Effect of Nonlinear Properties of Stress-Cone-Enhanced Insulation on Electric Field Distribution in HVDC Cable Terminations Postprint

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Abstract

The steady-state electric field distribution in high-voltage DC cables and accessories primarily depends on the conductivity of insulating materials, which is closely related to electric field strength and temperature, rendering the electric field distribution in DC cable accessories more complex than that in high-voltage AC cable accessories. To this end, under fixed conditions of cable terminal XLPE insulation, silicone oil conductivity, and temperature gradient, this paper employs multi-physics coupling software to simulate and investigate the influence of the nonlinear properties of stress cone reinforced insulation on the steady-state electric field distribution in outdoor composite terminations of high-voltage DC cables. Simulation results demonstrate that for composite outdoor high-voltage DC cable terminations, the tangential electric field at the interface between factory insulation and reinforced insulation may exhibit maximum values at the root and tip of the stress cone; furthermore, the electric field on the inner surface of the semi-conductive stress cone may also show maximum values at the root and tip; and comprehensive control of the electric field distribution in composite cable terminations can be achieved by regulating the nonlinear properties of the reinforced insulation material.

Full Text

Preamble

Effect of Nonlinear Properties of Stress Cone Reinforced Insulation on Electric Field Distribution of HVDC Cable Terminal

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Abstract

The steady-state electric field distribution in HVDC cables and accessories primarily depends on the conductivity of insulating materials, which is closely related to electric field strength and temperature. This makes the electric field distribution in DC cable accessories more complex than that in HVAC cable accessories. Therefore, under fixed conditions of XLPE insulation conductivity, silicone oil conductivity, and temperature gradient in the cable terminal, this paper investigates the influence of nonlinear properties of stress cone reinforced insulation on the steady-state electric field distribution in outdoor compound HVDC cable terminals using multi-physics coupling software. Simulation results demonstrate that in compound outdoor HVDC cable terminals, the tangential electric field at the interface between factory insulation and reinforced insulation may exhibit maximum values at the root and top of the stress cone. Additionally, the electric field on the inner surface of the semi-conductive stress cone may also show maximum values at the root and top. Comprehensive regulation of the electric field distribution in compound cable terminals can be achieved by adjusting the nonlinear properties of the reinforced insulation material.

Keywords: HVDC cable terminal, stress-cone reinforced insulation, material nonlinear properties, electric field distribution

1 Introduction

High-voltage direct current (HVDC) transmission is becoming an essential component of China' s high-voltage power grid due to its long transmission distance, large capacity, and flexible control characteristics. HVDC cables are the inevitable choice for DC transmission across sea straits, through tunnels, and in urban areas [1-3]. The development of high-voltage and ultra-high-voltage DC transmission technology provides broad prospects for HVDC cables. HVDC cable accessory technology is one of the key technologies for HVDC cables. Operational experience indicates that, apart from improper installation or mechanical damage, most breakdown accidents are closely related to insulation materials and insulation structures in cable systems [4-5].

Under DC voltage, the steady-state electric field distribution in cable accessory insulation structures is determined by conductivity, which is a nonlinear function of electric field strength and temperature, making the electric field distribution in multi-layer insulation cable accessories particularly complex. In cable accessory structures, electric stress concentration at the discontinuity of the insulation shield can cause partial discharge and even breakdown inside the cable accessories [6-8].

There are two approaches for electrical stress control in cable accessories: first, optimizing the semi-conductive stress cone structure to regulate electric field distribution through electrode geometry; second, using nonlinear insulating materials as reinforced insulation to regulate electric field distribution through the nonlinear conductivity or polarization characteristics of the reinforced insulation material [7-8]. The first approach is a traditional method that has been widely applied. The second approach has been practically applied in low-voltage cable accessories but not in high-voltage cable accessories. The organic combination of these two approaches may be an effective way to develop higher voltage level cable accessories. Considering the potential application of nonlinear insulating materials in complex insulation structures, domestic and international scholars have conducted fundamental research on material formulations, dielectric properties, and mechanisms [9-14].

Cable accessories include cable terminals and joints. The electric field distribution in cable terminals is more complex than in joints. Therefore, this paper selects cable terminals as the research object. Considering that integrated prefabricated cable terminals have not been applied in HVDC cable lines, this paper takes a 320kV HVDC cable outdoor compound terminal filled with silicone oil as an example and adopts the simplified cable terminal structure model shown in Figure 1 [Figure 1: see original paper].

The cable terminal has an axisymmetric structure, so a two-dimensional field is used to solve the temperature field and electric field. To make the simulation closer to reality, the air boundary problem is considered when determining the finite element calculation domain for the cable terminal. After repeated trials, a calculation domain with a radial length of 12.00m and an axial length of 8.00m is determined. Further expanding the domain only increases computation time without significantly affecting the calculation of temperature and electric field distribution inside the cable terminal.

The overall calculation domain is shown in Figure 2 [Figure 2: see original paper]. Using electric field numerical simulation technology to investigate the influence law of nonlinear properties of stress cone reinforced insulation on the steady-state electric field distribution in HVDC cable accessories has important guiding significance for subsequent cable accessory material development and structural design.

2 Model Establishment and Solution Method

Commercial COMSOL Multiphysics software is used to solve the temperature field and electric field. Before solving, preparations such as model structure, calculation domain, material properties, and boundary conditions must be determined.

2.2 Definition of Cable Accessory Insulation Material Properties

Within the engineering application temperature and electric field range, the conductivity of insulating materials follows the hopping conduction mechanism, and the relationship between conductivity and electric field strength and temperature is [15-16]:

$$\gamma = A \exp\left(-\frac{\phi}{k_b T}\right) \frac{\sinh(10^6 B|E|)}{10^6|E|}$$

where A is a material-related constant (V/(Ω · m²)); is the activation energy (eV); q is the electron charge (C); k__b is the Boltzmann constant (J/K); T is the material temperature (K); B is the electric field dependence coefficient (m/V); and E is the electric field strength (kV/mm).

Through actual measurement, the insulation performance parameters of XLPE and silicone oil are obtained as shown in Table 1 .

Table 1. Material Property Parameter Values

Material	A [V/(Ω · m²)]	B (m/V)	(eV)
XLPE	7.10×10	2.32×10	0.85
Silicone oil	5.39×10	3.48×10	0.23

Through extensive experimental formulation research, the relevant parameter ranges for reinforced insulation materials are determined: coefficient A ranges from 5.39×10 to 53.90 (V/Ω · m²); electric field dependence coefficient B ranges from 9.00×10 to 6.00×10 m/V; activation energy ranges from 0.23 to 0.60 eV; and relative permittivity is 2.7.

Considering the small temperature and electric field variation ranges at the FRP casing and silicone rubber composite insulator, the conductivity of both is defined as constant at 5×10^{1} S/m, with relative permittivities of 3.7 and 2.6, respectively.

2.3 Solution of Cable Terminal Steady-State Temperature Field

According to reference [17], the thermal parameters of various materials in the cable terminal are determined as shown in Table 2 .

Table 2. Thermal Parameter Values of Materials

Material	Thermal Conductivity [W/(m · K)]	Heat Capacity [J/(kg · K)]	Density (kg/m³)
XLPE	0.28	1900	920

Material	Thermal Conductivity [W/(m · K)]	Heat Capacity [J/(kg · K)]	Density (kg/m^3)
Reinforced insulation	0.20	1900	1100
Silicone oil	0.15	1400	960
FRP casing	0.40	1000	1850
Silicone rubber	0.30	1100	1200

Currently, the long-term operating temperature of HVDC XLPE cable conductor is 70°C, with future research aiming to increase the operating temperature of XLPE DC cable conductor to 90°C [18]. Therefore, the cable conductor temperature is set to 90°C in the simulation model. According to the definition of three types of boundary conditions in heat transfer [19-20], when calculating the steady-state temperature field distribution of the cable terminal, boundary a is set as the first type boundary condition (ambient temperature 20°C), and boundary c is set as a free boundary. Using the steady-state solver, the steady-state temperature field distribution of the cable terminal is obtained, as shown in Figure 3 [Figure 3: see original paper].

As shown in Figure 3, the temperature range of the XLPE part of the cable terminal is 88.48–89.83°C, and the temperature range of the reinforced insulation part is 84.88–88.48°C. This steady-state temperature field distribution is used as the condition for electric field solution of the cable terminal.

2.4 Voltage Application Method and Solution for Electric Field Calculation

In the DC steady-state electric field simulation of the cable terminal, the cable conductor potential is defined as 230 kV, boundaries b and c in Figure 2 are set to zero potential, and boundary a is a free boundary. Using the transient solver, the electric field distribution basically reaches a steady state after 5,000 s. The steady-state electric field distribution depends not only on boundary conditions but also on space charge polarization formed by spatial gradient changes in material dielectric properties [21-22].

3 Cable Terminal Steady-State Electric Field Simulation and Analysis

Research shows that nonlinear insulating materials have the function of homogenizing electric field distribution [13-14,23-24]. The conductivity of reinforced insulation follows equation (1), with parameters set as A = 5.39×10^{3} V/(Ω ·

m^2), B = 3.48×10 m/V, and = 0.23 eV as typical values. The steady-state electric field distribution obtained from simulation is shown in Figure 4 [Figure 4: see original paper].

As shown in Figure 4, the cable terminal has a multi-layer insulation structure, and the interface is the weak link in insulation. Therefore, subsequent research selects the electric field strength at the inner surface of the stress cone and at the interface between XLPE factory insulation and reinforced insulation as the main research objects for cable terminal electric field distribution.

3.1 Influence of Material Coefficient A on Steady-State Electric Field Distribution

With electric field dependence coefficient B = 3.48×10 m/V and activation energy = 0.23 eV, simulation results for the relationship between interface tangential electric field strength and stress cone surface electric field distribution with different coefficient A values are shown in Figure 5 [Figure 5: see original paper].

Figure 5a shows that the maximum electric field on the inner surface of the stress cone decreases significantly with increasing parameter A. When $A > 5.39\times10^{3}$ $V/(\Omega\cdot m^2)$, the electric field on the inner surface of the stress cone can be controlled around 1 kV/mm.

Figure 5b shows that when the A value is too large or too small, the interface tangential electric field at the stress cone root and the three-phase junction point of cable insulation and silicone oil (point h in Figure 1) both exhibit maximum electric fields with different directions. When $A = 5.39\times10^{3}$ $V/(\Omega\cdot m^2)$, the corresponding maximum interface tangential electric field value is 0.8 kV/mm, meeting the control target requirement of less than 1 kV/mm for composite insulation interface tangential field strength [21].

Combining Figures 5a and 5b, both excessively large or small A values cause severe electric field distortion in the cable terminal, and controlling A around 5.39×10^{3} $V/(\Omega\cdot m^2)$ is more appropriate.

3.2 Influence of Electric Field Dependence Coefficient B on Steady-State Electric Field Distribution

With material coefficient $A = 5.39\times10^{3}$ $V/(\Omega\cdot m^2)$ and activation energy = 0.23 eV, simulation results for the relationship between stress cone surface electric field strength and XLPE insulation interface tangential electric field strength with different electric field dependence coefficient B values are shown in Figure 6 [Figure 6: see original paper].

Figure 6a shows that within the given B value range, its influence on stress cone surface electric field strength is relatively small. As the electric field dependence coefficient B increases, the stress cone surface electric field strength generally decreases. When B 1.50×10 m/V, the position of the maximum electric field strength on the stress cone surface transfers from the stress cone root point e to the stress cone top point f.

Figure 6b shows that the electric field dependence coefficient B has little overall effect on the distribution of interface tangential electric field strength. As the B value increases, the interface tangential electric field strength near the stress cone root point e gradually decreases, while the interface tangential electric field strength near the reinforced insulation end point h first decreases positively and then increases negatively.

Combining Figures 6a and 6b, when the B value is in the range of (1.50-6.00)×10 m/V, the maximum interface tangential electric field strength is less than 1 kV/mm, meeting the control requirement for composite insulation interface tangential field strength.

3.3 Influence of Activation Energy on Steady-State Electric Field Distribution

With material coefficient A = 5.39×10 ^{3} V/(Ω·m^{2}) and electric field dependence coefficient B = 3.48×10 m/V, simulation results for the relationship between stress cone surface electric field strength and XLPE interface tangential electric field strength with different activation energy values are shown in Figure 7 [Figure 7: see original paper].

Figure 7 shows that the activation energy value has a significant impact on the stress cone surface electric field and XLPE surface interface tangential electric field strength in cable terminals. As the value decreases, the maximum electric field strength of both the stress cone surface and XLPE surface interface tangential electric field decreases. When = 0.23 eV, the interface tangential electric field strength near point h is close to 0, and the maximum electric field on the inner surface of the stress cone is controlled below 1 kV/mm. This demonstrates that the lower the activation energy of reinforced insulation material, the lower the stress cone surface electric field, XLPE interface tangential electric field, and stress cone inner surface electric field.

4 Conclusions

Through numerical analysis of the steady-state electric field in HVDC cable terminals, the following conclusions are drawn:

1. In the structure of HVDC cable compound terminals, the tangential electric field at the interface between factory XLPE insulation and stress cone reinforced insulation may exhibit maximum electric field values at two locations: the stress cone root and the top of the stress cone reinforced insulation.
2. In the structure of HVDC cable compound terminals, the maximum electric field on the inner surface of the semi-conductive stress cone flare may also appear at two locations: the flare root and the flare top.

3. Comprehensive regulation of the electric field distribution in HVDC cable terminals can be achieved by adjusting the nonlinear properties of the stress cone reinforced insulation.

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Note: Figure translations are in progress. See original paper for figures.