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Electric Field Response in XLPE to Various Void Sizes and Void Distances to Electrodes

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Abstract: XLPE is widely used as an insulating material in electrical systems due to its excellent dielectric properties. However, the effectiveness and dependability of the insulation might be severely impacted by the existence of voids inside it. The objective of this research is to simulate the electric field intensity in an XLPE matrix under varying voltages (15 kV, 20 kV, and 25 kV), with a focus on assessing cable aging. The study aims to examine how void size and void location influence the electric field distribution within the XLPE material. Additionally, the research seeks to explore the impact of void presence on stress concentrations and the electric potential drop within the defect area. To achieve these objectives, the study utilizes COMSOL Multiphysics software and the Finite Element Method (FEM) for the simulations. The simulation process considers different void sizes and varying distances between voids and electrodes. The electric field distribution is analyzed under the different voltage conditions to observe the effects of voids on the electric field and potential drop. The study highlighted that void location significantly impacts electric field distribution, with voids positioned closer to high-voltage electrodes resulting in higher electric field intensities, while voids located farther away exhibit lower field intensities. Additionally, the comparison between the absence and presence of voids showed that voids create stress concentrations, resulting in a more drastic drop in electric potential within the void-defect area. The examination of void location on electric field intensity has revealed the significant impact of void positioning on the distribution of electric fields, emphasizing the importance of precise insulation design and void detection strategies.

Keywords: XLPE, Electric field Intensity, Void

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1. INTRODUCTION

To ensure a high quality of electric power supplied to customers, it is crucial to assess the ageing status of installed cables after commissioning. When selecting the insulating material for medium voltage (MV) power cables, an important consideration is the degradation that leads to partial discharges at the degradation site. This degradation site is typically a void or gaseous cavity, either pre-existing or created by in-service stresses, which initiates an ionization process within the insulating walls [1, 2]. Voids and gaseous cavities can form in conductor insulation systems through various mechanisms, including both normal and improper manufacturing processes, as well as severe or cumulative mechanical and environmental stresses, and differential thermal expansions [3, 4]. The occurrence of discharges within these insulation cavities is a key aging process in polymeric insulated power cables. These internal discharges are triggered by strong and inhomogeneous electrical fields, often caused by voids, bubbles, or defects in the material [1].

Cross-linked polyethylene (XLPE) is a widely used material for electrical insulation, known for its excellent dielectric properties and mechanical strength. Its extensive application in high-voltage cables highlights its importance in ensuring the reliability and safety of power transmission systems. However, the presence of voids within XLPE can significantly undermine its insulating properties, leading to potential failures and reduced operational lifespan [4]. Therefore, this research focuses on investigating the electric field intensity within the XLPE matrix under different voltage applications. The XLPE cable is subjected to voltages of 15kV, 20kV, and 25kV to examine the electric field intensity generated inside the XLPE insulation.

2. METHODOLOGY

2.1 Simulation setup

2D COMSOL Multiphysics software is used in the present study. This software provides automatic mesh generation on the geometries for solving electrostatic problems by a differential operator FEM [5, 6]. It can display the equipotential and field lines in meshed regions. Besides, it can also plot the electric field and electric potential values at any constructed boundary. Figure 1 shows the cross-sectional structure diagram of a single core XLPE insulated cable with 7 layers which will be referred when building the model geometry in COMSOL. The specifications of the simulated XLPE cable such as material, radius, and relative permittivity of each layer are tabulated in Table 1.

Table 1. Single core XLPE insulated cable specification

Layer	Material	Radius (mm)	Relative Permittivity
1	Copper	5.7	1.0
2	Carbon black	6.4	1.0
3	XLPE	11.7	2.3
4	Carbon black	12.4	1.0
5	PVC	12.9	2.9
6	Aluminium	13.9	1.0
7	PVC	21.9	2.9

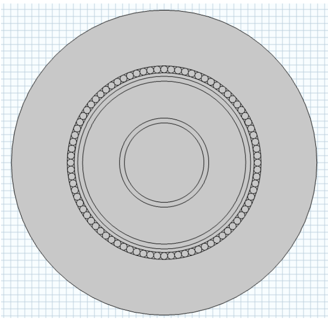


Figure 1. Single core XLPE insulated cable model geometries without void

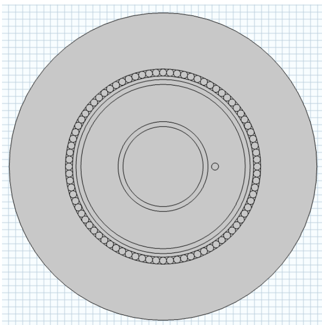


Figure 2. Single core XLPE insulated cable model geometries with void

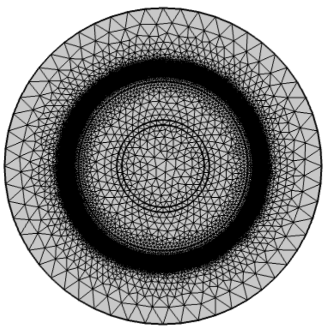


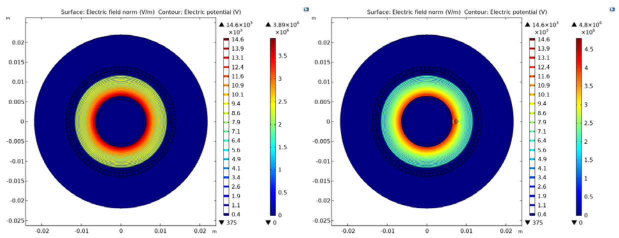
Figure 3. Single core XLPE insulated cable model meshing

Figure 1 and Figure 2 shows the simulation model geometries of single core XLPE insulated cable without void and with void respectively that has been built in COMSOL for the present study. The innermost circle represents layer 1, followed by other layers subsequently until layer 7 at outermost circle. In Figure 2, the void is filled with air which has a relative permittivity of 1.0. Each layer is defined according to Table 1. whereas Figure 3 shows the meshed simulation model using FEM for numerical analysis on the electric field intensity and potential.

3. RESULTS

3.1 Electric field intensity in XLPE matrix with different voltage application in the absence of void

The electric field intensity and electric potential contour line diagram without and with void from the electrostatic study is shown in Figure 4 (a) and (b) at 15 kV, 20 kV and 25 kV respectively. The electric field intensity is longer the strongest at the conductor surface and the weakest at the cable insulation end as in the no void condition. Instead, the electric stress developed inside the void is higher than the electric stress developed in the XLPE insulation material. Besides, the electric field intensity inside the cable does not behave symmetrically anymore as mentioned in the no void condition. In fact, the radial electric stress of XLPE matrix around the void-defect is higher than the axial electric stress.



(a) (b)

Figure 4. Electric Field Distribution and Equipotential Line developed inside a XLPE cable; (a) without void, (b) with void

The electric potential distribution with respect to the length across the XLPE matrix at 15kV, 20kV, 25kV applied voltages for both the absence of void condition and presence of void condition are plotted in a same graph as shown in Figure 5. From the graph in Figure 5, it can be observed that when void is absent, the electric potential distribution across the XLPE matrix is more linear with a smaller gradient change. Whereas when void is present, the electric potential distribution drops more drastically with a larger gradient inside the void-defect and maintains a relatively smaller gradient outside the void.

Figure 6 to Figure 8 shows the comparison on electric field intensity between the absence of void condition and the presence of void condition under 15 kV, 20 kV and 25 kV applied voltage respectively. To make the analysis becomes easier, the maximum electric field intensity with respect to each applied voltage in both conditions are tabulated in Table 2. From the Table 2, we can observe that the maximum electric field intensity developed inside the cable with void is always higher than that in cable without void under any applied voltage. This is because the voids are filled with medium of lower dielectric strength and lower permittivity like air which has been defined as the material for the void throughout this simulation. Therefore, the electric stress inside the void is higher compared to the main part of the insulator as it is less resistant to the electric stress development. Partial discharge tends to occur inside the air void due to the higher electric field stress inside it. It is also possibly setting off a positive feedback loop whereby an electron avalanche can occur, which is known as electrical breakdown.

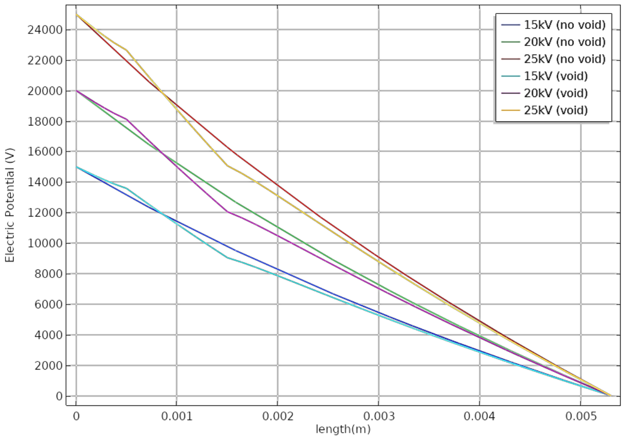


Figure 5. Electric Potential (V) vs Length (m) graph at different voltage levels for the absence of void and presence of void

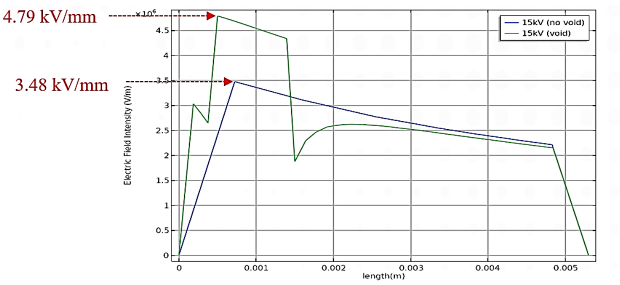


Figure 6. Electric Field Intensity (E) vs Length (m) graph at 15 kV level

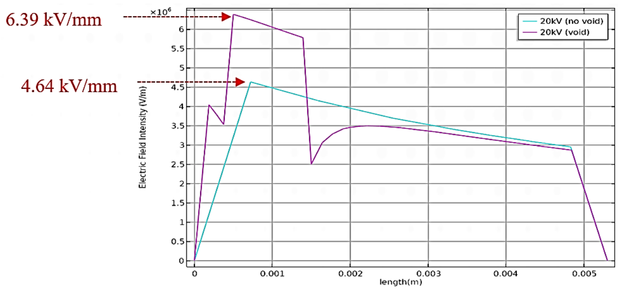


Figure 7. Electric Field Intensity (E) vs Length (m) graph at 20 kV level

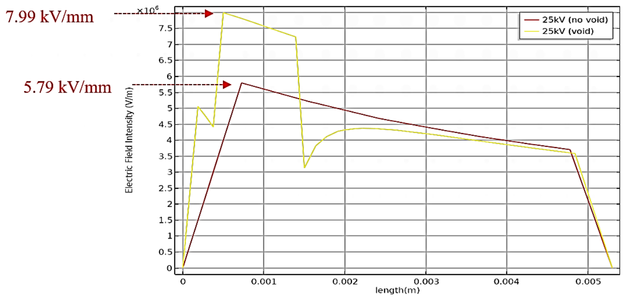


Figure 8. Electric Field Intensity (E) vs Length (m) graph at 25 kV level

Table 2. Maximum electric field intensity with respect to applied voltage in the absence of void and presence of void conditions

Applied Voltage, V (kV)	Max Electric Field Intensity with No Void, E (kV/mm)	Max Electric Field Intensity with Void, E (kV/mm)
15	3.48	4.79
20	4.64	6.39
25	5.79	7.99

3.2 Effect of Void Location on Electric Field Intensity in XLPE Matrix with Different Voltage Application

The effect of void location on electric field intensity in XLPE matrix is analyzed by simulating the XLPE insulation with air void located at several different distances away from the conductor shielding subsequently under 25 kV applied voltage. From the previous observation, since we know that the electric field is always the strongest at the conductor surface and the weakest at the insulation end regardless of the applied voltage level, therefore only one voltage level is applied in this void location study which is 25 kV. The chosen distances of void for simulation are 1 mm, 2 mm, 3 mm and 4mm away from the conductor shielding as shown in Figure 9 to Figure 12 respectively. The conductor shielding is made of semiconductor material but it is different to the semiconductor that we understand in electronics field. The material is a polymer base mixed with a conductivity imparting agent such as carbon black [7-9]. This semiconductive layer acts as conductor when the temperature in the copper conductor part rises.

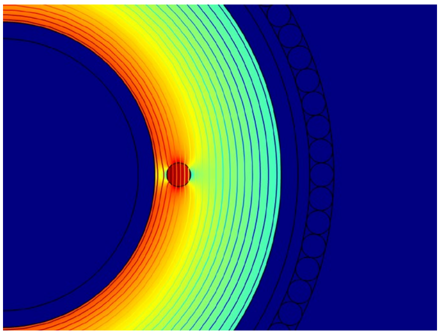


Figure 9. Void is 1 mm away from semiconductive layer

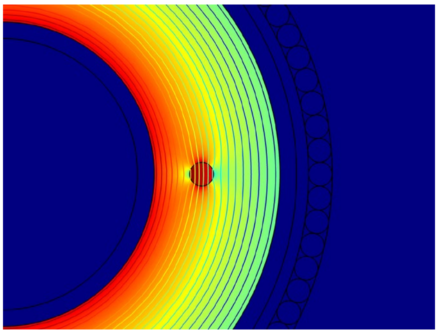


Figure 10. Void is 2 mm away from semiconductive layer

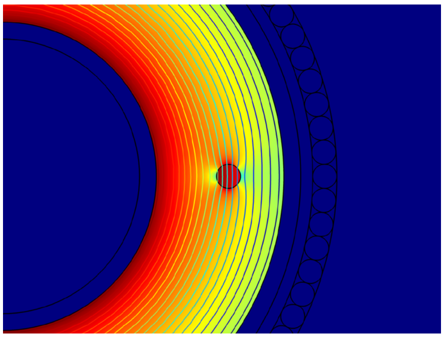


Figure 11. Void is 3 mm away from semiconductive layer

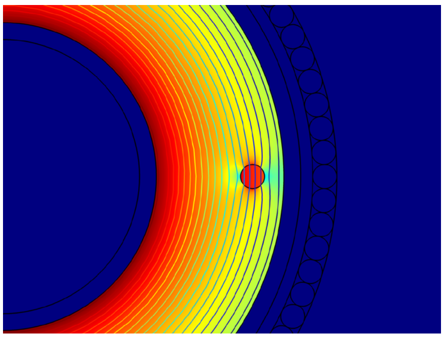


Figure 12. Void is 4 mm away from semiconductive layer

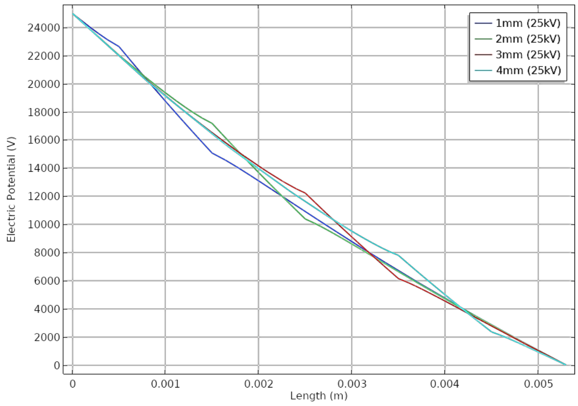


Figure 13. Electric Potential (V) vs Length (m) graph at different locations of void

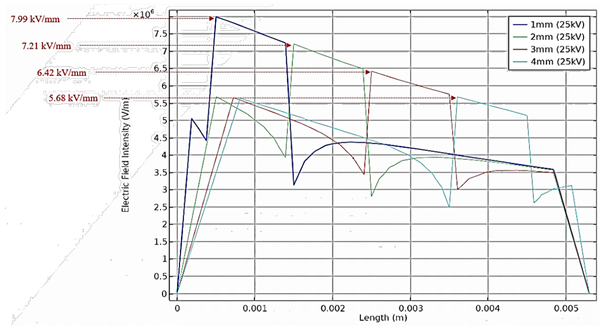


Figure 14. Electric Field Intensity (E) vs Length (m) graph at different locations of void

Table 3. Maximum electric field intensity with respect to the location of void

Distance of Void from the Conductor (mm)	Max Electric Field Intensity, E (kV/mm)
1	7.99
2	7.21
3	6.42
4	5.68

Figure 13 shows the graph of electric potential distribution across the XLPE length at different locations of void. At each of the different air void locations, the electric potential distribution always drops more drastically with a larger gradient inside the void-defect and maintains a relatively smaller gradient outside the void. By referring to Figure 14, it is significant that the location of void will affect the maximum electric field intensity developed inside the XLPE insulation. Table 3 tabulates the maximum electric field intensity with respect to the location of void. The value of electric field at a void area decreases when the distance of void from the conductor is increased. It shows that electric field inside the XLPE insulation will be more distorted when the presence of void is nearer to the conductor. This phenomenon can be explained from the equation 1 and 2 where the electric field intensity E is numerically equal to the voltage gradient ∇V.

$$\nabla \cdot D = \rho v \quad (1)$$

$$E = -\nabla V \quad (2)$$

As the void located far away from the conductor, the voltage is lower, resulting in a lower electric field intensity. Voids located closer to electrode surfaces can significantly reduce the breakdown strength. This is due to the higher electric field strength near the surfaces, which can be exacerbated by the presence of voids.

3.3 Effect of Void Size on Electric Field Intensity in XLPE Matrix With Respect to The Applied Voltage

The effect of void size on electric field intensity in XLPE matrix is studied by simulating the XLPE insulation with different sizes of air void subsequently under 25 kV applied voltage. The chosen radius of void for simulation are 0.2 mm, 0.3 mm, 0.4 mm and 0.5 mm as shown in Figure 13 to Figure 16 respectively. Since the XLPE insulation part has a thickness of 5.3 mm from the measurement, therefore its middle location is taken for setting up the void which is approximately 3mm away from the conductor shielding.

Refer to the electric potential over XLPE length graph as shown in Figure 17, at different sizes of void, the electric potential distribution always drops more drastically with a larger gradient inside the void-defect and maintains a relatively smaller gradient outside the void. However, the impact of void size on the electric potential is not significant. On the other hand, the effect of void size on the electric field intensity inside the XLPE matrix can be seen from Figure 18 and Figure 19. The maximum electric field intensity inside the XLPE matrix with respect to the size of void is tabulated in Table 4. It can be determined that the electric field is the highest when the size of the void is the smallest. Smaller diameter of void causes the collision between electrons getting higher. This will eventually lead to a higher ionization rate inside the void, resulting in higher electric field inside it.

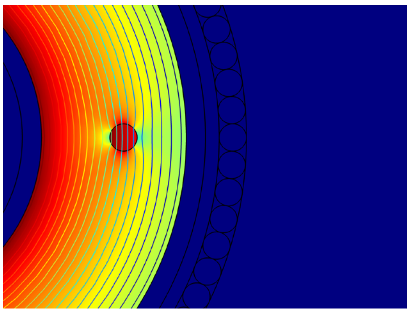


Figure 14. Void with 0.2 mm radius, 3 mm away from semiconductive layer

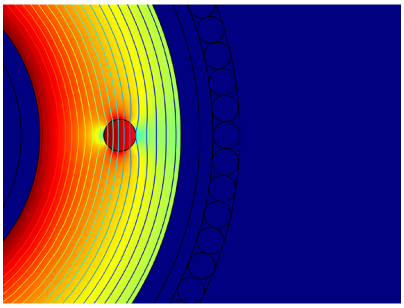


Figure 15. Void with 0.3 mm radius, 3 mm away from semiconductive layer

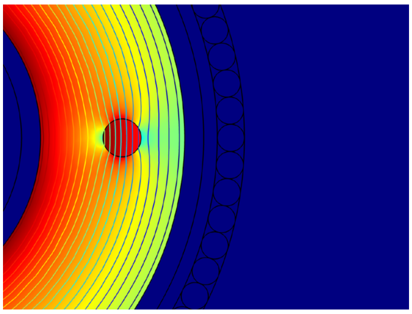


Figure 16. Void with 0.4 mm radius, 3 mm away from semiconductive layer

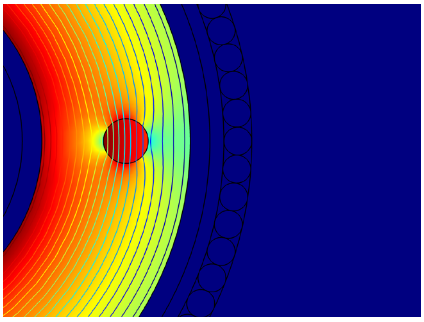


Figure 17. Void with 0.5 mm radius, 3 mm away from semiconductive layer

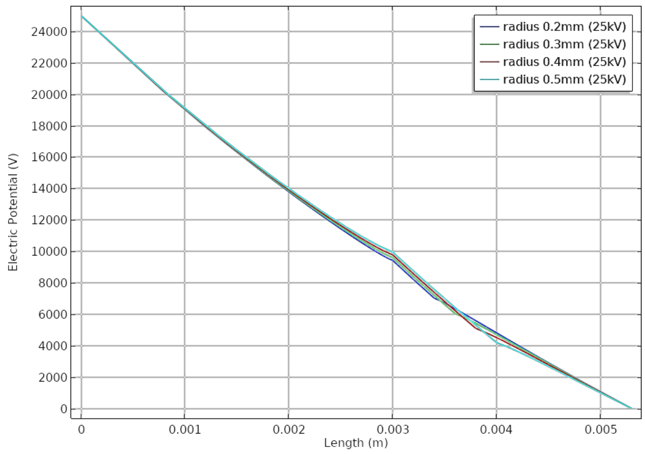


Figure 18. Electric Potential (V) vs Length (m) graph at different sizes of void

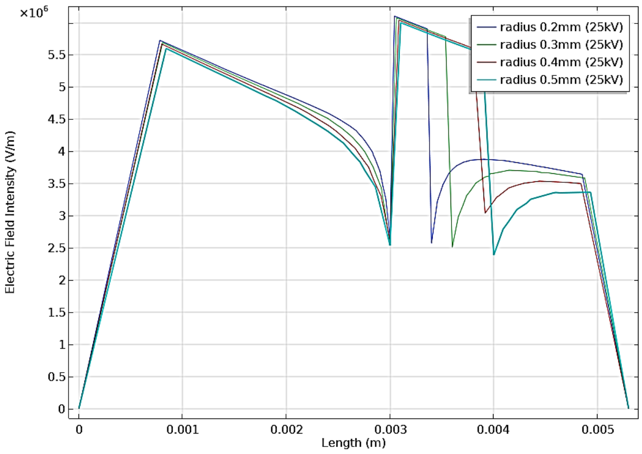


Figure 19. Electric Field Intensity (E) vs Length (m) graph at different sizes of void

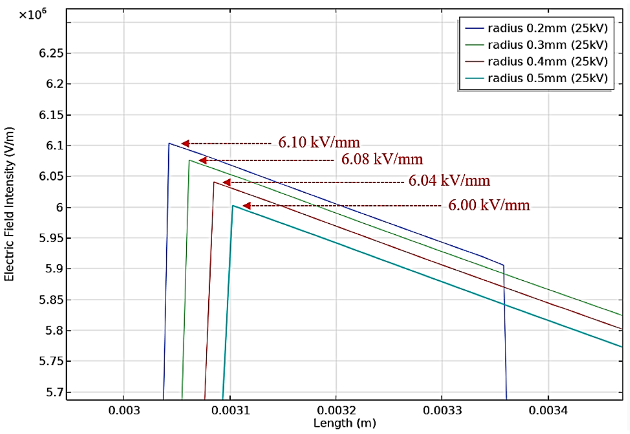


Figure 20. Electric Field Intensity (E) vs Length (m) graph at different sizes of void (Enlarged view)

Table 4. Maximum electric field intensity with respect to the size of void

Radius of Void (mm)	Max Electric Field Intensity, E (kV/mm)
0.2	6.10
0.3	6.08
0.4	6.04
0.5	6.00

The combined effect of void size and location plays a crucial role in determining the overall performance and stability of materials, particularly in high-voltage environments. These factors can create a variety of complex interactions that are not immediately apparent through simple analysis. For example, a large void located near an electrode can dramatically influence the electric field distribution within the material. The proximity of the void to an electrode can lead to a concentration of electric fields, potentially causing localized stress that exceeds the material's breakdown strength [10-12]. In contrast, a smaller void situated in a less critical area may not have the same severe impact, as it might not contribute to the same level of field intensification. This illustrates how void size alone is insufficient in predicting material performance; the location of the void can significantly amplify or mitigate its effects. As a result, understanding the interplay between void size, position, and their influence on electric field distribution is essential for accurate predictions of breakdown strength and for designing materials that can withstand high-stress environments without failure. This insight is vital for industries relying on high-voltage systems, where material integrity is crucial for safety, performance, and longevity [13, 14].

4. CONCLUSION

The analysis of electric field intensity in XLPE matrix under varying voltage applications, both in the presence and absence of voids, has provided crucial insights into the behaviour of electric fields within high voltage cables. The comparison between the absence and presence of voids has demonstrated notable differences in electric field distribution and potential stress points within XLPE cables. When voids are present, the electric potential distribution exhibits a more drastic drop with a larger gradient inside the void-defect, emphasizing the vulnerability of cable insulation to void-induced stress concentrations. The examination of void location on electric field intensity has revealed the significant impact of void positioning on the distribution of electric fields, emphasizing the importance of precise insulation design and void detection strategies. Furthermore, the study on the effect of void size on electric field intensity has highlighted the role of void dimensions in influencing the overall electric field distribution within XLPE insulation. Understanding how void size affects electric field behaviour is essential for optimizing cable design and mitigating potential risks associated with partial discharges and insulation breakdown.

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