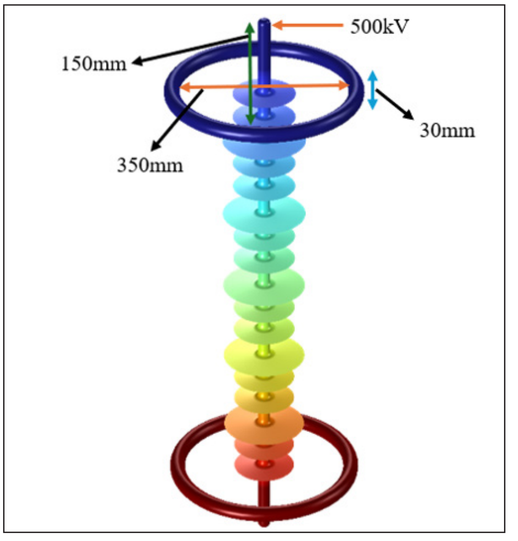


Figure 1. The pictorial dimension of the insulator string, together with the parameter setting

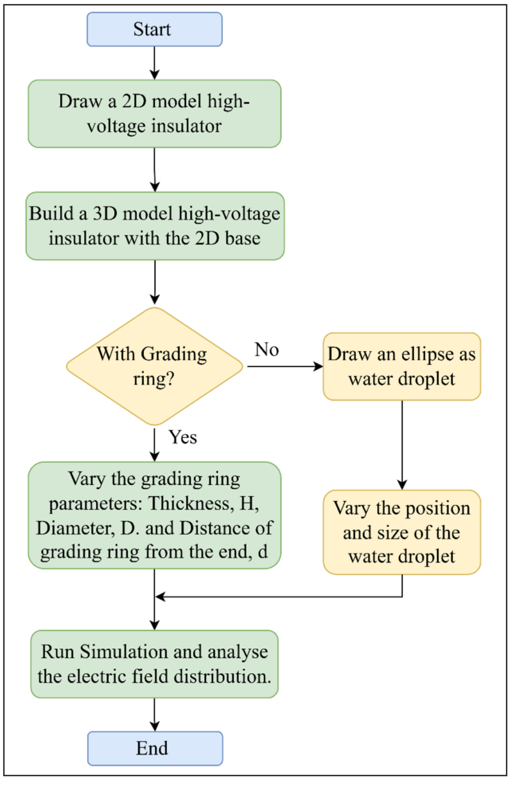


Figure 2. The flowchart of the method applied to perform the simulation

Diameter of the Grading Ring

The diameter of the grading ring varies within the industry based on several factors, including the installation location, the load it is designed to carry, and its specific functionality. Several samples and industrial sizes of the insulator with a grading ring are used to improve and enhance the insulator's performance and distribute a more uniform and balanced electric field on the high-voltage insulator's surface to reduce the insulator's stress level (Tsinghua University, 2020). The industry usually uses the diameter 700-900 mm (Ndoumbe et al., 2023), but the 700-1100 mm range data is simulated in this simulation for comparison purposes, as tabulated in Table 3.

The Thickness of the Grading Ring

On the other hand, an observation is made of the size of the ring itself, which is measured based on the thickness of the grading ring. The thickness is one of the critical elements in ensuring the grading ring can perform optimally and insulate the conductor from any fault or surge. The industry usually uses a thickness of 100 mm (Ndoumbe et al., 2023). To simulate a comparison of the insulator's performance, as shown in Table 4, five different data sets (100 to 500 mm) on the thickness of the grading ring are simulated. The thickness values are varied from 100 mm to 500 mm to make the comparison clearer as small differences in thickness, such as 100 mm to 150 mm, can make the variations in the results difficult to see.

Table 3
Grading ring diameter (mm) data range

Grading Ring	Diameter Size (mm)
A	700
B	800
C	900
D	1000
E	1100

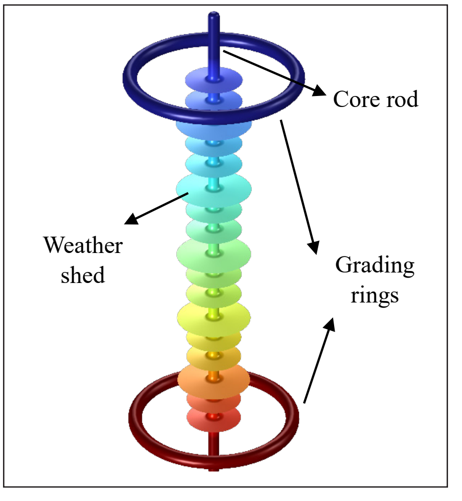


Figure 3. The designed and simulated 3D model of the grading ring with the high-voltage insulator

Distance of the Grading Ring from the End

Generally, a grading ring is usually placed 150 to 200 mm from the end of the insulator according to the industry standard (Zhang et al., 2022). However, the range in this research is wider, which is from 150 mm to 350 mm, to allow a deeper investigation into the effects of varying the grading ring placement on the insulator's performance. In this study, the performance of the insulator will be evaluated by comparing five different values of the distance of the grading ring from the end of the high-voltage insulator, as outlined in Table 5. It will provide valuable insights into optimal design parameters to enhance efficiency and reliability in high-voltage applications. The simulation data will be analysed to understand the impact of these variations on the electric field distribution and the overall effectiveness of the insulator.

Table 4
Grading ring thickness (mm) data range

Grading Ring	Thickness (mm)
A	100
B	200
C	300
D	400
E	500

Location of the Water Droplet

A superhydrophobic coating is needed for an insulator to facilitate optimal water drainage from its surface (He & Guo, 2021). In high-voltage applications, this is important where minimising water retention is essential to maintain operational integrity and safety (M'Hamdi et al., 2016). In this research, the location of the water droplet is also being studied since it is one of the factors that can disturb the distribution of the electric field. There are three different places of water droplets to observe the outcome from the simulation because the water droplets from the environment can decrease the hydrophobicity element or characteristic of the insulator. The first location of the water droplet is in the centre of the insulator shed. Second, at the end of the insulator shed, and lastly, at the end of the insulator shed. The water droplets at each location have the same size to ensure an accurate result. Figure 4 shows how the location allocates the water droplet on the insulator shed. Simulations are conducted at these three locations to observe how the electric field is distributed on the high-voltage insulator.

Table 5
Distance of the grading from the end (mm) data range

Grading Ring	Distance of the Grading Ring from the End (mm)
A	150
B	200
C	250
D	300
E	350

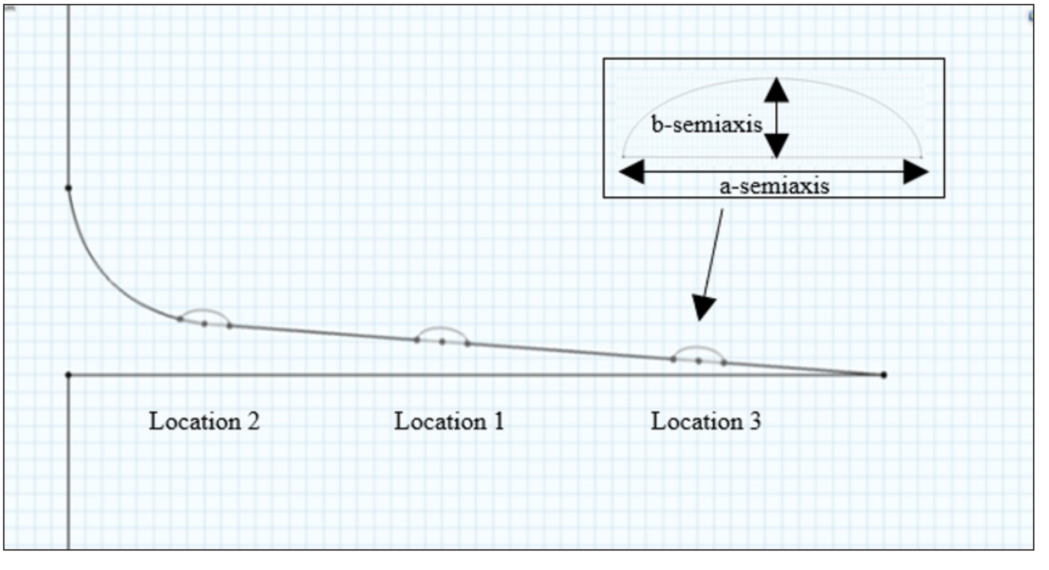


Figure 4. The three locations of the water droplets

Size of the Water Droplet

The water droplet size and shape can significantly affect the electric field distribution on the high-voltage insulator (Shrimathi & Mondal, 2021). In this study, water droplets are represented using elliptical geometries. This specific shape is a standard modelling simplification widely utilised in literature to accurately approximate the gravitational deformation and surface tension of droplets resting on inclined insulator weather sheds (Ali & Hackam, 2008). Furthermore, the selected dimensions from 1.2 mm to 1.8 mm in length and the specific locations tested, which were middle, curve, and end of the shed were chosen because statistical distributions of condensation and rain accumulation on silicone rubber demonstrate that the vast majority of discrete droplets stabilise in this sub-3 mm range before sliding occurs (Guedri et al., 2024; Jiang et al., 2019). This reflects practical, real-world accumulation patterns typically observed during varied environmental wetting conditions. This approach allows for a realistic and comprehensive analysis of localised field enhancement. The water droplet size is varied by changing the values in the setting under the a-semiaxis and b-semiaxis of the ellipse as per Table 6. The a-semiaxis controls the lengthwise of the water droplet for the semimajor axis. In contrast, the b-semiaxis controls the radius of the water droplet for the semi-minor axis, as illustrated in Figure 5. The cross-section plot method and the distribution of the electric field are presented in Figure 5. For the simulations involving the water droplets, the droplet domain is modelled as a solid homogeneous medium. The relative permittivity of water (ε_r = 81) is assigned to the entire volumetric domain of the

Table 6
The length and width (mm) of water droplets

Size	Length, a-semiaxis (mm)	Width, b-semiaxis (mm)
A	1.2	0.5
B	1.5	0.8
C	1.6	0.9
D	1.8	1.2

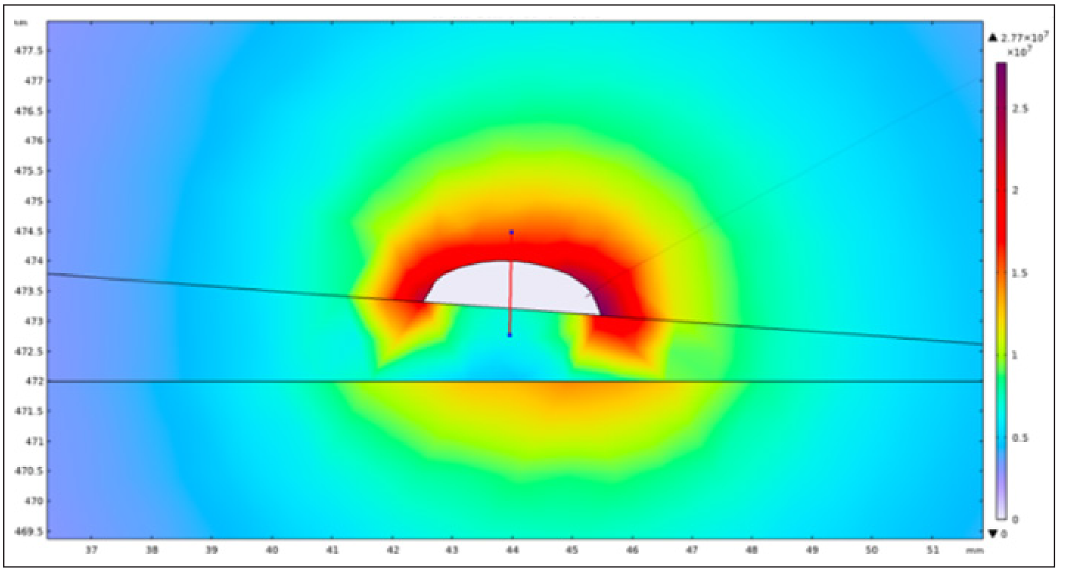


Figure 5. The illustration of the cross-section plot method and how an electric field is presented

ellipse, rather than treating the interior as a void. The surrounding medium is defined as air (ε_r =1), establishing a distinct dielectric interface at the boundary. The electric field distribution is then extracted across these regions using COMSOL's Electrostatics interface, which accurately computes the field dampening within the bulk water and the field enhancement at the boundaries.

RESULT AND DISCUSSIONS

Diameter of the Grading Ring

This section, it presents and discusses the simulation results on various grading ring design parameters and the presence of water droplets on the electric field distribution of high-voltage insulators. The analysis is organised into five sub-sections based on the parameters analysed. Figure 6 illustrates how varying the grading ring diameter affects the electric field distribution across the insulator surface. The data indicate that the diameter impacts field behaviour specifically, increasing the diameter appears to enhance the distribution potential, which may help mitigate electric stress on the insulator.

As the diameter increases, the field concentration on the insulator surface is altered, which is critical for minimising breakdown risks. Conversely, a smaller diameter creates localised areas of higher intensity, whereas the larger ring diameter, which is 1100 mm, demonstrated the most significant potential for field distribution compared to the other tested sizes. Therefore, within the scope of this study, a larger grading ring is shown to enhance protection and ensure maximum insulation performance against surges. It will also lower the probability of insulation failure under high-voltage conditions.

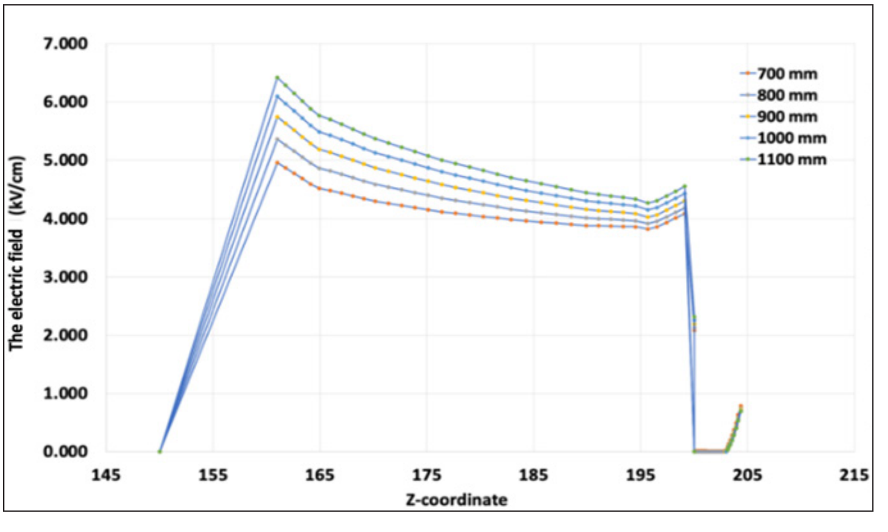


Figure 6. The electric field of the simulation is based on the different diameters of the grading ring

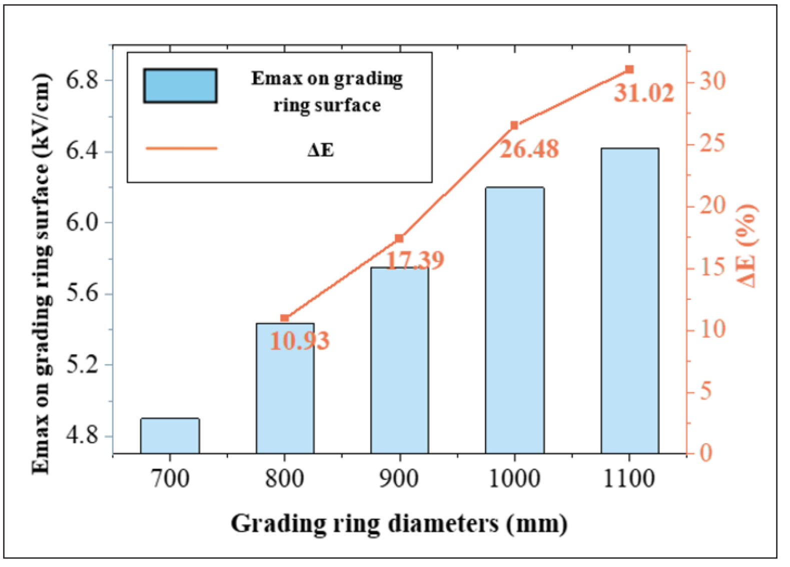


Figure 7. Emax in the grading ring is based on the different diameters of the grading ring

As presented in Figure 7, this study found that increasing the grading ring diameter within the 700 - 1100 mm range resulted in a 31.02% increase in the maximum electric field (Emax) on the grading ring. It is crucial to clarify that this Emax refers to the localised field enhancement on the surface of the metallic grading ring itself, not on the insulator weather sheds. While a larger diameter effectively redistributes the electric field away from the critical termination points of the polymer insulator, thereby improving insulation performance, the grading ring simultaneously becomes a site of higher localised field concentration. Current industrial standards typically range from 700 to 900 mm to prevent the ring itself from becoming a source of high-intensity field stress (Ndoumbe et al., 2023). This localised enhancement is expected since the larger metallic grading ring attracts and concentrates electric field lines around its curvature. Therefore, the observed increase in Emax does not indicate deterioration of the insulation system; rather, it reflects the intentional transfer of electric field stress from the vulnerable insulator surface to the grading ring, which is specifically designed to withstand higher localised electric field intensity.

Thickness of the Grading Ring

Figure 8 illustrates the electric field distribution across the simulation for the different grading ring thicknesses. While conventional electrostatic theory suggests that increasing the thickness of a conductor should reduce the surface electric field by increasing the radius of curvature, the simulation results in Figure 9 demonstrate a localised over-grading effect specific to this 3D geometric model. Specifically, the 100 mm thickness ring produced the most favourable outcome, maintaining the lowest maximum electric field (Emax) in the

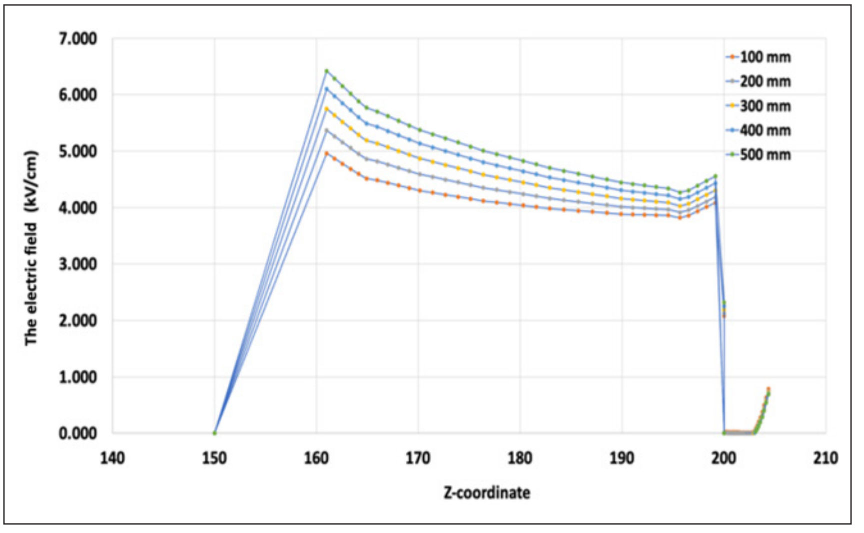


Figure 8. The electric field of the simulation is based on the different thicknesses of the grading ring

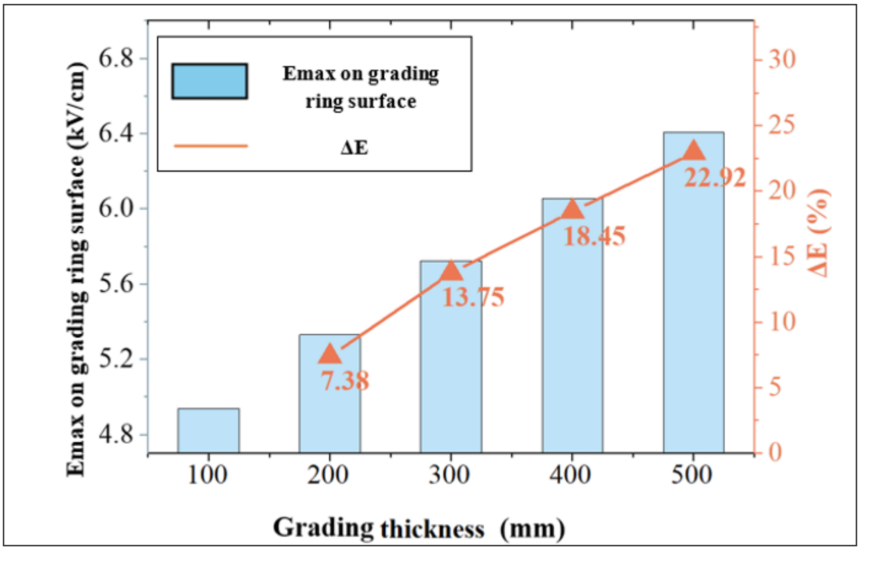


Figure 9. ΔE based on the different thicknesses of the grading ring

grading ring of 4.960 kV/cm on the grading ring. As the thickness was increased to 500 mm, the grading ring Emax increased to 6.420 kV/cm, representing a 22.74% increase in localised field intensity. Although increasing the grading ring thickness increases the effective curvature radius, the modification of the ring geometry simultaneously alters the electric field distribution and charge accumulation pattern within the specific insulator–electrode configuration used in the simulation.

As the ring thickness increases, the grading ring captures a larger portion of the electric field and shifts the electric stress away from the polymeric insulator surface. Consequently, localised field enhancement may occur in certain regions of the grading ring itself, even though the electric field stress along the insulator surface becomes more uniform and reduced. Therefore, the increase in E_{max} does not necessarily indicate poorer insulation performance but rather reflects a transfer of electric field concentration from the insulator surface to the metallic grading ring, which is intentionally designed to withstand higher localised electric field stress. This contradictory behaviour is caused by the geometric boundary conditions of the simulation: a massive increase in ring thickness significantly alters the local capacitance of the system, dragging the equipotential lines too close to the critical regions and concentrating electric stress on the expanded ring surface rather than the insulator sheds. (Ndoumbe et al., 2023).

Distance of the Grading Ring from the End

The distance of the grading ring from the end of the high-voltage insulator can significantly influence the electric field distribution across the insulator's surface. The "spacing" or "clearance" of the grading ring shapes the electric field profile, ensuring effective control of the high-voltage insulator. If the grading ring is positioned too close to the termination point, the insulator is more likely to experience breakdown due to the high electric field stress concentrated at that point. Conversely, placing the grading ring at an optimal position on the insulator promotes even distribution of the electric field, reducing the risk of breakdown. Observations confirm that the placement of the grading ring is a critical factor in managing electric field distribution on high-voltage insulators. An effective approach to mitigate surface stress on the high-voltage insulator is positioning the grading ring at an appropriate distance between the conductor and the insulator's line end. Figure 10 shows that as the grading ring is positioned further from the termination point, its ability to optimise electric field redistribution decreases. From the graph, the most effective placement is 150 mm, as it continuously promotes an even distribution of electric field stress across the surface of the high-voltage insulator.

As illustrated in Figure 11, placing the grading ring at a 150 mm distance results in a localised electric field concentration of 4.261 kV/cm on the ring itself, which correlates with the most effective surface stress reduction on the insulator compared to the other configurations. This finding is consistent with industrial research identifying an optimal placement height between 150 mm and 200 mm (Zhang et al., 2022). Conversely, the 300 mm position shows the least effective performance, registering a localised field of 3.557 kV/cm on the ring. This shows a difference of 20.46% in localised field concentration, indicating poorer field redistribution along the insulator sheds. Thus, the position of the grading ring must be precisely configured to minimise localised field enhancement and ensure optimal performance.

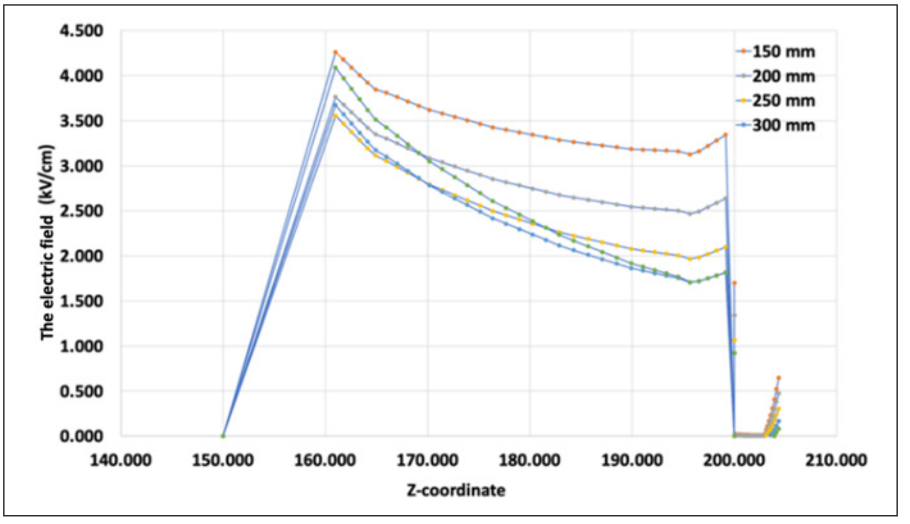


Figure 10. Electric field of the simulation at different distances from the grading ring

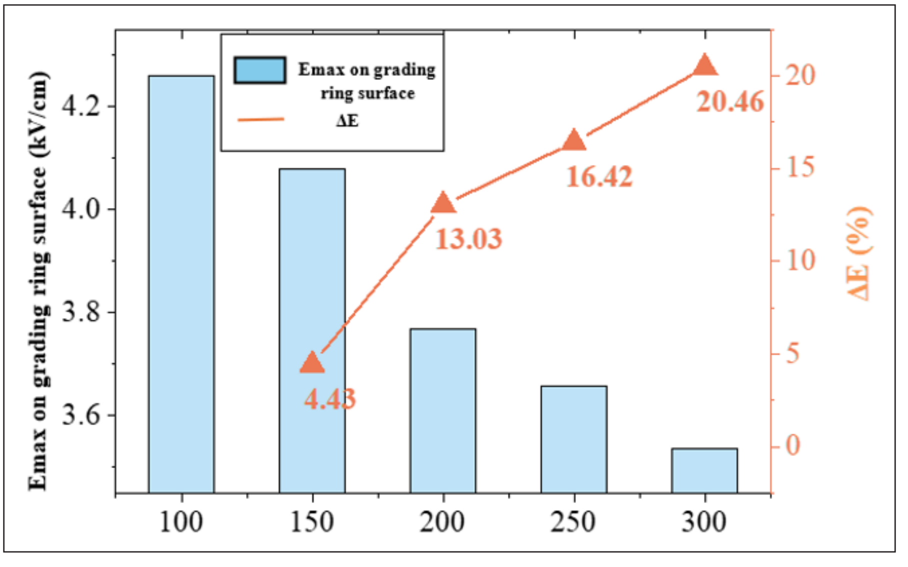
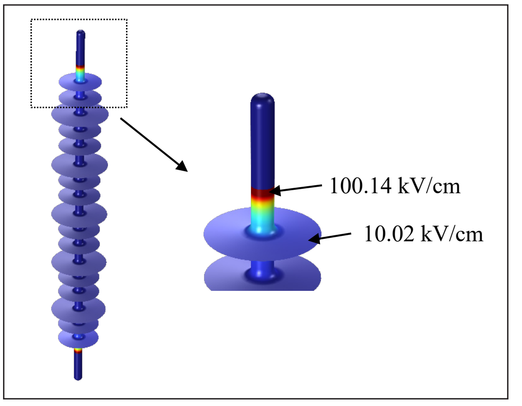


Figure 11. The ΔE is based on the different distances of the grading ring

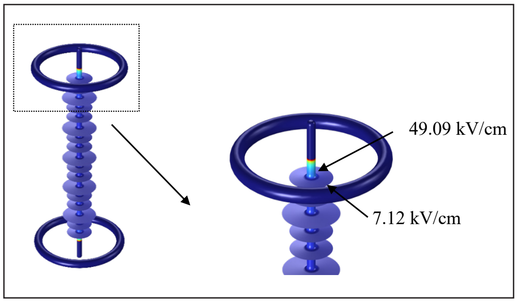
Location of the Water Droplet

For the case of water droplets, based on the findings of the electric field across water droplets under various grading ring characteristics, the grading ring with the lowest electric field was selected, and the electric field along the insulator surface was simulated using the chosen grading ring. Figures 12 and 13 illustrate the 3D and the electric field distribution along the insulator surface under the original and selected grading ring.

The results in Figures 12 and 13 show that the chosen grading ring reduced the electric field E_{max} on the insulator surface from 7.12 kV/cm to 5.68 kV/cm (20.22%) as compared to the original ring. The location of the water droplet can significantly disturb the aid performance of the high-voltage insulator due to its hydrophobicity capability and its energy discharge on the surface coated with a layer of hydrophobic material (Ye et al., 2021). The hydrophobicity of the high-voltage insulator surface can minimise the potential of the water droplet to stay on the surface of the high-voltage insulator. Figure 14 shows the simulation results of three different locations of water droplets. The three locations will produce three different results regarding the potential of the electric field distribution for each designed location. Changes in the relative permittivity of the medium—such as the presence of water—can alter the electric field distribution, potentially increasing local field intensity at critical points.



(a)



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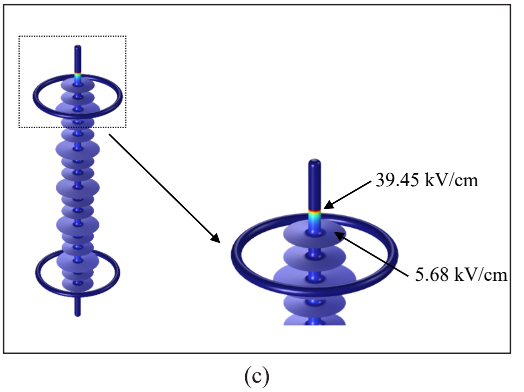

(c)

Figure 12. 3D electric field distribution, (a) without grading ring; (b) original grading ring; and (c) selected grading ring

In this case, the water droplet will have a higher permittivity than the air outside the high-voltage insulator. In comparison, the air will have the lowest relative permittivity. From the graph in Figure 14, a conclusion can be made that each location has its own withstand value of the electric field. The second location of the water droplet, which is on the curved side of the water droplet, can withstand the highest electric field. This is due to the electric field stress, highest on the curve or sharp edges, where it was concentrated and focused on that area. The different values that can be observed indicate a difference in relative permittivity. For example, consider the second location. The electric field value initially drops from 1.49×10^7 Kv/cm to 0 Kv/cm, indicating a transition from air to the interior of the water droplet. Subsequently, the electric field increases from 0 Kv/cm to 2.12 × 10^7 Kv/cm, which suggests a transition from within the water droplet to the surface of the high-voltage insulator. This behaviour demonstrates that a higher relative permittivity medium, such as water, reduces the electric field intensity within it, thus confirming that as the relative permittivity increases, the electric field strength in that region decreases.

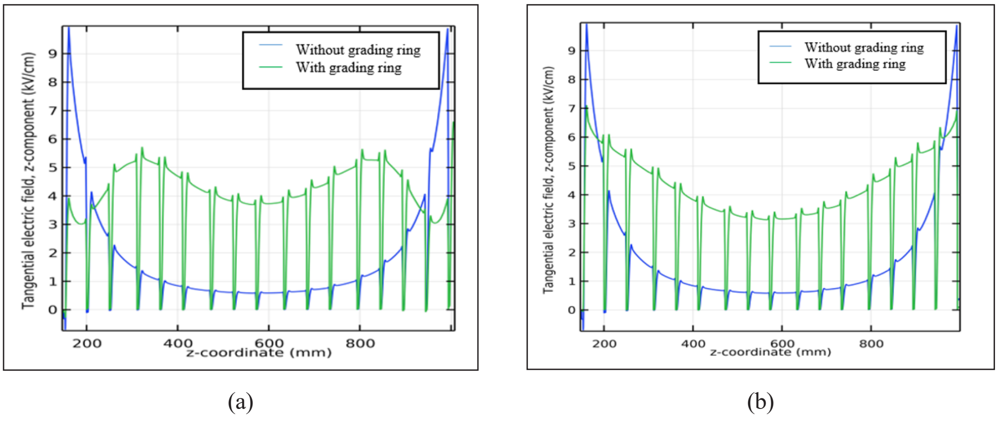

Figure 13. Comparison of the electric field distribution: (a) without the grading ring and with the original grading ring; (b) without the grading ring and with the selected grading ring

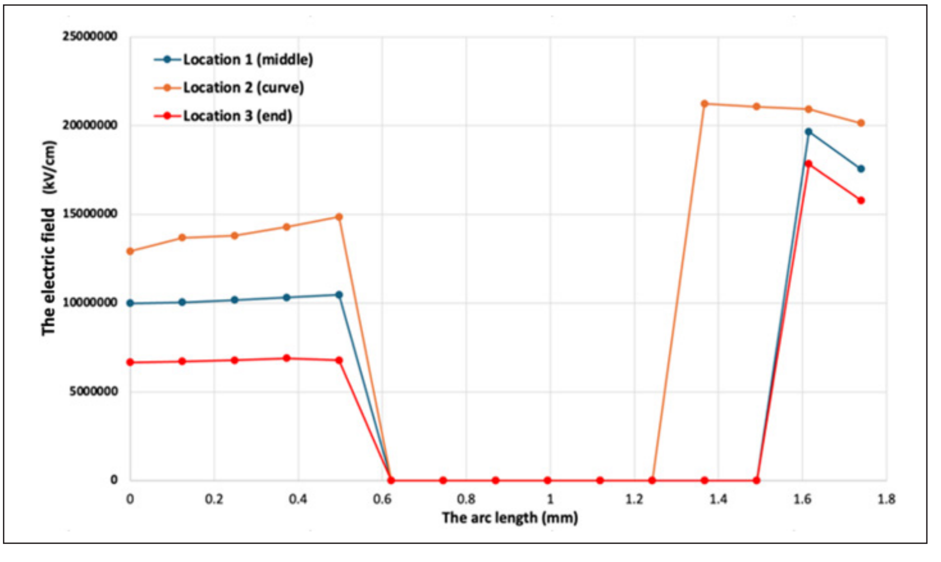

Figure 14. Simulation results of the electric field distribution across three different droplet locations (middle, curve, and end of the shed). The sudden drops to zero represent the highly dampened internal field of the water droplets due to water's high relative permittivity

From the graph output in Figure 14, the data presents the electric field profile as it traverses from the surrounding air, across the water droplet, and into the insulator. The sharp drop in the electric field to near-zero within the droplet is not due to the region being a physical void; rather, it is a direct electrostatic consequence of water's high relative permittivity. The bulk water heavily polarises, acting as a dielectric shield that drastically dampens the internal electric field. The electric field then sharply rises again at the transition boundary from the water droplet to the surface of the high-voltage insulator.

Size of the Water Droplet

The water droplet that falls from the rain will be attached to the surface of the insulator and can be considered one of the leading factors that can affect the performance of reducing and minimising the electric field stress. The contact angle of the water droplet and its sizing should be studied more extensively to ensure a better understanding of high-voltage performance (Liu & Du, 2014). Based on Figure 15, it can be concluded that varying sizes of water droplets significantly affect the electric field distribution on the surface of the high-voltage insulator.

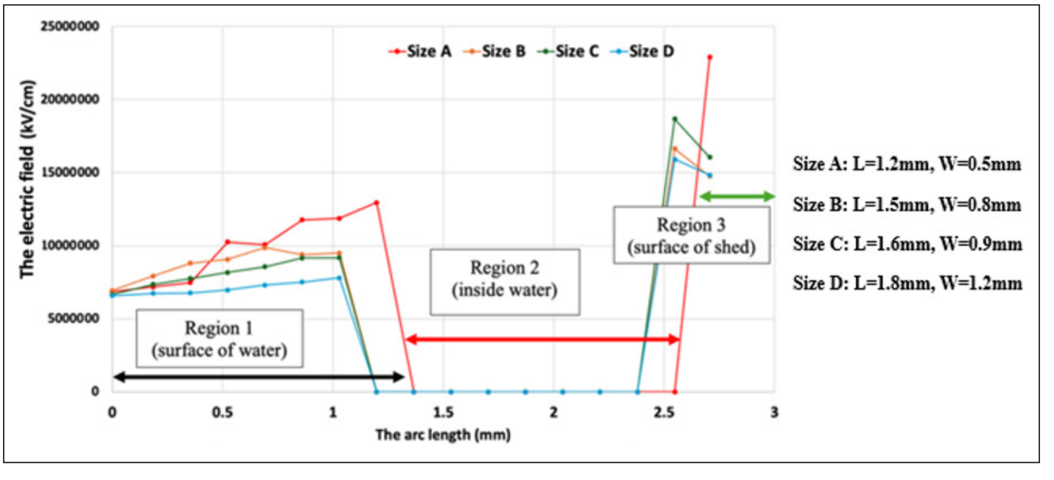

Figure 15. Electric field distribution simulation based on varying water droplet sizes. Region 1 represents the localised stress at the air-water interface, Region 2 shows the dampened internal droplet field, and Region 3 highlights the stress concentration at the boundary between the droplet and the polymer shed

The influence of water droplet location on electric field distribution can also be observed by varying the water droplet sizes. Although relative permittivity plays a key role, this analysis is focusing in examining how different sizes of droplets can affect the field behaviour. According to the result, Size A, which is the smallest droplet among all sizes, has the highest electric field, while Size D, which is the biggest droplet, has less ability to withstand an electric field. The outcomes from the simulation indicate that different droplet sizes have different electric field distribution patterns on the high-voltage insulator surface. Size A is used as a reference to draw a basic conclusion from the simulation results. The transitions in the electric field observed in Figure 15 directly correspond to the geometric boundaries defined within the simulation. The initial enhancement of the electric field (Region 1) occurs at the air-water interface, where the field concentrates heavily on the outer surface of the droplet. Following this, the electric field drops to 0 kV/cm (Region 2). In this simulation, Region 2 was deliberately modelled as a void as a computational simplification to eliminate internal dielectric dampening. This approach isolates the parameters to strictly observe the worst-case localized stress at the boundaries. Finally, the abrupt spike (Region 3) marks the critical geometric boundary between the water droplet and the polymer shed surface. As proven by the results, the high Emax is primarily concentrated at these exposed surfaces (Region 1 and Region 3), demonstrating that varying water droplet sizes significantly alter the boundary conditions and create severe localised stress at the interfaces.

CONCLUSION

In conclusion, this study focuses on the analysis of the electric field distribution on high-voltage insulators based on simulation. The results show that varying parameters, which are the thickness, diameter, and positioning of grading rings, can give impact on the insulator's performance. As the diameter and thickness were increased, the E_{max} increased by 31.02% and 22.74%, respectively. This suggests that excessive sizing can lead to unintended stress concentrations. For the distance of the grading ring from the end, the most effective position is placing the grading ring 150 mm from the termination end. Besides that, the study shows that water droplet size and location affect the electric field distribution on the surface of the high-voltage insulators. Smaller water droplets improved the electric field distribution, which helps mitigate steady-state localised corona stress on the insulator surface. Thus, this proves that the main reason hydrophobicity characteristics play a significant role in minimising the concentration of the electric field on the surface of the high-voltage insulator. This underscores the need for superhydrophobic coatings to prevent water accumulation on insulator surfaces. This research highlights the importance of the analysis of high-voltage insulator design to get the most effective performance. Each design must be simulated and analysed to ensure optimal performance and reliability according to the specific requirements of the electrical system. One of the most important elements to be focused on is the precision in design to ensure it safeguards the industry's electrical energy transmission and distribution. For future recommendations and improvements for the study, more real data is needed to collect more detailed industrial for the grading ring of the high-voltage insulator.

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