Influence of Silicone Grease on the Electric Field at the XLPE–Silicone Rubber Interface

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ABSTRACT The application of silicone grease at the interface of XLPE/silicone rubber is a key step in the production of cable intermediate joints. However, staff members are not sufficiently aware of the importance of application of silicone grease. It's Often to find silicone grease not applied or unevenly smeared. The effect of silicone grease on the interface electric field has not been reported. Therefore, this paper established a three-dimensional finite element model of the 10kV cable intermediate joint to analyze the electric field distribution under three working situations, that silicon grease is applied or not; silicon grease is distributed evenly and unevenly; and the focus on the inhibitory effect of silicone grease on other defects. The simulation results show that, when no grease is applied, the maximum field strength of the interface is 3.79 times larger than that of when silicon grease is applied, the maximum field strength under the situation that silicon grease is distributed unevenly is 2.8 times larger than that of when the silicon grease is unevenly applied. Absence of silicone grease and unevenly distributed silicon smearing both cause serious distortion of the interface electric field distribution. In addition, when there is a main insulation impurity in the silicone grease, the field strength at the impurity is much less than that when the interface has main insulation impurity with silicon grease unapplied. It shows that the application of silicone grease has optimizing function on electric field distribution under impurity defects situation. Applying silicone grease is an indispensable part of on construction.

INDEX TERMS the cable intermediate joint; the interface of XLPE/silicone rubber; silicone grease; effect on electric field.

I. INTRODUCTION

In recent years, power cable faults are reported frequently, certain types of faults appearing just a few years after the power cables were first used in some extreme cases, intermediate joint failures have escalated into explosive accidents [1]–[3]. The fabrication quality of cable intermediate joints in the field is inherently influenced by the technical competency of installation personnel and on-site supervisors. Deviations from standardized procedures during jointing may result in the introduction of latent defects. Once an intermediate joint is sealed, what is inside can no longer be seen, making it impossible to check directly. As a result, any hidden flaws will stay undetected. Over time, these invisible issues may affect the long-term safety and stable operation of the power cable system.

In actual cable intermediate joints, silicone grease is usually applied uniformly between the main insulation of the accessory and the insulation of the cable to ensure tight contact. This grease coating is the sole means of guaranteeing the seal integrity and surface tracking resistance at the joint interface [4]. However, due to limited understanding of this application process among field technicians, common issues include missed application, uneven distribution, and contamination with foreign particles during application. Research on the impact of these factors on joint electric fields remains unreported.

Reference used finite element simulation to compare the effects of applying conventional silicone grease (CSG) versus fluorinated silicone grease (FSG) on the interface characteristics of cable intermediate joints. Reference [5] employed COMSOL finite element simulation software to calculate electric fields for four typical defects: scratched main insulation, impurities in the joint, incorrect use of insulating tape on the connecting tube, and moisture ingress in the joint. Reference [6] investigated the effect of air gap thickness on electric field distribution in 10kV cable joints with air gap defects in the connecting tube, and performed high-voltage testing on the defect using an oscillating wave test system. The cable joint models were established to calculate the impact of air gaps at different locations on the electric field at these locations in the research papers [7]–[14]. In the above these papers, discussions on the influence of different joint faults on the electric field from different angles provided a certain reference value. However, some finite element models in these references are simplified: they omit chamfers at stress cones and semiconductor layers inside/outside joints, and exclude silicone grease layers, resulting in discrepancies from actual cable joint structures. Furthermore, certain studies on asymmetric defects employ two-dimensional models, which cannot accurately simulate real-world joint conditions.

In this paper, based on the time-harmonic electromagnetic field equations, the electric field distributions under five scenarios—interface with applied thermal grease, interface without thermal grease, unevenly applied thermal grease, thermal grease containing impurities during application, and interface without thermal grease but containing impurities—were calculated using finite element software to investigate the electric field distributions in these cases. By comparing with the electric field under the normal conditions, the study aims to investigate the change of the electric field with no grease applied, as well as the impact of the uneven application of the grease on the interface electric field. Special attention is paid to the investigation of the relationship between the electric field and the thickness of the air gap with the uneven application of the grease. Furthermore, comparisons are made between the electric field distributions when grease application contains impurities and when no grease is applied but impurities are present, providing a deeper analysis of how grease application optimizes the electric field at impurity defect locations.

II. NUMERICAL ELECTRIC-FIELD COMPUTATION AND MODELING OF CABLE INTERMEDIATE JOINTS

A. NUMERICAL FORMULATION FOR ELECTRIC FIELD COMPUTATION

Because high-voltage power equipment usually runs on a 50-Hz AC power supply, the voltage distribution inside the joint can be seen as nearly steady. This makes it possible to use an electrostatic model for both theory and simulation work [15]. Based on this, we built a three-dimensional model and ran a finite element analysis to find out how the electric field is spread inside the cable joint.

The basic rules that control the electrostatic field inside insulating materials are shown here:

$$D_i = \varepsilon_m E_i \tag{1}$$

$$E_i = -\frac{\partial \varphi}{\partial x_i} \tag{2}$$

$$\frac{\partial D}{\partial x_i} = 0 \quad (i = 1, 2) \tag{3}$$

The functional expression of the electric field energy is given by:

$$W(\varphi) = \iint_D \frac{1}{2}\varepsilon E^2 \, dD = \iint_D \left[\frac{\varepsilon}{2}(\nabla\varphi)^2 - \rho\varphi\right] dD \tag{4}$$

The variational form of the functional is expressed as:

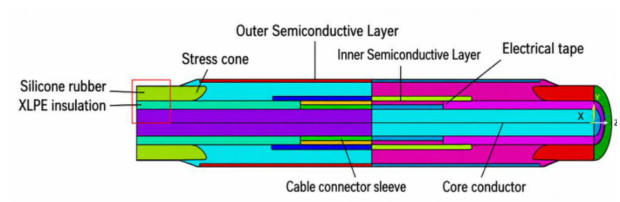
$$\delta W(\varphi) = \iint_D \left[\varepsilon \nabla\varphi \cdot \nabla(\delta\varphi)^2 - \rho\varphi\right] dD \tag{5}$$

At last, by using the special traits of these equations, the voltages at each point are found with integral calculations, and this finishes the work on the electric field.

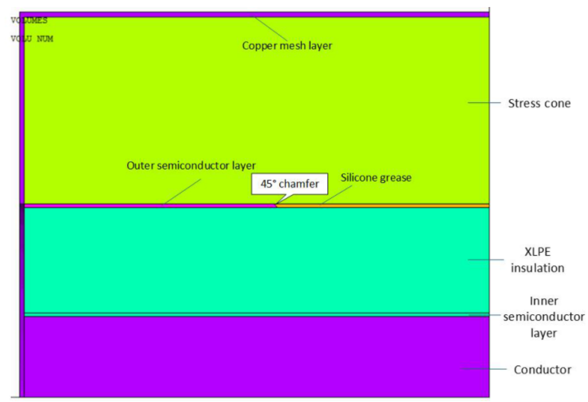
B. DEVELOPMENT OF THE CABLE INTERMEDIATE JOINT MODEL

1) THREE-DIMENSIONAL MODEL OF THE CABLE INTERMEDIATE JOINT

The 3D model we built for this cable joint study is shown below in Fig. 1. All geometric dimensions are configured on a 1:1 scale based on the specifications of a commercially manufactured 10-kV XLPE cold-shrinkable intermediate joint. Since the inner and outer semiconductive layers, silicone grease, and copper mesh are relatively thin, their structures are illustrated separately in Fig. 1(b).



a. 3D Model of the Cable Intermediate Joint.



b. Detailed View of the XLPE–Silicone Rubber Interface.

FIGURE 1. 3D model of the cable intermediate joint.

2) MATERIAL PARAMETERS OF THE CABLE INTERMEDIATE JOINT

The material parameters used in the simulation model are listed in Table I:

TABLE I. Parameters of materials used in intermediate cable joint

Component	Relative permittivity	Thickness /mm	Radius /mm	Length /mm
Conductor	10000	–	9.3	–
Splicing sleeve	10000	3.4	–	118
Copper mesh	10000	0.28	–	Covering the entire joint
Semiconductive layer	1000	0.3	–	268
Silicone grease	5	0.3	–	Set according to the cross-section
Stress cone	1000	10.3	–	57.4
Air	1	–	–	–
Silicone rubber	2.8	13/10	–	158
XLPE insulation	2.5	5.8	–	268
Insulating tape	1000	2.8	–	11.8

The parameter settings defining the four main scenarios analyzed in this work—the absence of silicone grease, its uneven application, the presence of impurities within the grease, and the case of impurities without any grease—are provided in Table 2.

TABLE II. Parameters of Defects applied

Specification	Configuration / Description
Baseline Case	Silicone grease applied uniformly in accordance with standard procedures.
No Grease Applied	An air gap introduced at the XLPE insulation-silicone rubber interface.
Uneven Grease Application	A rectangular air gap (6 × 5 × 0.3 mm) embedded within the grease layer.
Impurities in Grease	A rectangular sand particle (5 × 5 × 0.3 mm) embedded within the grease layer.
Impurities without Grease	A rectangular sand particle (5 × 5 × 0.3 mm) placed at the XLPE insulation-silicone rubber interface.
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Specification	Configuration / Description

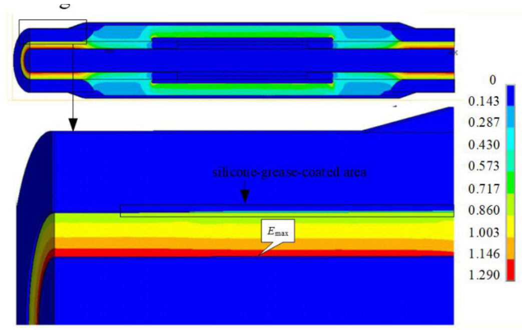
3) MESH GENERATION AND BOUNDARY CONDITION SETTINGS

In the meshing process carried out through the simulation environment ANSYS by means of the APDL parametric scripting language, the bodies with chamfered geometrical features are first meshed by proportional subdivision of the edges and subsequent volumetric subdivision. The bodies without any chamfers are meshed by the SmartSize level-4 meshing technique. For the slender shell-like geometries like the copper mesh and the silicone grease layer, the mapped meshing technique is adopted. This technique is useful for controlling the mesh size while ensuring the quality of the elements. Mesh refinement is carried out in areas with acute angles. For the boundary conditions, the voltage level $10\sqrt{3}$ kV is given as for the conductor, while the outer copper shielding layer of the joint is kept at zero potential.

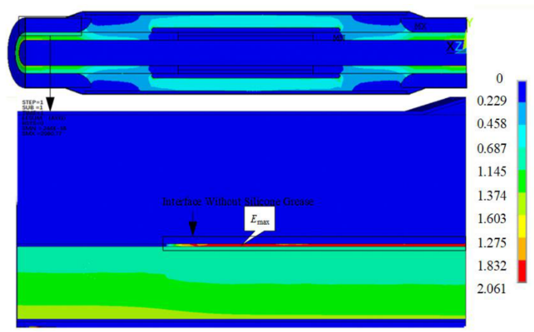
III. RESULTS AND ANALYSIS

A. EQUATIONS

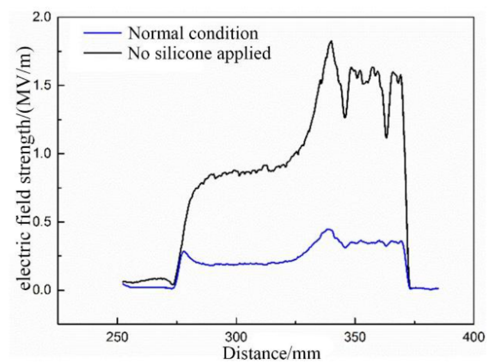
Influence of Silicone Grease on the Interfacial Electric Field Distribution



a. Electric Field Distribution Under Normal Conditions.



b. Electric Field Distribution at the Grease-Free Region 2.



c. Electric Field Variation Along the Cable Core.

FIGURE 2. Inner electric field distribution curves under two situations.

Figure 2(a) illustrates the cable joint fabricated strictly in accordance with standardized installation procedures. Under this condition, the electric field inside the joint exhibits a symmetric distribution, with the maximum field strength—1.35 MV/m—occurring at the interface between the main insulation and the inner semiconductive layer near the stress cone. As shown in the detailed view of Fig. 2(a), the electric field strength at the outer semiconductive layer is nearly zero, while the field at the interface between the XLPE insulation and the silicone rubber is approximately 0.43 MV/m.In contrast, the condition without silicone grease, shown in Fig. 2(b), results in an air gap at the XLPE–

silicone rubber interface. Since cable insulation operates under an alternating electric field, the local field intensity is inversely proportional to the dielectric permittivity. The air gap has a significantly lower relative permittivity than the adjacent insulating materials, producing a permittivity discontinuity at the interface. The interfacial electric field strength increased by 3.8 times compared to normal conditions, reaching 2.06 MV/m. Although this did not reach the air breakdown field strength, the electric field at the interface had already undergone severe distortion compared to normal conditions. In AC lines, once the voltage reaches its peak or an overvoltage occurs, the field strength will increase linearly. Air discharge is highly likely to occur at the interface, reducing the joint's insulation strength and potentially causing joint breakdown.

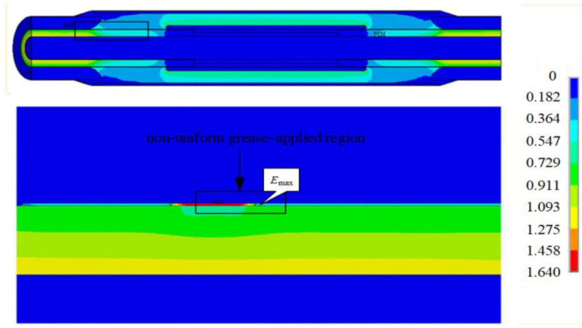
Take a path along the cable core direction from the outer semiconductive layer to the outer end of the cable joint tape. Plot the electric field strength values along this path under both conditions in Figure 2(c). The figure shows that without applying silicone grease, the electric field strength at all interface locations is higher than under normal conditions. As a result of the application of silicone grease, the trend of the field strength curve is smooth, compared to the field strength curve without silicone grease, which has many abrupt changes in electric field strength. This is because the uniform application of silicone grease enhances the airtightness of the cross-section, thus eliminating abrupt changes in relative permittivity. This proves that the application of silicone grease enhances the electric field in the cable joint significantly.

B. EFFECT OF UNEVEN GREASE ON THE FIELD AT THE INTERFACE

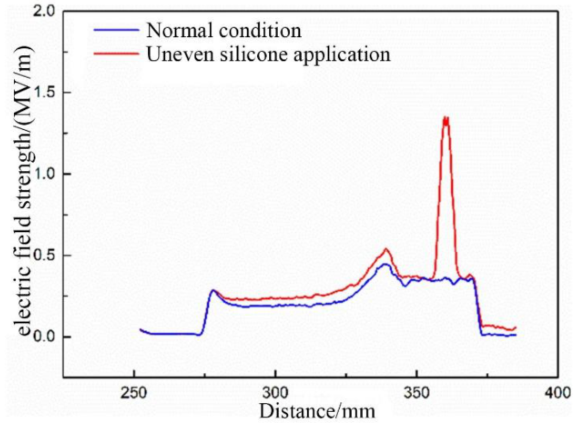
During actual joint fabrication, we may find small gaps at the interface when applying silicone grease. These gaps can cause the grease to spread unevenly. In areas where the grease is not evenly coated, air gaps may appear. The shapes of these gaps are naturally random. They could be circular, rectangular, or even highly irregular. These cases involve complex structures. The many possible shapes make it hard to model and mesh features like chamfers. Therefore, to save computing time, we simplify the problem. In simulations, we model air gaps as rectangular prisms.

1) EFFECT OF EVEN AND UNEVEN GREASE ON THE FIELD AT THE INTERFACE

Here we look at two cases side by side. One case has grease put on evenly. The other case has grease put on unevenly. Their electric field patterns are shown in Fig. 3.



a. Electric Field Profile in the Uneven Grease Application Area.



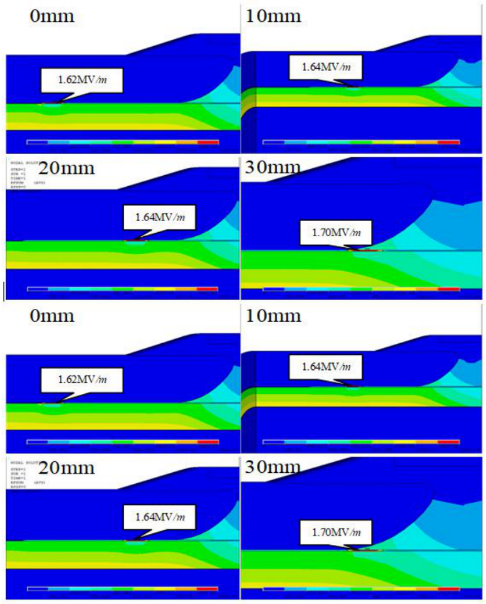
b. Comparison of Electric Field Distribution Along the Cable Core in Two Scenarios.

FIGURE 3. Normal application of thermal grease vs. uneven application of thermal grease.

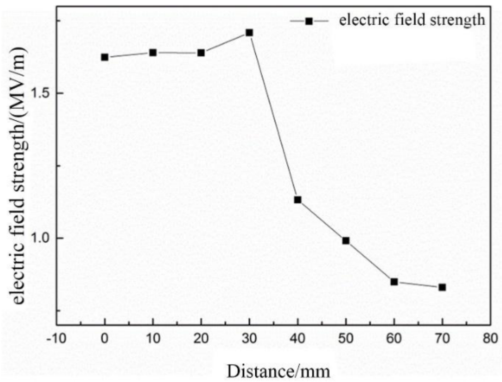
It is observed from Figure 3(a) that when the thermal grease is not evenly applied, an asymmetrical distribution of the electric field is observed along the axis of the conductor. The point where the thermal grease is unevenly applied on the left-hand side of the cable joint experiences the maximum electric field strength of 1.64 MV/m, while the right-hand side experiences an electric field strength of 0.55 MV/m. Severe distortion occurs in the electric field at the unevenly applied grease area, primarily due to the presence of air gaps during uneven application, which have a lower dielectric constant. Figure 3(b) illustrates the electric field distribution curves for both uniform and non-uniform thermal grease application. Overall, the electric field strengths are very similar in the uniformly coated areas. However, severe distortion occurs at the non-uniformly coated locations, where the field strength is significantly higher than at the corresponding uniformly coated positions.

2) EFFECT OF AIR-GAP POSITION ON THE ELECTRIC FIELD IN UNEVEN GREASE–APPLIED REGIONS

Using the cutoff point of the outer semiconductor layer as the reference, the relationship between the axial position relative to the cutoff point and the field strength was analyzed for different locations within the air gap. Simulation results are shown in Figure 4(a), and the field strength at various positions within the air gap is plotted in Figure 4(b).



a. Electric Field Distribution at Various Air-Gap Positions From the Outer Semiconductive Cut-Off.



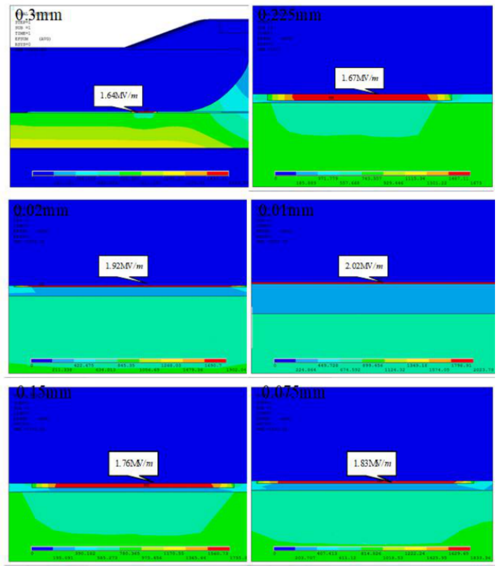
b. Effect of Different Air Gap Positions on the field strength.

FIGURE 4. Effect of Different Air Gap Positions on the Electric Field.

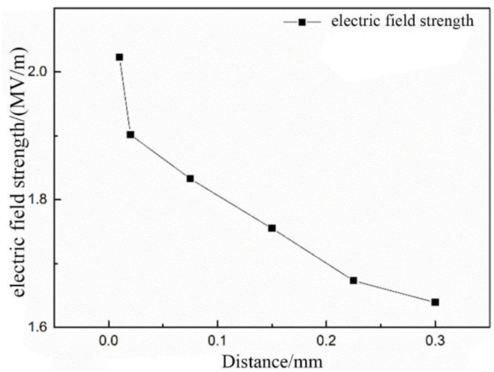
As shown in Figure 4(a), when the thermal grease is not applied evenly, the electric field inside the cable joint becomes asymmetric along the conductor axis. On the left side, where the grease is uneven, the electric field is at a maximum value of 1.64 MV/m. On the right side, where the grease is applied uniformly, the value of the electric field is 0.55 MV/m.The electric field is severely distorted on the area where the grease is unevenly applied. This is mainly because air gaps are formed as a result of unevenly applied grease. These air gaps have a lower dielectric constant. Figure 4(b) shows the electric field distribution curves for both uniform and non-uniform grease application. Overall, the field strengths are quite similar in the areas where the grease is uniform. However, in the areas where the grease is non-uniform, the field strength is much higher. These values are significantly larger than those in the corresponding uniform areas.

3) EFFECT OF AIR-GAP THICKNESS ON THE ELECTRIC FIELD IN UNEVEN GREASE–APPLIED REGIONS

The thickness of the air gap, at a distance of 20 mm axially from the outer semiconductor cutoff point, was set to 0.3 mm, 0.225 mm, 0.15 mm, 0.075 mm, 0.02 mm, and 0.01 mm, respectively. The results of the simulation are presented in Figure 5(a), and the electric field distribution in the air gap for various thicknesses is presented in Figure 5(b).



a. Electric Field Distribution for Different Air-Gap Thicknesses.



b. Relationship Between Air-Gap Thickness and Electric Field Strength.

FIGURE 5. Effect of Different Air Gap Thicknesses on Electric Fields

Examining gaps from 0.01 mm up to 0.3 mm thick, the field changes from 1.64 MV/m to 2.02 MV/m. That is about 2.8 to 3.7 times higher than normal with grease. For all these sizes, the field around the gap is badly bent. Also, when the gap gets thicker, the field around it gets a bit weaker. This is because the field inside the gap acts like a steady field. Old tests show that thinner gaps bend the field more. So, the thinner the gap, the higher the field.

C. MITIGATING EFFECT OF SILICONE GREASE ON ELECTRIC FIELD DISTORTION CAUSED BY IMPURITY DEFECTS

Cable joints are often made right at the work site, out in the open. The conditions there can be messy. If workers are not careful, bits of stuff—like scraps from cutting the outer conductive layer or sand—can stay on the main insulation. If grease is also missed at that spot, these bits get stuck. This leads to dirt spots with no grease [19], [20]. To see how grease As shown in Figure 6(a), the main insulation has impurities, and the interface has been coated with silicone grease evenly. In this case, the highest value of the electric field occurs at the semiconductor layer inside the cable, with the value equal to 1.27 MV/m. At the interface coated with the grease, the value is 0.42 MV/m. At the point close to the impurity, the value increases to 0.7 MV/m, which is 66.7% higher than the value at the coated interface. This occurs because the impurities change the value of the dielectric constant, which causes the value of the electric field to increase. In Figure 6(b), the interface has impurities, and the interface has not been coated with silicone grease. In the absence of the grease, the main insulation and the accessories are separated by a layer of air. This causes the value of the electric potential to be concentrated in the interface. As a result, the value of the electric field becomes highly distorted, with the value equal to 1.97 MV/m. At the point with the impurities, the value of the electric field becomes 1.3 MV/m, which is 1.88 times higher than the value shown in Figure 6(a). Figure 6(c) presents the electric field distribution curves for both cases. Overall, the field strengths at the measured points are higher without silicone grease than with it. In particular, the field strength at the impurity location is higher when no grease is applied. This shows that applying silicone grease can significantly reduce electric field distortion near impurities in the main insulation. It also highlights the importance of using silicone grease in cable joints.

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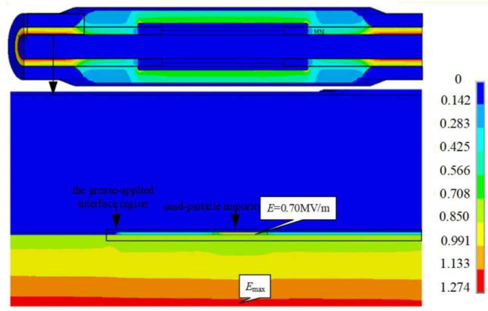
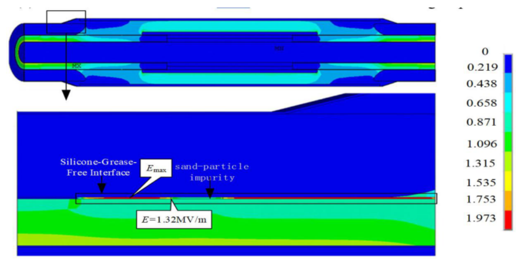
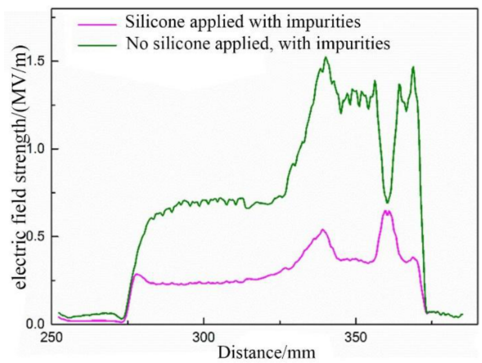


a. Electric Field Distribution With Silicone Grease Containing Impurities



b. Electric Field Distribution for Grease-Free Interfaces Containing Impurities.



c. Electric Field Profile in the Vicinity of the Impurity.

FIGURE 6. Effect of Different Air Gap Thicknesses on Electric Fields.

IV. CONCLUSION

(1) When silicone grease is not applied, the interfacial electric field exhibits severe distortion compared with the normal greased condition.

(2) Regions with non-uniform silicone grease application show a significant increase in electric field strength relative to the uniform condition. The distortion is most pronounced

when the air gap created by uneven grease application is located near the stress cone, and the field intensity decreases gradually as the air-gap position moves farther away from the stress cone. Therefore, during cable joint fabrication, particular attention must be paid to ensuring uniform grease application around the stress cone. In addition, thinner air gaps in non-uniformly greased regions lead to higher field intensities and more severe distortion.

(3) When silicone grease is applied, the electric field strength at impurity defects within the main insulation is reduced by approximately 47% compared with impurity defects in the absence of grease. These numerical results demonstrate that silicone grease substantially mitigates electric-field distortion associated with potential impurity defects at the interface and provides a significant improvement in the local electric field profile.

(4) Although the electric field strength under conditions of no grease application or non-uniform grease application does not exceed the breakdown field, it exhibits severe distortion relative to the normal condition. Under voltage peaks or overvoltage conditions during cable operation, these regions—particularly those lacking grease or having non-uniform grease coverage—will experience even more pronounced electric-field distortion, which may diminish the insulation strength of the joint and pose a significant safety risk to cable-line operation.

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