Three-dimensional simulation analysis of electric field distribution at the middle joint of 110 kV cable with typical defects

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Abstract. The joint of high-voltage cable is the weakest part in the whole cable system, and the local defect of the middle joint will affect the distribution of the internal electric field. This paper establishes a three-dimensional model by finite element simulation software based on the electric field calculation equation in Maxwell equation system. The influence of typical defects such as impurity, scratch and air bubble on the electric field distribution in the middle joint is analysed. The results show that the internal defects of the middle joint may cause distortion of the local electric field strength in the middle joint, which may lead to deterioration of the insulation.

1. Introduction
With the rapid urbanization process and the maturation of polyethylene material process, XLPE power cable has been widely recognized for its excellent mechanical performance and high-quality insulation performance, and has been widely used in the power industry. At the same time, the middle joint used with power cables is also widely used because the length of the power cables has been fixed before leaving the factory, the cables need to be cut off during the construction on site, and the middle joint of the cables is used to connect the cables. Although the improvement of modern manufacturing and installation technology make the possibility of cable and cable middle joint failures due to their own quality problems greatly reduced, according to the operation experience of high-voltage cables, aging of insulation, water intrusion, irregular engineering installation, external force damage are still the main reasons that may lead to failure of high-voltage cable system [1]. Moreover, the structure of the cable middle joint is much more complex than that of the cable body. As the weakest part in the whole cable system, the middle joint is prone to local defects, which may cause uneven distribution of electric fields in the insulation and affect its conduction and polarization, and may even cause partial discharge [2,3], thereby affecting the life of the insulation, at last the reliability of the insulation will directly affect the safety of power supply.

For various defects caused by cable and cable middle joint in the process of production and installation, scholars have carried out corresponding simulation calculations and obtained some preliminary conclusions [4]. However, at present, most of the electric field simulation of cable and cable middle joint is done by building models under the electrostatic field. The results sometimes do not really reflect the distribution of electric field, especially after the introduction of conductive media, this
situation becomes more serious. The electric field distribution is affected not only by the relative
dielectric constant $\varepsilon$ but also by the conductivity $\sigma$. Therefore, no accurate data can be obtained by
analysing the electric field distribution in the middle joint under the electrostatic field.

In this paper, 110 kV middle joint is discussed. The conductor shielding layer and stress cone
structure contained in the middle joint are made of semi-conductive material. In addition, the defect
simulation needs to introduce the defect of conductive particles, so the leakage current under the power
frequency voltage cannot be ignored, so the accurate calculation results cannot be obtained by simulating
its electric field under the electrostatic field, it should be carried out under the quasi-static field [5,6].
The dimension of the model depends on the geometric characteristics of the middle joint. If the middle
joint is axially symmetric, a two-dimensional axially symmetric model is recommended. However, the
axially symmetry of the middle joint is destroyed when the defects are introduced. Therefore, a three-
dimensional stereo model is used to reflect the spatial distribution of the electric field inside the cable
middle joint.

2. Structure of 110 KV cable middle joint

Figure 1 is a simplified structure of 110 kV cable middle joint, in which the copper core is connected
through the connecting tube, the cross-linked polyethylene and the silicone rubber of the middle joint
prefabrication act as the main insulation, and the stress cone, grading ring and semi-conductive shielding
layer of the prefabrication solve the problem of excessive changes in stress and electric field caused by
the cable middle joint, and play the role of supporting the middle joint prefabrication. The copper screen
is a layer of copper wire mesh, which guarantees a potential of 0. The outer sheath protects the cable.

![Figure 1. Structure of 110 KV cable middle joint](image)

1- Cable core, 2- Connecting tube, 3- Grading ring, 4- Cross-linked polyethylene, 5- Stress cone,
6- Semi-conductive shielding layer of the prefabrication, 7- Silicone rubber of the joint
prefabrication, 8- Outer sheath, 9- Copper screen.

3. Electric field simulation of 110KV cable middle joint

3.1. Simulation model

Referring to the actual structure drawings of 110kV cable middle joint, a 1:1 simplified model was
constructed by COMSOL, and the relative dielectric constant and conductivity of the corresponding
materials were set according to Table 1.

| NO. | Materials                              | Relative dielectric constant | Conductivity [S/m] |
|-----|----------------------------------------|------------------------------|--------------------|
| 1   | Cable core                             | 10000                        | 5.997*10^7         |
| 2   | Connecting tube                        | 10000                        | 5.997*10^7         |
| 3   | Grading ring                           | 10000                        | 5.997*10^7         |
| 4   | Cross-linked polyethylene              | 2.5                          | 1*10^{-13}         |
| 5   | Stress cone                            | 100                          | 6                  |
| 6   | Semi-conductive shielding layer of the prefabrication  | 100                          | 6                  |
Because this simulation studies the electric field distribution of 50Hz power frequency voltage of the cable middle joint, the voltage variation is relatively slow. For simplified calculation model, this can be considered as an electrostatic field, therefore, the governing equation is as follows

\[ \nabla \cdot J = Q_f \]  
\[ J = \sigma E + J_e \]  
\[ E = -\nabla \phi \]  

Where \( \nabla \) is the vector differential operator, \( J \) is the current density vector, \( A/m^2 \); \( Q_f \) is the current source, \( A/m^2 \); \( \sigma \) is the conductivity, \( S/m \); \( E \) is the electric field strength vector, \( V/m \); \( \phi \) is the electric potential, \( V \); \( J_e \) is the external injection current density, \( A/m^2 \). In this equation system, the basic parameter to be solved is \( \phi \), and the other parameters are based on \( \phi \).

According to the 110kV line voltage as the reference, the cable core, connecting tube and grading ring are set as an equipotential body, the voltage of 63.5kV is applied, and the copper shielding layer is grounded, which is the zero potential reference. Frequency domain research is adopted, and the frequency is set as 50 Hz. The simulation model of cable middle joint is shown as figure 2. The total number of nodes of the mesh generation is about 1.8 million.

Figure 2. Simulation model of cable middle joint

### 3.2. Electric field distribution in the middle joint without defects

Figure 3 and 4 show the electric field strength and potential distribution of the defect-free cable middle joint model. From the diagram, it can be seen that the electric field strength is relatively even. Because the insulation part of the cable middle joint is composed of the main insulation layer of the cable and the main insulation layer of the cable middle joint, the electric field strength is smaller than that of the insulation layer of the cable, and decreases with the thickness of the insulation layer. In the potential distribution, because of the electrostatic shielding effect of the pressure equalizing ring and the semiconducting conductor, the cable core, the connecting tube and the semi-conductive shielding layer of the prefabrication are nearly an equipotential body, so even if there are some burrs at the surface of the connecting tube, it has little effect on the electric field distribution.
3.3. Electric field distribution in middle joint when main insulation is scratched

During the installation of the middle joint of the cable, the main insulation of the cable is scratched by knife when the semi-conductive layer on the main insulation surface of the cable is peeled off, or scratches are left on the outer surface of the main insulation due to imprecise pushing of the prefabricated parts, which results in air gap. To simulate scratch defects, a 1*1*20mm air gap is created on the main insulation surface of the cable between the stress cone and the semi-conductive body of the prefabrication, located directly above the main insulation, as shown in figure 5. The distribution of electric field in transverse and longitudinal sections is shown in figure 6.
A scratch defect on the main insulation

Figure 5. Location of main insulation scratch

Figure 6. The distribution of electric field in transverse and longitudinal sections

It can be clearly observed that the electric field near the outer surface of the defect in figure 6 has obvious distortion, the closer it is to the outer surface of the defect, the greater the field intensity distortion; along the horizontal and vertical arrow directions in the figure above, the electric field intensity distribution curve of the main insulation of cable is obvious shown in figure 7 and 8, it can be seen that the electric field distortion on the surface of the defect is obvious, and shows a decreasing trend from left to right along the horizontal red arrow, the closer it is to the stress cone, the larger the electric field intensity is; along the vertical red arrow direction, the electric field from inside to outside shows a decreasing trend, and the most obvious distortion is on the outer surface of the defect. The mean electric
field inside the air gap is about $1.0 \times 10^6$ V/m, and the red circle is marked as the maximum electric field. This corresponds exactly to the left end of the defect, which is about $2.68 \times 10^6$ V/m. In the absence of defects, the electric field here is about $1.35 \times 10^6$ V/m, after the introduction of defects the electric field increases by about 98%; the average surface electric field is about $1.9 \times 10^6$ V/m, and $1.28 \times 10^6$ V/m without defects, and the electric field increases by about 48%. The main insulation scratches, on the one hand, damage the main insulation of the cable, resulting in insufficient insulation, on the other hand, air gap will be generated, may resulting in partial air gap discharge. The increase of electric field intensity will aggravate the insulation damage of cable and cable middle joint, and eventually lead to insulation breakdown.

![Figure 7. Electric field distribution curve in horizontal direction](image1)

![Figure 8. Electric field distribution curve in vertical direction](image2)

### 3.4. Electric field distribution with impurities on main insulation surface

This model is used to simulate that after the connecting tube is installed and grinded, the remaining conductive particles are not cleaned up and remain on the main insulation surface, resulting in local concentration of the field strength on the main insulation surface, finally leading to discharge. A $1\times1\times1$ mm cubic copper particle is set on the main insulation surface in the model, which is located on the main insulation surface of cable between the stress cone and the semi-conductor of the prefabrication,
as shown in figure 9. The distribution of electric field in transverse and longitudinal sections is shown in figure 10.

Figure 9. Location of conductive impurities on main insulation surface

Figure 10. The distribution of electric field in transverse and longitudinal sections

From figure 10, it can be seen that the electric field distortion around the conductive impurity surface is very obvious, and the closer to the defect surface, the greater the field strength. Because of the electrostatic shielding effect, the internal field strength of the impurity is 0. Because of the tip effect, the electric field distortion at the corner of the cube is the largest. Generally, the conductive impurities are non-smooth sharp particles, so the electric field distortion at the tip is especially strong. Along the horizontal and vertical direction of the red arrow in the figure above, the electric field distribution on the main insulation surface is shown in figure 11 and 12. The red circle is marked as the maximum electric field, which is about 8.2*10^7 V/m. The average electric field on the outer surface of the defect is about 3.5*10^7 V/m. When there is no defect, the electric field here is about 1.28*10^6 V/m. Therefore,
the defect makes the electric field around the defect increase by nearly 27 times, which may lead to partial discharge or even breakdown in the insulation near the defect, and seriously endangers the safe operation of the cable system.

![Electric field distribution curve in horizontal direction](image1.png)

**Figure 11.** Electric field distribution curve in horizontal direction

![Electric field distribution curve in vertical direction](image2.png)

**Figure 12.** Electric field distribution curve in vertical direction

3.5. *Electric field distribution with air bubble in main insulation of prefabrication*

This model is used to simulate the bubble defect of silicone rubber in prefabrication. Usually, this kind of bubble defects is caused by imperfect process control during the curing process of silicone rubber. In the simulation model, a spherical air field with a radius of 0.5-2.1 mm is set in the silicone rubber insulation of prefabrication to study the effect of bubble size on the distortion of electric field.
Air bubble in silicone rubber

Figure 13. Location of bubble defect in silicone rubber of prefabrication

Figure 14. Electric field distribution around silicone rubber bubble defect of prefabrication

It can be clearly seen that the electric field distortion is strongest at the top of the arc. The electric field intensity distribution curve along the red axis is shown in figure 15. When the bubble radius is 0.5mm, the electric field intensity at the arc top is about $1.78 \times 10^6$ V/m, and the electric field here is $0.86 \times 10^6$ V/m without defect, increasing by 107%. The larger the bubble size is, the greater the electric field distortion on the top of arc surface is.

Figure 15. Electric field intensity distribution curve along the axis (bubble radius: 0.5mm)
4. Conclusion

In view of the typical defects of 110kV cable middle joint, this paper establishes three-dimensional simulation models of three typical defects by finite element simulation software, calculates the electric field distribution under these typical defects, and draws the following conclusions:

(1) Each typical defect of cable middle joint will result in the increase of electric field strength at the defect location. The defect itself will destroy the overall insulation performance of the insulator. With the increase of electric field strength, the possibility of local discharge at the defect location will be improved.

(2) The effect of different types of defects on the distribution of electric field in the middle joint is obvious, among which the metal particle impurities are the most obvious. Especially if there is a tip in the metal impurities defect, the tip effect causes the sharp increase of charge density at the tip, which makes the electric field distortion at the tip especially severe. The electric field distortion caused by silicone rubber bubble defects varies with the size of the bubble.

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