Transient Simulation Model for Electric Field Distribution in Cable Joint

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Abstract. The analysis of the impact of the switching impulse voltage on the internal electric field of the cable joint plays a key role in studying the breakdown of the joint. In this paper, the finite element method is used to simulate the transient electric field of the axisymmetric model of the cable joint. By changing the closing moment, the influence of different closing moments on the electric field intensity distribution is studied and analyzed. The results show that under the switching voltage excitation, when the closing moment at $t = nT$, the electric field distribution in the cable joint is consistent with the steady state without distortion. Others, the point near the root of the stress cone will distort when the switch is closed, the closing moment is at 7.5ms, which is the most serious. The closing time is at 10ms, has the greatest influence on the electric field intensity distribution in the cable joint, especially the stress cone end, the bottom of the high voltage shield and the position near the high voltage conductor in the air domain.

Keywords: Cable joint; switching impulse voltage; electric field intensity distribution; finite element method.

1. Introduction

Dense overhead lines are not only dangerous but also affect land utilization and the appearance of the city. With the advancement of urbanization, more and more low-voltage cables have been used to replace overhead lines in network operation [1]. The joint is the basic component of the power cable system. In the process of power transmission, the cable is affected by electric field, magnetic field, heat, light, impurities and other factors, which make the insulation performance become worse and cause partial discharge even insulation breakdown [2]. Among all the factors that cause cable faults, according to previous faults in the power system, the number of cable joint failures accounted for 70% of the total number of cable system failures [3], which greatly affected the safe and stable operation of the power system. Therefore, the cable joint structure needs to be carefully designed as a weak link in the cable system, to make its internal electric field intensity distribution uniform and reasonable.

At present, researches on cable joints are mostly focused on the influence of the space charge distribution on the electric field intensity in the cable intermediate joints. Improve the electric field distribution inside the joint by optimizing the surface curve of the stress cone, the length and thickness of the stress cone, and the length and thickness of the shield of high-voltage conductor [4]-[6]. These analyses are based on steady-state fields, and there are transient processes such as switching impulse voltage during cable transmission. These transient processes will accelerate the damage of the cable system. According to statistics of faults, insulation breakdown accidents of cable joints mostly occur during closing. Therefore, it is of great significance to study the electric field distribution of cable joints under switching impulse voltage and to establish a transient analysis model of cable joints.
In this paper, an axisymmetric model of the cable joint is established. The closing moment is a variable in the simulation. By changing the switching voltage applied to the conductive copper, the electric field intensity distribution in the joint is calculated.

2. Structure and Material of Model

According to the characteristics of cable joint, the cylindrical coordinates corresponding to the axisymmetric field are selected as the coordinate form for the model. The model of the 10kV AC cable joint is shown in Figure 1. The model consists of 9 parts: conductive copper, inner semi-conductive layer, main cable insulation layer, outer semi-conductive layer, stress cone, high-voltage shield, reinforced insulation layer and insulation shield. The material parameters of each part are shown in Table 1.

![Figure 1. Structure of the 10kV cable joint.](image1)

![Figure 2. Boundary condition of 10 kV cable joint.](image2)

| Materials          | Relative permittivity | Conductivity(S/m)       | Application          |
|-------------------|-----------------------|-------------------------|----------------------|
| Copper            | 1                     | $5.8 \times 10^8$       | Cable conductor      |
| XLPE              | 2.3                   | $1 \times 10^{-15}$     | Main insulation      |
| Silicone Rubber   | 4.3                   | $2.727 \times 10^{-12}$ | Joint insulation     |
| Semi-conducting   | 20                    | 10                      | Conductive layers and stress cone |
| material          |                       |                         |                      |

3. Control Equation

In this paper, the boundary conditions of the model are set as shown in Figure 2. On the boundary 1, applying the switching impulse voltage at different turn-on time ($t_0=0, 2.5, 5, 7.5, 10, 20)$ms. Because the model contains conductive materials and insulating materials, the conduction current and displacement current coexist. It is a quasi-static electric field. The basic equations are shown in equations (1)–(6).

\[ \nabla \times \vec{E} = 0 \]  \hspace{2cm} (1)

\[ \nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \]  \hspace{2cm} (2)

\[ \nabla \cdot \vec{D} = \rho \] \hspace{2cm} (3)

\[ \nabla \cdot \vec{B} = 0 \] \hspace{2cm} (4)
\[
\vec{D} = \varepsilon \vec{E} \\
\vec{J} = \gamma \vec{E}
\]

Where \(\vec{E}\) is the electric field intensity vector, \(\vec{H}\) is the magnetic field intensity vector, \(\vec{J}\) is the current density vector, \(\vec{D}\) is the electric displacement vector, \(\rho\) is the charge density, \(\vec{B}\) is the magnetic induction intensity vector, \(\varepsilon\) is the relative permittivity, \(\gamma\) is the conductivity.

4. Analysis of Electric Field Intensity Distribution

Six kinds of switching impulse voltages were simulated respectively. Since the conductivity of the reinforced insulation is a function of the electric field intensity, it is a non-linear material, and the study is a time-varying problem. Therefore, a transient solver is used to solve the problem, and the solver time step is set to 0.1ms. The effective value of the AC excitation voltage is 10kV, and the electric field intensity distribution of the cable joint under the six excitations is shown in Figure 3.

![Electric field intensity distribution of 10kV cable joint under different switching voltage.](image)

Comparing Figure 3(a),(b),(c),(d),(e) and (f), it can be seen that the internal electric field intensity of the joint is zero when the closing moment is at 0ms and 20ms, indicating that there is no changes in the voltage at the closing moment, which can be regarded as a steady-state excitation. In the following analysis, the electric field distribution under the \(t_0=0\)ms excitation is used as the basic value of the switching electric field. The electric field is mainly concentrated inside the main insulation when the closing moment is at 2.5ms, 5ms, 7.5ms and 10ms. To further illustrate the effect of the closing moment on the electric field distribution, 4 points were taken in the model: point A near the root of the stress cone, point B near the bottom of the high-voltage shield, point C near the middle of the high-voltage shield, and point D in the air domain; two curves were taken: stress cone curve \(l_1\) and high-voltage shield bottom curve \(l_2\); two lines are taken: air domain section \(l_3\) and high-voltage shield and reinforced insulation boundary line \(l_4\). The distribution of points and lines are shown in Figure 4.

![Distribution of points and lines.](image)

For different switching moments at points A, B, C, and D, the potential changes with time are shown in Figure 5. It can be seen that the voltage at the point A is distorted at the closing moment, and the waveform is no longer a sine wave. When the closing moment is at 2.5ms, 5ms and 7.5ms, the voltage change is 1.5 times, 2 times and 2.9 times of the steady state, respectively. At points B, C, and D, there is no distortion of the voltage at the closing moment, and the waveform is still a sine wave.
Figure 5. Potential vs. time.

At different switching moments, the ratio of the electric field intensity on the curve $l_1$, $l_2$, and the line $l_3$, $l_4$ to the steady-state electric field intensity varies with the position as shown in the figure 6. The $r$ in the figure 6 refers to the arc length from the start point of the curve, $z$ refers to the axial coordinate of the point on the curve, and the ordinate is the ratio of the electric field intensity under the switching voltage and the steady state. When the closing time is at 10ms, the electric field intensity distort at some positions. For curve $l_1$, when the closing time is at 7.5ms, the electric field intensity distort at the root of the stress cone, when the closing time is at 10ms, the electric field intensity distort at the end of the stress cone, and the distortion of the latter is much greater than that of the former. For curve $l_2$, when the closing time is at 10ms, the electric field intensity distort greatly at the bottom of the high-voltage shield. For line $l_3$, when the closing time is at 10ms, the electric field intensity distort near the high-voltage conductor. For line $l_4$, when the closing time is at 10ms, the electric field intensity decreases compared with the steady state. In conclusion, the closing time is at 10ms, has the greatest influence on the electric field intensity distribution in the cable joint, especially the stress cone end, the bottom of the high voltage shield and the position near the high voltage conductor in the air domain.
5. Conclusions
1. At the closing moment \( t_0 = nT \) (\( T \) is the steady-state voltage cycle, \( n \) is a positive integer), the electric field distribution in the cable joint is consistent with the steady state.
2. When the closing moment is not the integer times cycle, the potential of point near the root of the stress cone of the joint will distort at the moment of the switch closing, which will cause the distortion of the electric field intensity. When the closing moment is at 7.5ms, the electric field intensity distortion is the most serious, which is 2.5 times of the steady-state.
3. Under the switching voltage, the electric field intensity of stress cone curve, high-voltage shield bottom curve and air domain of the cable joint will increase compared with the steady state, especially when the closing time is at 10ms.

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