Research on the Influence of the Relative Permittivity of the Reinforced Insulation of the Cable Intermediate Joint on the Electric Field Intensity

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Abstract. The reinforced insulation material of the Intermediate joint (IJ) of 10kV power cable directly affects its insulation performance. Unfortunately, up to now, few people have specifically discussed the specific relationship between the two. The relationship between the electric field intensity in the IJ and the relative permittivity in the reinforced insulation is studied in this paper. People can use the relative permittivity as one of the indicators to judge the quality of the cable intermediate joints produced by different manufacturers. The maximum electric field intensity of the IJ reduce to minimum when the relative permittivity of the reinforced insulation is around 4.2. Increasing the relative permittivity of the reinforced insulation can effectively reduce the electric field intensity of the reinforced insulation area, but it will increase the electric field intensity in the cable insulation, and the increase in magnitude is relatively large. This will reduce the insulation performance of cable insulation. The research conclusions in the article have an important guiding role in the selection of the IJs of 10kV power cables.

Keywords: Cable IJ; Finite element method; Relative permittivity; Reinforced insulation; Electric field intensity.

1. Introduction
With the development of power grid, power cables are increasingly used in urban low-voltage distribution networks[1]. The cable Intermediate joint (IJ) is an important part of the power cable. But because of its complex structure, the IJ is prone to failure[2]. Silicone rubber is widely used in the reinforced insulation part of power cable IJs due to its unique superior performance[3]-[4]. There are also many excellent composite materials used in cable accessories in the field of HVDC[5]. The application of these materials greatly reduces the failure rate of cable accessories and improves the stability of the power system.

There is great practical significance to explore the influence of the electrical properties of different materials on the insulation properties of cable accessories, which can help us judge the advantages and disadvantages of cable accessories according to the electrical properties of materials. Literature [6] studied the change rule of electrical properties of silicone rubber insulation during the service process of cable IJs. It is found that as the service time of the intermediate joint increases, the permittivity of silicone rubber will increase. Literature [7] studied the influence of thermal aging on the dielectric properties of 220kV cable IJs insulation materials, and obtained the result that the relative permittivity of silicone rubber samples gradually increase with the increase of aging temperature and aging time. literature [8] verified that there are relaxation processes α, δ and electrode polarization processes in
silicone rubber materials. However, there are few Researches which specially studied the influence of the change of the relative permittivity of cable IJs insulation materials on the electric field intensity distribution. In this paper, the relative permittivity of the material is studied to explore the influence of the change of the relative permittivity of the cable accessories reinforced insulation materials on the electric field intensity distribution.

The finite element method will be used to analyze the influence of the relative permittivity of the reinforced insulation of the 10kV cable IJ on the electric field distribution in the 10kV cable IJ in this paper. Literature [9] and literature [10] use the finite element analysis software to simulate the cable intermediate joint. Finite element analysis is the use of mathematical approximation method for real physical systems. And by using simple and interacting elements, namely unit, can use a limited number of unknown variables to approaching infinite unknown quantity of the real system. Through simulation analysis, the mechanism of the variation of the electric field intensity in the IJ with the relative permittivity of the reinforced insulation is obtained, which provides a reference for the selection of the cable IJ in the actual project.

2. Quasi-static Electric Field Analysis Model

2.1. Quasi-static Electric Field Governing Equation

For the 50 Hz power frequency electromagnetic field in the cable accessories, the effect of the electric field generated by the changing magnetic field is small and can be ignored. It can be regarded as the quasi-static electric field. When all materials in the study area are isotropic linear materials, for the power frequency steady state, according to the Maxwell equations in phasor form, the governing equations of potential can be obtained[11]-[12].

\[
\vec{E} = -\nabla \phi
\]

\[
\nabla \cdot (\gamma + j\omega \varepsilon) \nabla \phi = 0
\]

Where \( \vec{E} \) (unit: V/m) is the phasor of the electric field intensity vector; \( j \) is Imaginary unit; \( \omega \) (unit: rad/s) is angular frequency; \( \gamma \) (unit: S/m) is conductivity; \( \varepsilon \) is permittivity; \( \phi \) (unit: V) is the electric potential; \( \nabla \) is the vector differential operator.

2.2. Establishment of Simulation Model of 10 kV Cable IJ

The basic simulation model used in this article is a 10 kV cable IJ which is shown in Figure 1. The dimension of each part of the IJ is shown in Table 1, and the material parameters of each part are shown in Table 2. The finite element analysis software was used to divide the model, and the number of mesh units was 37517.

1. Copper conductor; 2. Waterproof tape; 3. Insulation shield; 4. Stress cone; 5. Cable insulation; 6. High voltage shield; 7. Crimping tube; 8. Reinforced insulation; 9. Air gap; 10. Outer shield; 11. Core shield; 12. Semi-conductive; 13. calculation path of the axial electric field intensity of the IJ (R=40mm); 14. calculation path of the radial electric field intensity of the IJ (Z=-118mm).

Figure 1. Schematic diagram of 1/2 axisymmetric plane of 10 kV cable IJ.
Table 1. Structural parameters of 10 kV cable IJ.

| Parameter                | Value/(mm) |
|--------------------------|------------|
| Conductor radius         | 10.2       |
| Conductor length         | 500        |
| Length of crimping pipe  | 94         |
| High voltage shielding length | 166   |
| Joint length             | 400        |
| Cable insulation length  | 200        |
| Outer shield thickness   | 1          |
| Reinforced insulation thickness | 35   |
| Cable insulation thickness | 4.5    |
| Core shielding thickness | 0.5        |
| High voltage shielding thickness | 3    |
| Insulation shielding thickness | 1    |

Table 2. Material parameters of various structures of 10 kV cable IJ.

| structure            | Relative permittivity | Conductivity/(S/m) |
|----------------------|-----------------------|--------------------|
| Crimping tube        | 1                     | 5.998´10^7         |
| Copper conductor     | 1                     | 5.998´10^7         |
| Insulation shield    | 10                    | 10                 |
| Core shielding       | 10                    | 10                 |
| Outer shield         | 10                    | 10                 |
| Stress cone          | 20                    | 0.1                |
| High voltage shield  | 20                    | 0.1                |
| Waterproof tape      | 3                     | 1.0´10^{-14}       |
| Reinforced insulation| 3                     | 1.0´10^{-15}       |
| Cable insulation     | 2.3                   | 1.0´10^{-17}       |

3. Influence of the Relative Permittivity of Reinforced Insulation on Electric Field Intensity in IJ

3.1. The Influence of the Relative Permittivity of the Reinforced Insulation on the Maximum Electric Field Intensity in IJ

At present, the silicone rubber material is generally adopted for the reinforced insulation of 10kV cable IJs, and its relative permittivity is about 3. The relative permittivity of the insulation is changed to study the influence of increasing or decreasing the relative permittivity of reinforced insulation on the maximum electric field intensity of the IJ. The range of permittivity is from 1.8 to 3.6, and step is 0.2. The variation curve of maximum of electric field intensity with permittivity is shown in Figure 2.

According to Figure 2, in the reinforced insulation area, when the relative permittivity of the reinforced insulation is less than or equal to 4.2, the maximum electric field intensity decreases with the increase of the reinforced insulation permittivity. When the relative permittivity of the reinforced insulation line is more than 4.2, the maximum electric field intensity increases with the reinforced insulation permittivity.
3.2. The Influence of the Relative Permittivity of Reinforced Insulation on the Axial Electric Field Intensity Distribution of the IJ

In order to study the relationship between the axial electric field intensity and the relative permittivity of the reinforced insulation, now take the cross-section of $R=40\text{mm}$ in cylindrical coordinates as the calculation area which is the red axial path shown in Figure 2. Now calculate the electric field intensity along the red radial path in Figure 2. Increase the relative permittivity of the reinforced insulation from 2 to 5, each time increasing by 1 to obtain the electric field intensity distribution curve of Figure 3.

![Figure 2](image1)

**Figure 2.** The curve of the maximum electric field intensity in the IJ with relative permittivity.

![Figure 3](image2)

**Figure 3.** Schematic diagram of the axial electric field intensity distribution of the IJ ($R=40\text{mm}$). It can be seen from Figure 3 that in the section area of $R=40\text{mm}$, the electric field intensity decreases as the relative permittivity of the reinforced insulation increases.
3.3. The Influence of the Relative Permittivity of the Reinforced Insulation on the Radial Electric Field Intensity Distribution of the IJ

From Figure 3 we can find that the difference of the axial component electric field intensity is greatest at $Z=-118$ mm when the relative permittivity of the reinforced insulation changes. We continue to study its radial electric field distribution at $Z=-118$ mm.

The radial component of the electric field intensity along the black radial path in Figure 2 is calculated. The relative permittivity of the reinforced insulation is from 2 to 5, increasing by 1 each time, and the variation curve of radial component electric field distribution is shown in Figure 4.

![Figure 4. Variation of the radial electric field distribution at the IJ z=-118 mm.](image)

The high voltage conductor is in area from $R=0$ mm to $R=11$ mm and the domain of the cable insulation is from $R=11$ mm to $R=15$ mm. The insulation material is cross-linked polyethylene which relative permittivity is 2.3. In this area the electric field intensity increases with the increase of the relative permittivity of the reinforced insulation, and the increase is relatively large. While $R>15$ mm, it is the reinforced insulation area. In this area the electric field intensity increases with the increase of the relative permittivity of the reinforced insulation, and the increase is relatively small.

4. Conclusion

The relationship between the electric field intensity of the IJ and the relative permittivity of the reinforced insulation has been studied in this paper.

1) In the whole area, the maximum value of the electric field intensity of the 10kV cable IJ first increases with the decrease of the relative permittivity of the reinforced insulation. When the relative permittivity of the reinforced insulation increases to 2.6, the maximum value of the electric field intensity remains constant; in the reinforced insulation area, the maximum value of electric field intensity first decreases with the increase of the relative permittivity of the reinforced insulation. When the relative permittivity of the reinforced insulation increases to 4.2, the maximum electric field intensity increases with the increase of the relative permittivity of the reinforced insulation. Therefore, the insulation performance of the IJ with the relative permittivity of the reinforced insulation around 4.2 is better. Therefore, we can preferentially choose the cable IJ with the relative permittivity of insulating material at 4.2.

2) The axial electric field intensity of the 10kV cable IJ decreases with the relative permittivity of the reinforced insulation.

3) In the cylindrical coordinate system where $Z=-118$ mm, the radial electric field intensity in the cable insulation area increases with the relative permittivity of the reinforced insulation, and the increase is relatively large; the radial electric field intensity in the reinforced insulation area...
decreases with the relative permittivity of the reinforced insulation, and the decrease is relatively small.

Under comprehensive consideration, the relative permittivity of the reinforced insulation area cannot be too large, otherwise the electric field intensity in the cable insulation may be too high and accidents may occur. We can preferentially choose the cable IJ with the relative permittivity of insulating material at 4.2 because of the first conclusion.

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