Research on Nonlinear EPDM for ±525kV HVDC Cable Accessories

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Abstract. High voltage *direct* current (HVDC) cable accessories are usually the weak link in the cable system for the electric field distribution is often extremely uneven, and it has a range of adverse effects in design and manufacture. In this paper, Ethylene-propylene-diene terpolymer (EPDM) was developed for ±525 kV HVDC cable accessories, and the conductivity, XLPE/EPDM interface charge behavior and breakdown strength were tested respectively. The electric field distribution of cable accessories was calculated by COMSOL analysis software. It is shown that the conductivity of EPDM is nonlinear with electric field, and it is possible to achieve the uniformity of electric field distribution by using a composite material with nonlinear conductive properties. Furthermore, the interfacial charge characteristics of XLPE/EPDM depend on the conductivity of EPDM. As a consequence, the research will make a potential application for ±525 kV HVDC cable accessories.

1 Introduction

In recent years, HVDC transmission technology develops rapidly, voltage level and transmission capacity increase quickly. HVDC extruded cable is one of the key power devices for realizing the flexible interconnection of large power grids, the power transmission with long distance and large capacity, and large-scale utilization of renewable energy [1]. The cable accessories are usually the weak link in the cable system, and its own electric field intensity is far beyond the average value of the overall electric field intensity, even several times the average value, and the electric field distribution is often extremely uneven [2]. It has a range of adverse effects in design and manufacture, which makes the importance and difficulty of insulation problems more and more obvious [3]. Therefore, reasonable improvement of the uniformity of electric field distribution of cable accessories and the relaxation of local high electric field intensity can reduce the technical difficulties of product design and manufacturing and improve the safety and reliability of equipment in long-term operation.

The improvement of electric field intensity distribution of stress cone mainly starts from the following two aspects. One is to optimize the prefabricated rubber stress cone structure, J. Cardinaels et al. proposed a terminal structure suitable for medium and high voltage dc plastic cable, the inner layer is ethyl-propylene rubber, the outer layer is silicone rubber, and two stress cone structures are arranged inside the terminal [4]. The second is to improve the electric field intensity distribution of cable terminals by using nonlinear composite materials, ABB adopts nonlinear resistive stress control technology, produced 525 kV extruded insulation DC cable terminal, which can satisfy the stability requirements of load cycle and transient process (lightning and operating pulse) under the condition of DC operation [5,6].

The optimization design of the stress cone structure is a very complex problem, which needs to be determined according to the actual cable parameters [7]. In this paper, the strength of stress cone electric field is improved by using the composite material with nonlinear conductance characteristics. The stress cone simulation model of 525 kV was established by COMSOL Multiphysics, and the distribution of stress cone electric field was studied with different materials were used in the insulation part of stress cone.

2 Experimental setup

2.1 Samples preparation

XLPE was designed for HVDC cable with voltage up to ±525 kV by Borealis (LS4258DCE), and EPDM insulation material was developed by NARI Group. Both XLPE and EPDM insulation were cured at 175°C for 15 min in an electrically heated press under identical pressure 20 MPa and cooled down to room temperature naturally. The samples were put into the drying oven for 12 h to eliminate crosslinked by-products and internal stress produced during the preparation process.

2.2 Conductivity measurements

Conduction currents were measured by an electrometer and the self-made trielectrode system, the voltage range of high voltage DC generator is 0~ 60 kV, with ripple coefficient less than 0.1%. Both XLPE and EPDM samples have a diameter of 160 mm and the thickness is 1 mm, and then the volume resistivity of XLPE and EPDM samples at 5~50 kV/mm was measured 40°C for 1 min. Finally, the corresponding conductivity value is calculated according to current measurement results, sample thickness and electrode size.

2.3 Interface charge measurements

Interface charge behaviors measurements between XLPE and EPDM by Laser Pressure Wave Propagation (PWP) Method. Pulse wavelength of the laser is 1064 nm, energy is 650 mJ, pulse width is 3~8 ns. The oscilloscope bandwidth is 200 MHz, and sampling rate is 1 GSa/s. Both XLPE and EPDM samples had a diameter of 160 mm and the thickness was 250 and 400 μm respectively. EPDM was connected to the high voltage electrode and XLPE was connected to the ground. The negative voltage of 20 kV/mm was applied to the sample step by step with 1800 s at 40°C.

2.4 DC breakdown measurements

A dielectric breakdown strength equipment was used to measure the DC breakdown strength of composites. The increasing rate of voltage was 1 kV/s until the specimen is broken down. Spherical electrodes with a diameter of 10 mm were chosen to be used, which were immersed in silicone oil during the test. Then, the Weibull statistical distribution was used to process the experimental data and determine the characteristic of DC dielectric breakdown strength according to the IEEE Standard 930-2004.

3 Results and discussion

3.1. Conductivity

The relationship between conductivity and electric field can be expressed as formula (1)

$$\sigma(E) = A \cdot \sinh(B \cdot E) \cdot E^{\gamma} \tag{1}$$

where σ is the electric conductivity, A and B is a constant, E is the applied electrical field, and γ is the nonlinear conductive modification coefficient [8].

Figure 1 shows the relationship between EPDM conductivity and electric field. Due to the complexity of materials, different materials can be described by different formulas. According to the experimental data measured in this paper, it is more consistent with formula (1) in the bilogarithmic coordinate system, and the fitting results are shown in table 1. In the range of 5 -60 kV/mm, the conductivity of EPDM is nonlinear with electric field. When electric field is lower than 20 kV/mm, the conductivity is linear to the electric field, and as electric field is higher than 20 kV/mm, the electric conductivity of EPDM increases rapidly with the increase of electric field. In terms of the formula (1), the fitting parameters of nonlinear conductivity of composites in this work were listed in Table I.

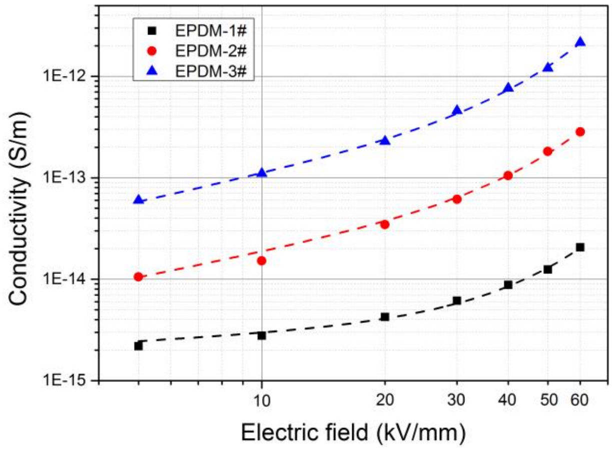


Figure 1. Relationship between the conductivity and electrical field with different samples.

Table 1. Fitting parameters of different samples.

Samples	**Fitting Parameters**		
	A	**B**	**γ**
EPDM-1#	2.87×10^{-14}	0.059	-0.78
EPDM-2#	5.37×10^{-14}	0.053	-0.20
EPDM-3#	2.50×10^{-13}	0.055	-0.11

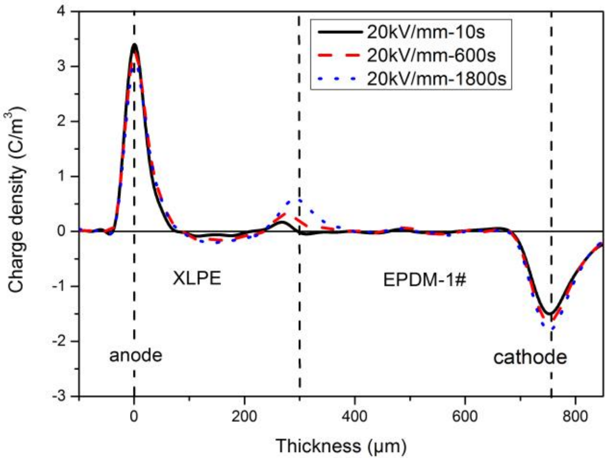
3.2 Interface charge

Figure 2 demonstrates the interface charge behavior between XLPE and EPDM under 20 kV/mm at 40℃, the horizontal coordinates in the figure are sample thickness, and the vertical coordinate is the charge density in the sample. The dotted line represents the position of the interface. In Figure 2(a), A small amount of charges are observed at the interfacial region. Besides, the value continues to grow with time under the applied field. The value of the interface charge density reaches 0.6 C/m3. there are negative charges accumulation in XLPE, while no signal is detected in EPDM.

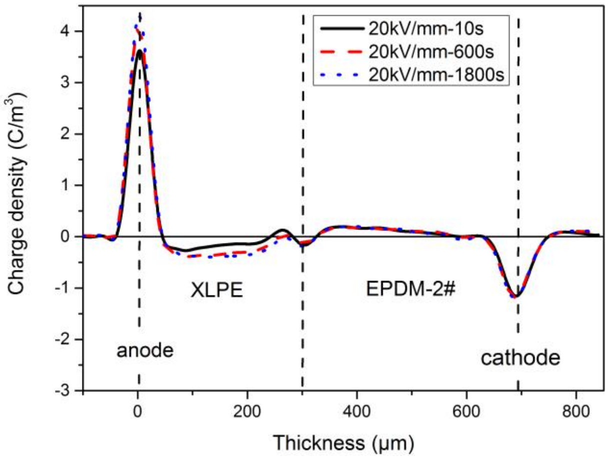
In Figure 2(b), a little signal is detected at the interface in the initial period. But the time for interface charge buildup is shorter than that in Figure 2(a), which is caused by the higher conductivity with this filler loading, the value of the interface charge density reaches 0.2 C/m3.

In Figure 2(c), large amounts of negative charges are accumulated at the interface, which gradually increases with time under the applied field over 1800 s, the value of the interface charge density reaches 1.2 C/m3. Besides, negative charges are accumulated in XLPE, and positive charges are accumulated in EPDM.

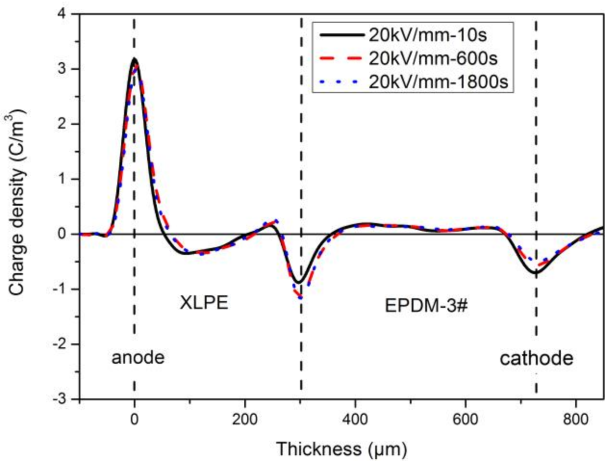
The mechanism of interface charge formation is influenced by many factors. On the one hand, according to the Maxwell Wagner (MW) polarization theory, since the conductivity of the two dielectrics has different relations with electric field, when the electric field change, the matching relationship between conductivity and dielectric constant changes, which may lead to the density change of interface charge. On the other hand, due to the difference in space charge characteristics of XLPE and EPDM, injection or impurity dissociation charges will be generated in the medium, which will migrate to the interface under applied electric field, and the polarity and charge density of the interface will also change.



(a) XLPE/EPDM-1#



(b) XLPE/EPDM-2#



(c) XLPE/EPDM-3#

Figure 2. Interface charge behaviors between XLPE and EPDM

3.3 Breakdown strength

The expression for breakdown results were fitted with a 2-parameter Weibull distribution is given by formula (2)

$$P = 1 - \exp\left[-\left(\frac{E}{\alpha}\right)^{\beta}\right] \tag{2}$$

where P is the cumulative probability of the electrical failure, E is the experimental breakdown strength, β is a shape parameter that evaluates the scatter of data and α is a scale parameter that represents the breakdown strength at the cumulative failure probability of 63.2%. The estimator for the α parameter was used in this work to compare the dielectric breakdown behavior of different kinds of samples and it was obtained from the weighted least squares regression technique described in [9]. The distribution plot can be seen in Figure 3, and the Weibull parameters of EPDM are also shown in Table 2. The breakdown strength of EPDM are 111, 101, 93 kV/mm respectively.

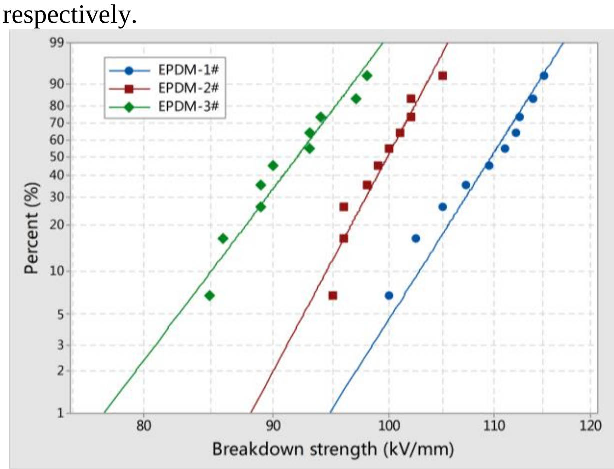


Figure 3. Weibull distribution plot of EPDM breakdown strength.

Table 2. Parameters of EPDM breakdown strength.

Samples	Parameters of Weibull distribution	
	α	β
EPDM-1#	111	29
EPDM-2#	101	34
EPDM-3#	93	24

3.4 Calculation of electric field distribution

A typical cable accessory structure is shown in figure 4, the conductivity properties of EPDM are studied above. A 525kV DC voltage was applied to the cable conductor and the conductive EPDM connects to ground, Potential maps of three simulation models is shown in Figure 5, and the electric field distribution along the stress cone curve is shown in Figure 6. In contrast to the simulation of different EPDM, In Figure 5(a), the electric field is mainly concentrated in the insulation part of the stress cone, and the maximum electric field at the root of the stress cone is 18.3 kV/mm. In Figure 5(b), the electric field is uniform distributed between cable insulation and stress cone insulation. At this time, the maximum electric field at the root of stress cone is 6 kV/mm. In Figure 5(c), the electric field is mainly concentrated in cable insulation, and the maximum electric field at the root of the stress cone is 3.2 kV/mm.

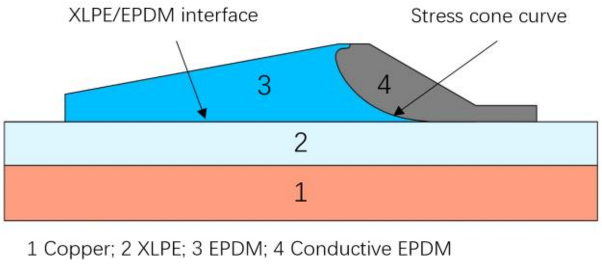
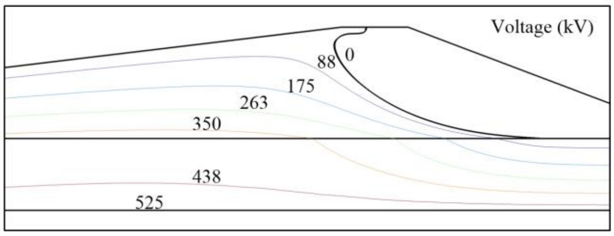
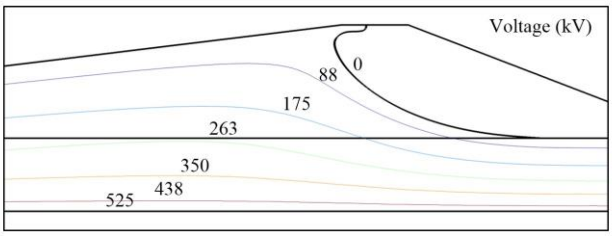


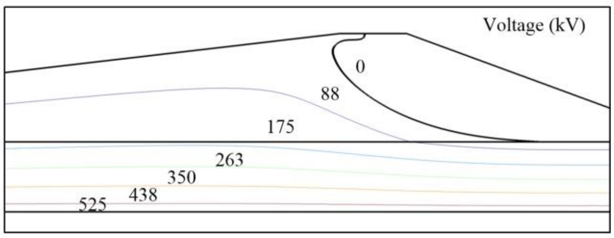
Figure 4. A typical cable accessory structure.



(a) EPDM-1#



(b) EPDM-2#



(c) EPDM-3#

Figure 5. Potential maps of three simulation models.

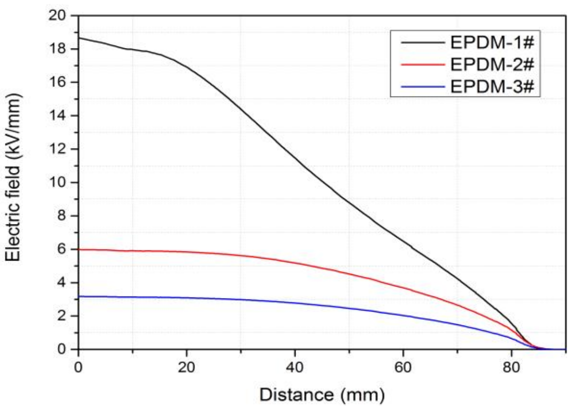


Figure 6. Electric field along the stress cone curve.

4 Conclusion

This paper presented the research on nonlinear EPDM for ±525 kV HVDC cable accessories, and the following conclusions can be drawn

- The conductivity of EPDM is nonlinear with electric field. When electric field is lower than 20 kV/mm, the conductivity is linear to the electric field, and as electric field higher than 20 kV/mm, the electric conductivity of EPDM increases rapidly with electric field.
- The formation of interface charge between nonlinear EPDM and XLPE is not only influenced by MW polarization, but also the injection charge or impurity dissociation charge of EPDM and XLPE will lead to changes in the polarity and charge density.
- In cable accessories stress cone, it is possible to achieve the uniformity of electric field distribution by using a composite material with nonlinear conductive properties.

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References

1. M. J. Non-Member, "HVDC, the Next Generation of Transmission: Highlights with Focus on Extruded Cable Systems," IEEE Transactions on Electrical & Electronic Engineering, 5, pp. 400–404, (2010).
2. Z. Zheng and S. Boggs, "Defect tolerance of solid dielectric transmission class cable," IEEE Electr. Insul. M., 21, pp. 34-41, (2005).
3. X. Yang, J. Hu, S. Chen, and J. He, "Understanding the Percolation Characteristics of Nonlinear Composite Dielectrics," Sci Rep, 6, p. 30597, (2016)..
4. J. Cardinaels, F. Gahungu, H. Janah, J. Matallana, and P. Mirebeau, "Synthetic material end for a DC electric cable,": US, 2008.
5. T. Christen, L. Donzel and F. Greuter, "Nonlinear resistive electric field grading part 1: Theory and simulation," IEEE Electr. Insul. M., 26, pp. 47-59, (2010).
6. L. Donzel, F. Greuter and T. Christen, "Nonlinear resistive electric field grading Part 2: Materials and applications," IEEE Electr. Insul. M., 27, pp. 18-29, (2011).
7. K. Shang, J. Cao, Z. Zhao, Z. Han, M. A. Libin, and L. I. Wenpeng, "Simulation Analysis and Design Optimization of 320 kV HVDC Cable Joint," Proceedings of the Csee, 36, pp. 2018-2024, (2016)..
8. N. Adi, G. Teyssedre, T. T. N. Vu, and N. I. Sinisuka, "DC field distribution in XLPE-insulated DC model cable with polarity inversion and thermal

gradient," in IEEE International Conference on High Voltage Engineering and Application, 2016.

9. P. Han, J. W. Zha, M. S. Zheng, Y. Q. Wen, and Z. M. Dang, "Nonlinear electric conductivity and thermal conductivity of WS2 /EPDM field grading materials," J. Appl. Phys., 122, p. 195106, (2017).