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Research on Improving Electric Field Distribution of Cable Terminal Based on Non-linear Materials

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Abstract: The electric field distribution of the power cable terminal is very complicated, and there is a large concentrated electric field at the interface between the stress cone and the main insulation. Such a high electric field will accelerate the aging of the insulation and lead to the breakdown of the insulation. In addition, the cable terminal need to be produced in the field, once the production process is poor, leaving bubbles or impurities and other defects in cable terminal, the electric field distribution of the cable terminal will be very uneven, local high field strength lead partial discharge, shorten the cable terminal life. In this paper, based on the non-linear insulation material can play a uniform electric field role in the non-uniform electric field, to explore the effect of non-linear SiC/silicone rubber composites on homogenizing electric field, the electric stress distribution of cables termination were simulated by COMSOL Multiphysics software. The results show that the maximum electric field strength at cable terminal decreases extremely when the 45wt% nano-SiC/silicone rubber composites were used.

1. Introduction

The development of nano-science and technology has provided new ideas and ways for the development of new materials and the modification of existing materials. In 1994, TJ Lewis firstly proposed the concept of nanometric dielectrics [1]. The emergence of nano-material has opened up a new field of application of the dielectric. Compared with the traditional dielectric, the nano-composite dielectric have greatly improved the electrical, thermal and mechanical properties [2-3].

At present, many results have been obtained in the research of polymers such as polyethylenes, silicon organic resins, epoxy resins, polyamides and polyimides, fillers such as Al2O3, TiO2, SiO2, ZnO and SiC, etc. In particular, non-linear nano-materials are added to the polymer to obtain a non-linear composite material. Conductive non-linear composites were obtained by adding nano-SiC into the silicone rubber, which showed that the conductivity of the composites changed nonlinearly with the applied field strength. When the field strength reached a certain value, the conductivity was very strong Of the field strength dependence [4-7]. the dielectric constant of non-linear composite material can be obtained by epoxy resin as a base material to add barium titanate material, the dielectric constant of composite material shows a nonlinear change with the change of electric field strength. When the field strength reaches a certain value, the dielectric constant shows a strong dependence of field strength, which can improve the electric field distribution of the insulation for high voltage electrical equipment [8-12].

Most of the electrical equipment insulation exists in the local electric field, such as transformer outlet casing, motor coil end, power cable terminal and so on, easily lead to insulation aging, and even breakdown. The distribution of electric field in the terminal of power cable is particularly complicated. There is a large concentrated electric field at the interface between the stress cone and the main insulation. In addition, the cable terminal must be produced on site, subject to the site environment constraints, easy to leave bubbles or impurities in the production process and other defects, resulting in cable terminal head of the electric field distribution will be very uneven. Local field is too high to cause partial discharge, shorten the life of the cable terminal.

Based on the non-linear insulating material can uniform electric field in a non-uniform electric field, this article discusses a method of improving the electric field distribution at the cable termination by using a non-linear conducting material, and also using the finite element simulation software to verify the electric field distribution at the cable termination.

2. Nonlinear conductivity materials

Nano-composite materials can be prepared by doping inorganic nano-particles in insulating materials. In this paper, the non-linear conductivity nano-silicon carbide silicon rubber composite materials were obtain by silicon rubber materials to join the nano-silicon carbide materials.

2.1 Non-linear material preparation

Room temperature vulcanized silicone rubber produced by Shanghai Silicone Polymer Materials Co., Ltd. and nano-silicon carbide produced by Beijing Decaux Island Gold Technology Co., Ltd. were used to prepare non-linear silicone rubber composites. The nano-silicon carbide has a β crystal form and an average particle size of 40 nanometers. Nano-SiC, silicone rubber, cross-linking agent and catalyst are mixed according to a certain proportion, and the bubbles are cured in a vacuum oven. Pure silicon rubber and nano-silicon carbide/silicone rubber composite materials with mass fraction of 15wt%, 30wt% and 45wt% were prepared respectively.

2.2 Nano-SiC/Silicone rubber composite conductivity testing

The conductivity of silicon carbide, pure silicone rubber and 15wt%, 30wt%, 45wt% nano-SiC/silicone rubber composites were tested using a three-electrode system. The main electrode diameter of three-electrode system is 50mm, The gap between the main electrode and the protective electrode is 2mm. HVDC maximum output voltage of 10kV, applied voltage 30 minutes, and using the EST122 electrometer to record steady-state current.

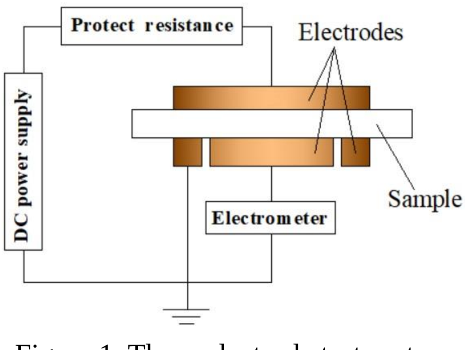


Figure 1. Three-electrode test system

The relationship between the conductivity and the field strength of the nano-SiC/silicone rubber composites can be expressed by empirical formula (1).

$$\gamma = \alpha E^{\beta} \tag{1}$$

Where β is the nonlinear conductivity of the material, α is a parameter related to the material properties and structure, and (1) takes the logarithm transformation into equation (2).

$$\lg \gamma = \lg \alpha + \beta \lg E \tag{2}$$

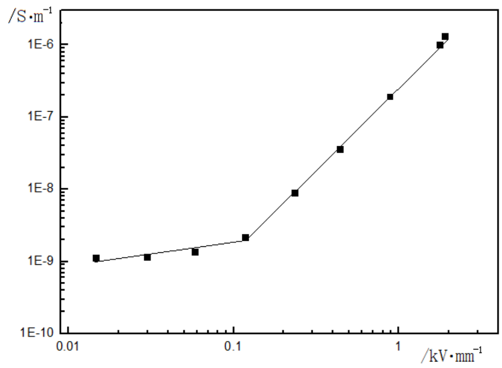


Figure 2. Relationship between the conductivity and the field strength of nano-SiC

Pure silicon carbide conductivity and field strength of the relationship shown in Figure 2, we can see that the conductivity curve of silicon carbide shows an inflection point when the electric field intensity is 0.114 kV/mm. Before the inflection point, the conductivity of the non-linear coefficient of 0.33, after the inflection point, the conductivity of the non-linear coefficient of 2.3.

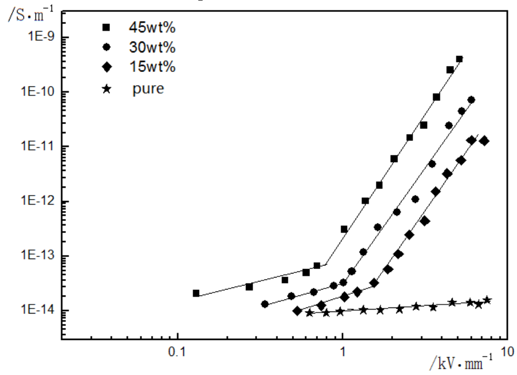


Figure 3. Relationship between the conductivity and the field strength of composites with different nano-SiC contents

Figure 3 shows the conductivity of nano-SiC/silicone rubber composites with 15wt%, 30wt% and 45wt% respectively. It can be seen that with the increase of nano-SiC contents, the conductivity increase, the inflection point of the field strength decreased. Table 1 shows the nonlinear coefficients β1, β2 before and after the inflection point, and the field strength corresponding to the inflection point of the composites with different nano-SiC contents.

Table 1. Non-linear conductivity and inflection point field strength of nano-SiC/silicone rubber composite with different silicon carbide content

Nano-SiC content	β_1	β_2	**Inflection point field strength(kV/mm)**
45wt%	0.604	4.309	0.673
30wt%	0.690	4.227	1.026
15wt%	1.012	4.171	1.563

3. Electric field simulation of cable terminal

Based on the non-linear insulation material can play a uniform electric field role in the non-uniform electric field, this paper intends to calculate the electric field of the terminal for 150kV DC cable, which the stress cone using nonlinear materials. And also simulated the electric field distribution of stress cone that the surface exist air bubbles and metal impurities respectively.

3.1 Model establishment

Figure 4 is a schematic diagram of the power cable terminal structure, the cable terminal includes conductors, cable main insulation, stress cones and external insulation. The stress cone consists of a conductive part and an insulating part. This paper attempts to use a non-linear conductivity of SiC/silicone rubber composite to improve the electric field distribution of cable terminal stress cone. In addition, COMSOL Multiphysics software was used to simulate the electric field distribution when the stress cone surface existed defects such as air bubbles and metal impurities. As the cable terminal with axisymmetric structure, so in the simulation modeling, using two-dimensional axisymmetric AC/DC module.

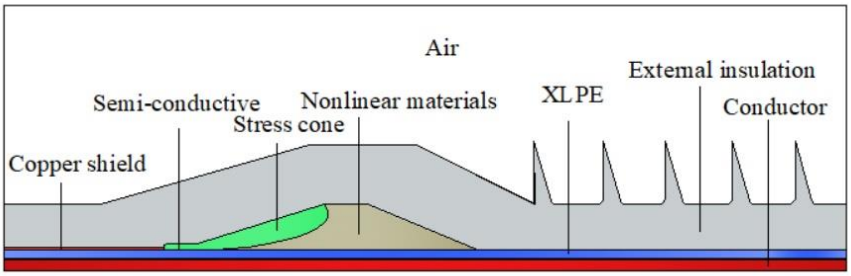


Figure 4. Insulation structure of cable terminal

The material properties are shown in Table 2. The conductivity is set by the formula that obtained from the data fit. In order to avoid the influence of the dielectric constant on the simulation results, the dielectric constant of the nonlinear material is uniformly taken as 3.7. When using different levels of Nano-SiC/Silicone rubber composites in electric field simulations, material properties field set different conductivity.

Table 2. Material Properties

Material	**Dielectric constant**	**Conductivity (S/m)**
Conductor	1	5.7e7
Copper shield	1	5.7e7
XLPE	2.3	1e-13
Non-linear materials	3.7	$\gamma = f(E)$
External insulation	2.9	1e-13
Air	1	1e-50

3.2 Boundary setting and mesh generation

The Auto-CAD software is used to establish the cable terminal geometry model, and import into the COMSOL software. The geometry model is choose to force into entities from the drawing menu bar in the COMSOL software, and then separate objects. After these operations, the boundary conditions and solution domains for the imported model can be setting.

The different boundaries have different boundary conditions by boundary setting. In the simulation, a DC voltage of 150 kV was applied to the cable core, the copper shield and air space boundary were set to ground, all the remaining internal boundaries were set to continuous, and the external boundary was set to be electrically isolated. As shown in Figure 5, due to the concentrated electric field in the stress cone, in order to improve the calculation accuracy, the meshing of the stress cone should be done.

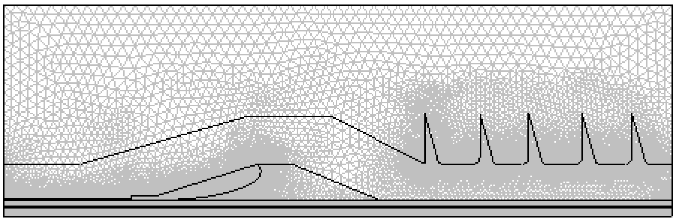
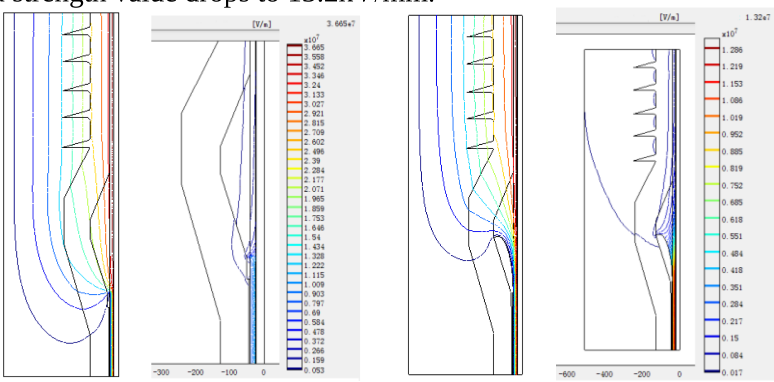


Figure 5. meshing of cable terminal

3.3 Electric field simulation analysis

Figure 6 (a) (b) shows the potential and electric field distribution of the cable terminal without stress cone. It can be seen from the figure 6 (a) (b), without the stress cone, the potential gradient at the copper shield cut-off point is very high and the maximum field strength value reached 36.7kV/mm, more easily lead to insulation breakdown.

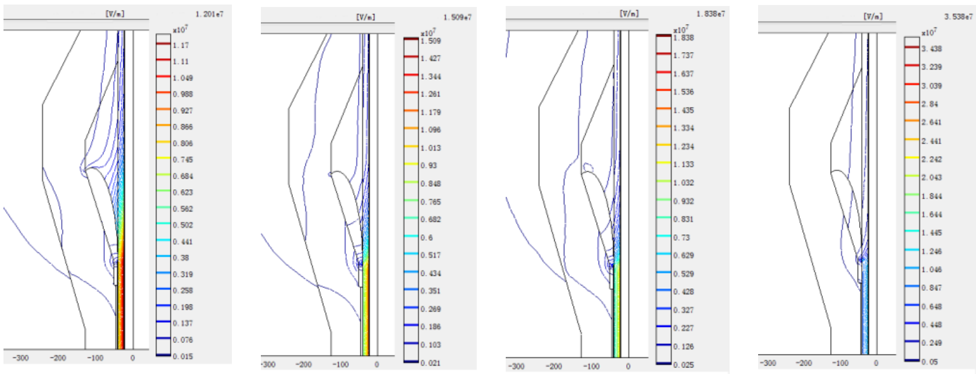
Figure 6 (c) (d) shows the potential and electric field distribution of the cable terminal withing stress cone. With the stress cone, the potential gradient at the copper shield cut-off point is small and the maximum field strength value drops to 13.2kV/mm.



(a) potential (b) electric field (c) potential (d) electric field

Figure 6. Potential and electric field distribution of cable terminal without stress cone and stress cone

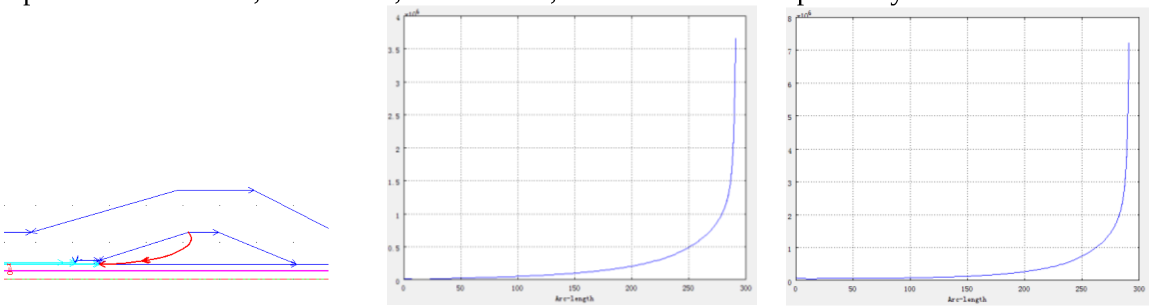
Figure 7 shows the cable termination field distribution using different levels of nano-SiC/silicone rubber composites. It can be seen from the figure that the maximum electric field value of the cable terminal using nano-SiC/silicone rubber composites with the content of 45wt%, 30wt%, 15wt%, and 0wt% is 12.0kV/mm, 15.1kV/mm, 18.4kV/mm, 35.4kV/mm respectively. Compared with the stress cone using common materials, the maximum field strength of stress cone root reduced by 9.1% with 45wt% non-linear conductive material.



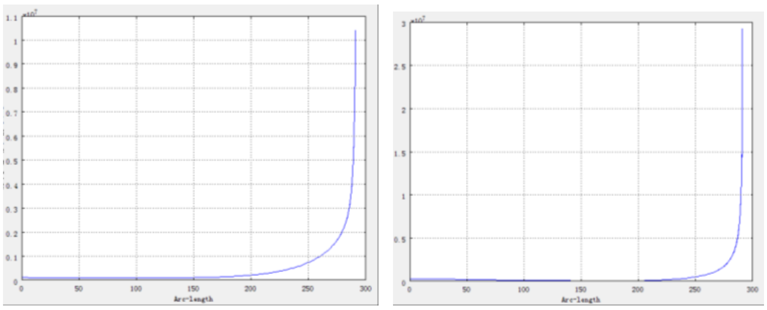
(a) 45wt% (b) 30wt% (c) 15wt% (d) pure

Figure 7. Electric field distribution of cable terminal

Figure 8 shows the electric field distribution along the stress cone interface of the cable terminated with different content of nano-SiC/silicone rubber composites. The red curve in Figure 8 (a) is the stress cone interface. It can be seen from the figure 8 that the maximum tangential electric field values at the stress cone interface using 45wt%, 30wt%, 15wt%, 0wt% content of nano-SiC/silicone rubber composite is 3.7kV/mm, 7.3kV/mm, 10.4kV/mm, and 29.0kV/mm respectively.



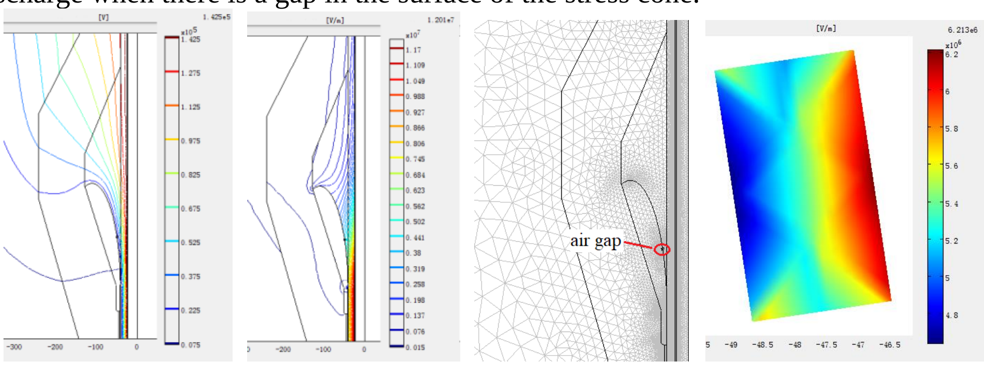
(a) The schematic of stress cone interface (b) 45wt% (c) 30wt%



(d) 15wt% (e) pure

Figure 8. Tangential electric field distribution of cable terminal stress cone interface

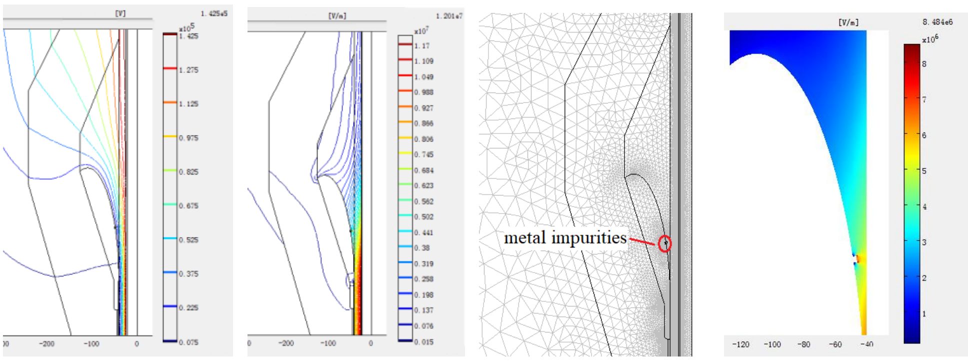
In addition, the cable terminal need to be produced in the field, once the production process is poor, leaving bubbles in cable terminal, the electric field distribution of the cable terminal will be very uneven, local high field strength lead partial discharge, shorten the cable terminal life. Figure 9 shows the potential and electric field distributions of the cable terminal when the stress cone surface exist air gap. Figure 9 (d) shows the electric field distribution inside the air gap. The maximum field strength is 6.2kV/mm, which is larger than the air breakdown strength of 3kV/mm. This indicates that there is a partial discharge when there is a gap in the surface of the stress cone.



(a) potential (b) electric field (c) air gap (d) electric field of air gap

Figure 9. Electric field distribution of the stress cone surface with air gap

The cable terminal need to be produced in the field, may leaving impurities in cable terminal. Figure 10 shows the potential and electric field distribution of metal impurities on the surface of the cable termination stress cone. It can be seen from figure 10 (d) that electric field concentration on the surface of the metal impurity, and the local electric field value reaches 8.5kV.



(a) potential (b) electric field (c) metal impurities (d) electric field

Figure 10. Electric field distribution of cable termination stress cone surface with metal impurities

4. Conclusion

Based on the DC cable terminal have large volume, the electric field concentration, and the limitation of production on site, easy to leave defects. In this paper, the conductivity characteristics of nano-SiC/silicone rubber composites with nonlinear conductivity are introduced. The nonlinear electric conductance material is used to improve the electric field distribution. The COMSOL simulation software is used to simulate the electric field distribution of the cable terminal under nonlinear, air gap and metal impurity respectively. Simulation results show:

1. The cable terminal stress cone uses different content of nano-SiC/silicone rubber composites, the greater the degree of non-linearity, the smaller the maximum field strength of stress cone.

2. Once the stress cone surface exist air gap, it will lead to partial discharge, and shorten the life of the cable terminal.

3. If there is metal impurity on the surface of the cable terminal stress cone, a concentrated field strength is formed on the surface of the metal impurity.

4. Compared with the traditional stress cone, the maximum electric field strength at cable terminal decreases extremely when used the 45wt% non-linear nano-SiC/silicone rubber composites.

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