Performance of Cross-linked Polyethylene Insulated Cable based on Detection of High Voltage Electric Field

Y Luo, J Luo*, B Li
State Grid Chongqing Beibei Power Supply Company,
Chongqing, 400700, China

ABSTRACT
High voltage direct current transmission has been widely used in long-distance power transmission because of its advantages such as low loss and large throughput. The safety of cable is very important in the long-distance transmission process. Cross-linked polyethylene insulated cable has the advantages of simple manufacture, good heat resistance and easy installation; therefore it has been widely used in long-distance power transmission. In this study, conductance, dielectric and voltage withstanding performance of the insulating layers of cross-linked polyethylene cables with working voltage of 220 kV which was never used and has been used for 2, 4, 6 and 8 years were tested by various evaluation methods. The conductivity of the insulating layers was affected by temperature only under high and low electric field intensities and was affected by temperature and electric field strength under middle electric field intensity. Dielectric loss factor could reflect dielectric properties of materials; the larger the dielectric loss factor, the poorer the performance. The dielectric loss factor decreased with the increase of applied electric field frequency and increased with the increase of service years. Breakdown electric field strength could reflect voltage resistance of materials; the larger the breakdown electric field strength, the better the performance. The breakdown electric field strength was inversely proportional to the service years of the insulating layer, and the decrease amplitude increased significantly when the service time exceeded 2 years. In summary, cross-linked polyethylene insulated material satisfies the safety requirement of high voltage direct current transmission and can be used for manufacturing long-distance transmission cables.

1. INTRODUCTION

With the development of economy, China's demand for energy is increasing. Electric energy is an important part of energy demand. Long-distance power transmission is a major difficulty as the national territorial area is large [1]. In order to reduce the loss of power during transmission, the power produced by generator is usually converted to high voltage through a transformer. High voltage direct current transmission is a kind of high-voltage transmission. Because of the characteristics of direct current in high voltage direct current transmission, this method has advantages of large transmission capacity, low loss and stable operation. Moreover, conversion technology has been matured. Therefore, high voltage direct current

*Corresponding Author: sjiawluo@yeah.net

transmission has been more and more applied in long-distance power transmission [2]. In order to ensure the safety of power transmission, it is necessary to wrap insulating materials around the conductor. Cross-linked polyethylene is used in the manufacture of insulating cables because of its advantages such as easy manufacture, strong heat resistance and convenient installation and maintenance [3]. Li et al. [4] studied the existence of copper-rich impurities in cross-linked polyethylene cable insulation by thermal oxidation aging and found that copper-rich impurities could reduce the melting temperature and crystallinity of cross-linked polyethylene during thermal oxidation aging and these impurities acted as potential catalysts in oxidation reaction accelerated the inhomogeneous deterioration of cross-linked polyethylene. Wang et al. [5] studied the space charge dissociation and periodically grounded direct current tree in cross-linked polyethylene and analyzed different electric fields in a wide temperature range, 20~80 °C. The results showed that the apparent release control mobility of space charge increased with the increase of temperature, that is, the charge depolarization was easier at high temperature. Tanaka et al. [6] observed the space charge accumulation behavior in cross-linked polyethylene and modified cross-linked polyethylene during polarity inversion of voltage by pulsed electroacoustic method (PEA). The results showed that a large number of enveloped charges were generated during the polarity inversion in cross-linked polyethylene, which was sufficient to significantly enhance the electric field, but it was not observed in the modified cross-linked polyethylene. The electric charge strengthened the local electric stress. In this paper, conductance, dielectric and voltage withstanding properties of the insulation layers of cross-linked polyethylene cables with working voltage of 220 kV which was never used and has been used for 2, 4, 6 and 8 years were tested by various evaluation methods.

2. THE CHARACTERISTICS OF ELECTRIC FIELD DISTRIBUTION IN INSULATED CABLES

The electric field strength in insulator is related to the dielectric constant of the insulator under alternating current voltage. The larger the dielectric constant of the insulator, the smaller the electric field strength in the insulator under a certain alternating current voltage [7]. In order to prevent electric shock accidents, an insulating layer is wrapped around the conductor of cables. Cross-linked polyethylene has been applied to the insulating layer of cables for its advantages of easy manufacture, high heat resistance, simple structure and easy installation. In normal operation, the temperature and electric field intensity produced by cables have little effect on the dielectric constant of cross-linked polyethylene, so Gauss theorem can be used to deduce the formula for the electric field distribution of cross-linked polyethylene cables under alternating current voltage [8]:

$$U = Er\,ln\frac{R}{r'} \tag{1}$$

where E stands for the electric field strength at the area which takes the centre axis of cables as the point of origin and r as the radius, V/m, U stands for phrase voltage, V, R stands for the external diameter of the insulating layer, m, and r' stands for the external diameter of inner shield, m. The electric field is the largest in the internal surface of the insulating layer and smallest in the external surface of the insulating layer. It can be noted from Equation (1) that the distribution of electric field in the insulating layer of cables is only correlated to the specification of cables and the connected voltage.

The electric field strength in the insulator is related to the conductivity of the insulator under direct current voltage. The greater the conductivity, the smaller the electric field strength under a certain direct current voltage [9]. In normal operation, the conductor in cables will generate heat, so that the temperature of cross-linked polyethylene insulating layer rises. Different from dielectric constant, the conductivity of cross-linked polyethylene can be easily affected by temperature. Therefore, the expression of electric field distribution of cross-linked polyethylene cables under direct current voltage [10] is as follows:

$$\begin{cases} \sigma = \sigma_0 e^{b\delta} \\ E = \frac{UAr^{A-1}}{R^A - r'^A} \\ A = \frac{b(\delta_c - \delta_s)}{ln\frac{R}{r'}} \end{cases} \tag{2}$$

where σ stands for the conductivity of cross-linked polyethylene, S/m, σ_0 stands for the conductivity of cross-linked polyethylene at 0 °C, δ stands for the temperature of cross-linked polyethylene, δ_c stands for the temperature of core in cables, δ_s stands for the shielding temperature of cables, b is a constant, and A stands for standardized temperature of cables. When $A < 1$, the electric filed distribution of the insulating layer is opposite with that under alternating current, the electric field was the smallest in the internal surface of the insulating layer and the largest. Besides the specification of cables and the connected voltage, the electric field distribution of the insulating layer of cables under direct current voltage is also related to the load of cables.

3. PREPARATION OF INSULATING LAYER OF CROSS-LINKED POLYETHYLENE

The preparation of the cross-linked polyethylene insulating layer [11] is shown in Figure 1. The first step was molding. Cross-linked polyethylene material was put into a mold, and then the mold was moved to the space between pressing plates of a computer program tablet machine. The second step was hot pressing cross linking. Before starting motor, the pressing plates of the tablet machine were heated to 175 °C, and the temperature was kept constant. After the starting of motor, the pressure between pressing plates was increased to 15 MPa; such temperature and pressure were kept for 30 min to achieve cross linking and hot-press forming of the material.

After hot-press forming, the pressure remained unchanged, and the temperature was cooled at a speed of 10 °C/min until it became 50 °C. After cooling, the pressure was discharged, and the mold was demolded. Next was coating. The cross-linked polyethylene sheets were fixed on the mold of a vacuum coating equipment for aluminum electrode evaporation and then kept at room temperature for 24 h.

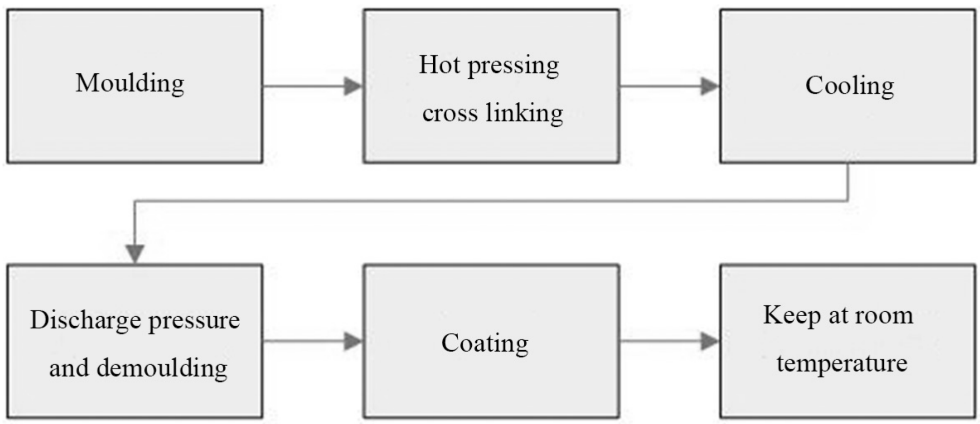

Figure 1: The preparation procedures of cross-linked polyethylene insulating layer

4. EXPERIMENT

4.1 Preparation of specimen

Five cross-linked polyethylene cables which have been used for 0, 2, 4, 6 and 8 years respectively were selected. The working voltage of those cables was 220 V. The cable specimens were cut into slices along the axis. The middle part of the insulating layer was taken as the sample. To prevent the influence of electric heat stress, the thickness of the sample was 1 mm.

Impurities on the surface of the samples were washed away by clean water and pure alcohol. Then they were processed by vacuum drying in a constant temperature oven at a constant temperature of 60 °C for 7 h to eliminate the mechanical stress during slicing [12].

4.2 Test method

(1) Test on the conductance performance of the insulating layer of cross-linked polyethylene cables.

A schematic diagram of the structure of the system which was used for testing the conductivity of the specimen [13] is shown in Figure 2. The shield box had the function of constant temperature drying. The insulating layer of the sample which was never used, i.e, the new cable, was put into the shield box, and the electrode was connected. The conductivity of the shield box was detected under constant external voltage of 3 kV and 9 kV when the temperature was kept constant at 35, 45, 55, 65 and 75 °C for 12 hours. The conductivity of the specimen was detected under different external electric field strength when the temperature was kept constant at 35, 45, 55, 65 and 75 °C.

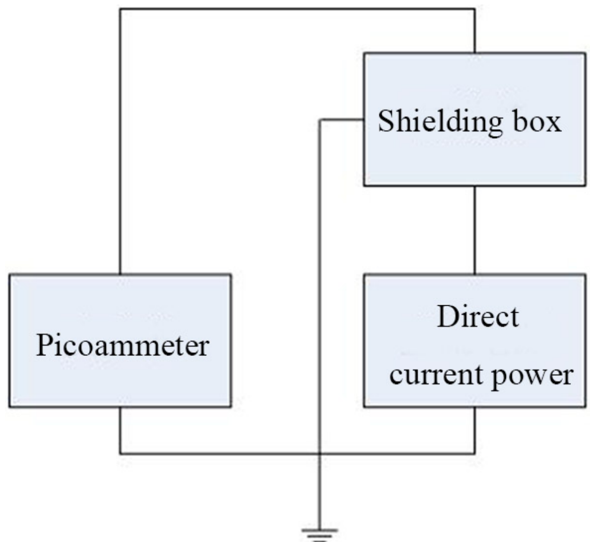

Figure 2: The sketch map of the conductivity performance test system

(2) Test on the dielectric performance of the insulating layer of cross-linked polyethylene cables

The dielectric performance of all the samples were detected using a concept40 broadband dielectric impedance spectrometer [14]. Before detection, a symmetrical gold-plated electrode whose radius was 10 mm was sandwiched. The dielectric performance of the samples was detected under 0.05 ~ 1000 Hz alternate frequency at room temperature.

(3) Test on the voltage withstanding performance of the insulating layer of cross-linked polyethylene cables

Test on the voltage withstanding performance of the specimen followed the regulations in GB/T 1048.1-2006 [15]. Silicone fluid for transformer was used. The experiment was carried out at the room temperature (25 °C), and the humidity was 48%. The transformer used for boosting voltage had a capacity of 100 kVA, 0 ~ 60 kV output voltage and 50 Hz voltage output frequency. Voltage was boosted for five kinds of specimens at a speed of 2 kV/s. The short-time breakdown electric field strength of the specimens was detected in the process of voltage boosting.

4.3 Test results

(1) Conductance performance

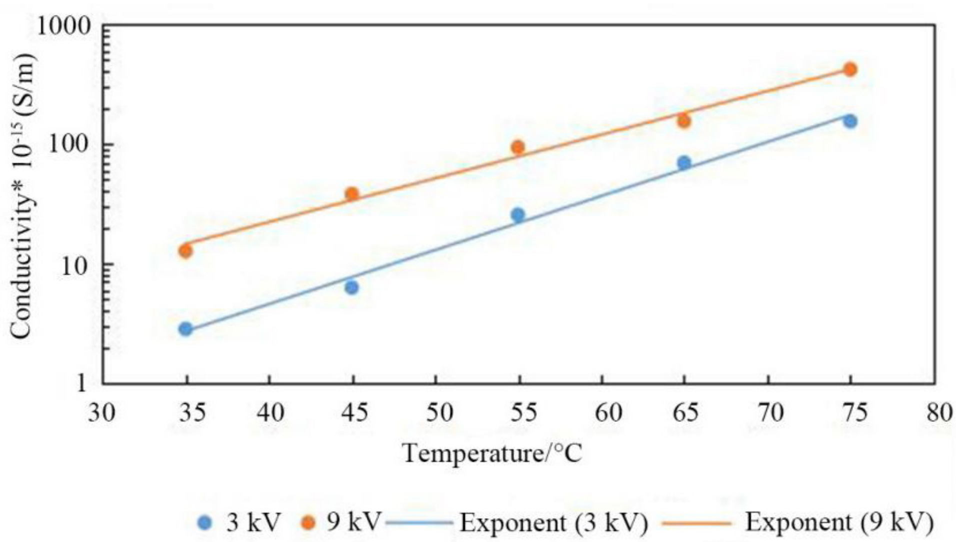

Figure 3: Changes of conductivity and temperature of the cross-linked polyethylene insulator under the fixed voltage

It could be found from equation (2) that the conductivity and temperature of the cross-linked polyethylene insulator were in exponential relationship, which was not beneficial to the intuitive distinction of the image. After logarithmic transformation, it was found that logarithm of conductivity $ln\,\beta$ which took e as the base was in a linear relationship with temperature δ.

Under the fixed voltage, 3 kV and 9 kV, the curve of conductivity temperature of the non-used specimen whose thickness was 1 mm is shown in Figure 3. It could be noted from Figure 3 that $ln\,\beta$ was in a linear relationship with, which was consistent with the exponential relationship between conductivity and temperature in Equation (2).

As shown in Figure 4, the conductivity of the cross-linked polyethylene (XLPE) insulator increased with the increase of temperature generally, which accorded with the experimental results above. Under different constant temperatures, the conductivity of the low electric field intensity and high electric field intensity did not change with the applied electric field intensity, but in different intervals of 0.5 ~ 20 kV, the logarithm of conductivity $lg\,\beta$ which took 10 as the base was basically linear with the applied electric field.

In conclusion, when the applied electric field is strong or weak, the conductivity of the XLPE insulator is only affected by temperature, and the electric field intensity has little effect on it. In a certain strength range of 0.5-20kV, the conductivity is affected by both temperature and electric field intensity, and then increases.

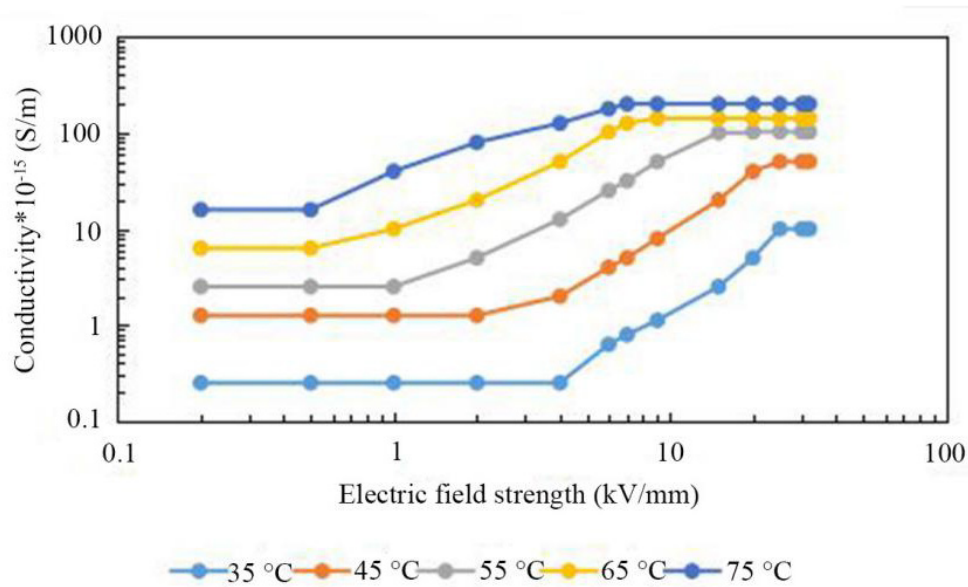

Figure 4: The relationship between the conductivity of the cross-linked polyethylene insulator and the applied electric field intensity under different temperatures

(2) Dielectric performance

Table 1 The dielectric loss factor of the cross-linked polyethylene insulating layer of cables ($tan\,\alpha$)

Frequency	0.05Hz	0.1Hz	1Hz	10Hz	100Hz	1000Hz
New cables	0.0075	0.005	0.0025	0.0024	0.0023	0.0023
Cables which have been used for 2 years	0.01375	0.01	0.005	0.0048	0.0047	0.0046
Cables which has been used for 4 years	0.0175	0.0138	0.0075	0.0065	0.006	0.005
Cables which has been used for 6 years	0.025	0.019	0.01	0.0075	0.007	0.0068
Cables which has been used for 8 years	0.0325	0.0252	0.0125	0.0078	0.0073	0.007

As shown in Table 1, $tan\,\alpha$, the tangent of dielectric loss angle, refers to the dielectric loss factor of the cross-linked polyethylene insulating layer. The parameter reflected the power loss of the material and was used for measuring the insulation performance. It could be noted from Table 1 that the dielectric loss factor of the cross-linked polyethylene insulating layer decreased with the increase of alternate frequency of the applied electric field. The comparison of the insulating layer of the cables which have been used for different years under the same frequency suggested that the dielectric loss factor of the cross-linked polyethylene insulating layer increased with the increase of service years and the increase amplitude was more obvious in the low frequency region, i.e., the insulating layer of cables which served for longer years had larger dielectric loss and poorer insulation performance, which was consistent with the actual condition.

(3) Voltage withstanding performance

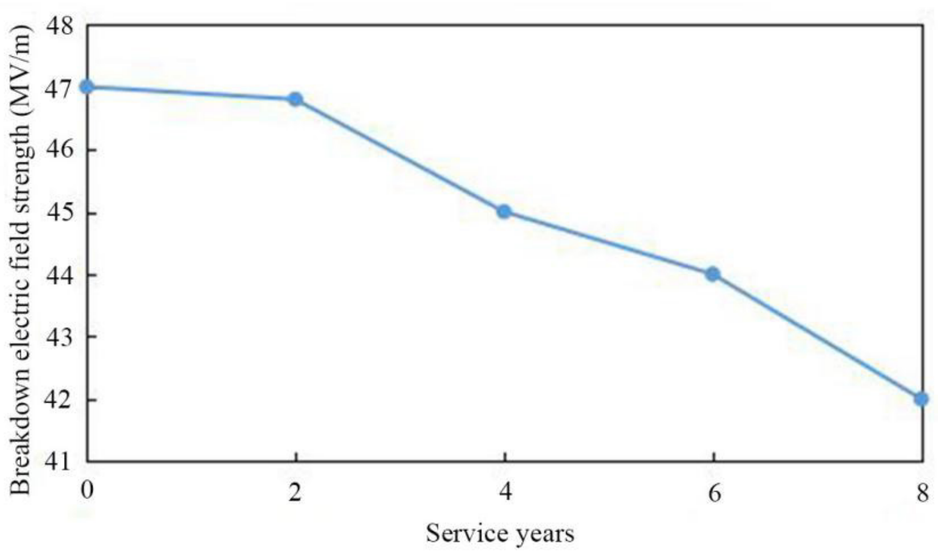

Figure 5: The relationship of the service years of the cross-linked polyethylene cables and the breakdown electric field strength of the insulating layer

The breakdown electric field strength is a parameter used to describe the insulation performance of insulating material. The insulation performance of insulating layer is very important to the safety of cable operation. As shown in Figure 6, the breakdown electric field intensity of the insulating layer of the cable decreased with the increase of the service years of the cable and the decrease amplitude of breakdown electric field intensity of the insulating layer of the cable which served for 2 years or less was small, and the breakdown electric field intensity decreased significantly when the service years exceeded 2 years.

5. CONCLUSION

In this study, conductance, dielectric and voltage withstanding performance of the insulating layers of cross-linked polyethylene cables with working voltage of 220 kV which was never used and has been used for 2, 4, 6 and 8 years were tested by various evaluation methods. The relationship of the conductivity of the insulating layer of cables which has not been used with temperature and applied electric field strength was detected using the conductance performance test system. The dielectric property of the insulating layer of the cables was detected using a broadband dielectric impedance spectrometer. The voltage withstanding performance of the insulating layer of the cables was detected according to the regulations described in GB/T 1048.1-2006. The conductivity of the cross-linked polyethylene insulating layer was in an exponential relationship with temperature under the fixed applied electric field, increasing with temperature. The conductivity of the insulating layer did not change with the electric field strength in the low and high electric fields under different temperatures. The conductivity grew exponentially with the electric field strength in some interval of 0.4 ~ 20 kV electric field strength. With the increase of the applied electric filed, the dielectric loss factor of the insulating layer decreased, and the decrease of the insulation performance reduced. The dielectric loss factor increased with the increase of the service years, especially in the low frequency region. The breakdown electric field strength of the insulating layer decreased with the increase of the service years, and the cable which has been used for more than 2 years had a significant decrease.

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