Study on the Influence of Defect Characteristics of XLPE Cable on Electrical Tree Deterioration

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Abstract. With the acceleration of urbanization, the use of power cables is increasing. However, unlike overhead lines, power cables are laid in underground pipe galleries. It is difficult for power grid operation and maintenance personnel to carry out patrol inspection of power cable lines through intuitive detection means. Therefore, many defects of power cables are difficult to be found in time. During the operation of power cables, the influence of insulation electrical treeing is very large. Electrical treeing is an irreversible insulation damage. Electrical treeing can easily lead to penetrating discharge channels in cable insulation, thus affecting the reliability of the entire transmission system. In response to the above problems, the project team carried out an experimental study on the influence of the defect characteristics of XLPE insulated cables on the initial voltage of electrical tree. Based on the experimental results, this paper deeply analyzes the influence mechanism of cable defect characteristics on electrical tree. The numerical model of cable defects is constructed, and the influence of various factors on the generation of electrical tree is analyzed. Finally, the technical measures to weaken the deterioration of electrical tree in cable insulation are put forward. This research work has guiding significance for optimizing the performance and quality of power cables and improving the operation level of cables.

Keywords: Cross Linked Polyethylene · Cable · Electric Tree Branch · Test Platform

1 Introduction

Cross linked polyethylene (XLPE) insulated cables are diffusely applied in power grids with medium and low voltage because of the outstanding insulating property and the characteristics of safe and reliable. With the proposal of the grounding plan of urban power grid, the application of XLPE cables has been further expanded. However, due to the shortcomings of the current production and installation process, some defects or impurities will inevitably appear in the cable insulation, which accelerates the deterioration of the cable insulation and leads to the generation of electrical branches, further

H. Yang et al. (Eds.): SmartGIFT 2022, LNICST 483, pp. 403–411, 2023.
https://doi.org/10.1007/978-3-031-31733-0_34

causing the overall Breakdown Failure of the cable, thus affecting the reliability of the entire transmission system [1]. Therefore, it is of high industrial and engineering value to explore the influence law of defects on the development of electric branches in cable and put forward efficient methods and measures to prevent the generation of electrical tree.

For the analysis of the generation and development of electrical branches in XLPE insulated cable under different defects, domestic and foreign scholars have carried out relevant research in the fields of actual engineering, experimental simulation and model building based on theory. In reference [2, 3], J.H. Mason introduced the formula of maximum field strength of extremely uneven electric field in the needle plate electrode model into the study of branch discharge of organic polymers, revealing the effect of needle tip curvature on the voltage level of branch development, however the effect of the actual material properties on the initiation of the electrical branch was not analyzed. Reference [4] has built a test platform for the simulation of needle plate electrode defects. Based on the simulation results, the influence law of defect dimension in cables on the reliability of electrical branches initiation has been explored, but the corresponding mechanism explanation has not been made. At present, most studies focus on the structure, growth features and contributing factor of electric branches [5–7], only a few researchers have studied the effect of internal defects of XLPE cables on the generation and growth of electrical branches. The existing studies select a single object, and do not fully and systematically consider the influence of disparate defect characteristics on the generation of electrical branches.

Consequently, based on the preliminary test results of the project team, this paper constructs a numerical model of cable defects and analyzes the influence of various factors on the generation of electrical tree. And the technical measures to weaken the deterioration of electrical tree in cable insulation are put forward. It can effectively guide the production, operation and maintenance of power cables.

2 Numerical Model of Cable Defects

To study the correlation between tip curvature and the initial voltage of electric tree, the influence of various factors on the generation of electrotree was analyzed, and the numerical analysis model between the curvature radius of needle electrode and the initial voltage of electrotree was established.

Based on the allocation rule of the internal electric field in the AC electric field, the electric field strength decreases with the increase of dielectric constant. When the air gap inside the cable is introduced, the voltage in the micropore is larger because its dielectric constant is smaller than that of cross-linked polyethylene. According to the electromagnetic distribution model under spherical pores:

$$E_v = \frac{3\varepsilon}{1 + 2\varepsilon} E_0 \tag{1}$$

where: E_v is the electric strength in themicrovoid. E_0 is the electric field strength in XLPE. Since the dielectric constant ε of XLPE is approximately 2.2, the above formula can be reduced to:

$$E_v = 1.2\, E_0 \tag{2}$$

According to the above formula, the electric strength in the microvoid is about 1.2 times that of crosslinked polyethylene. When the electric field strength raises, local breakdown and discharge will occur in the air interval, and the defects in the microvoid will became worse.

According to the electron collision theory, the energy obtained by charged particles under the acceleration of electric field is:

$$\Delta W = \frac{e^2 E^2}{2m} \overline{\tau} \tag{3}$$

where: m is the mass of charged particles. $\overline{\tau}$ is the time of mean free path.

Because the initiation of electrical treeing is determined by the energy of the particles injected into the material, the polymer will undergo molecular fracture and electric corrosion reaction under the action of high-energy particles, and the form of multi carbonization path will further develop. The maximum withstand energy threshold of XLPE under single electron impact is set as $\Delta W_{0,}$ which depends on is related to the properties of XLPE and other factors. When the charged particle energy is higher than the maximum withstand energy threshold, that is, $\Delta W \geq \Delta W_0$, the electrical tree has caused and further deterioration.

To identify the initial voltage of the electrical branch, let $\Delta W = \frac{e^2 E^2}{2m} \overline{t} = \Delta W_0$.

Since the combined fault model of bulge and air interval on the semiconductor layer can be approximately equivalent to the needle plate electrode model, based on the Mason formula of the maximum field strength under the needle plate electrode model, the maximum field strength of the cross-linked polyethylene layer can be derived as follows:

$$E_{\max} = \frac{2U_0\sqrt{(1 + \frac{d}{r})\frac{d}{r}}}{\ln(\frac{2d}{r} + 1 + 2\sqrt{(1 + \frac{d}{r})\frac{d}{r}})d} \tag{4}$$

where r is the radius of curvature of the needle electrode. U_0 is the test voltage. d is the distance between plate electrodes and needle.

When the cross-linked polyethylene at the front end of the air gap is carbonized, that is, the generation of electric branches, the corresponding voltage U_{i} can be recognized as the starting voltage of electric branches, and the relationship with the internal electric field strength of the material is as follows:

$$U_i = \frac{E_0 \times \ln(\frac{2d}{r} + 1 + 2\sqrt{(1 + \frac{d}{r})\frac{d}{r}})d}{2\sqrt{(1 + \frac{d}{r})\frac{d}{r}}} \tag{5}$$

Since the electric field in the small space at the front of the air gap is continuous, it can be assumed that the electric field intensity E_0 in the tip region remains the same at the initial stage, and the charged particles accelerate in the electric field and impact the air gap XLPE interface. Combining Eqs. (2), (3) and (5), the following simultaneous equations can be obtained:

$$\begin{cases} U_i = \dfrac{E_0 \times \ln(\frac{2d}{r} + 1 + 2\sqrt{(1+\frac{d}{r})\frac{d}{r}})d}{2\sqrt{(1+\frac{d}{r})\frac{d}{r}}} \\ E_v = 1.2\, E_0 \\ \Delta W_0 = \dfrac{e^2 E_v^2}{2m}\overline{\tau} \end{cases} \tag{6}$$

After converting the above relationship, the starting voltage U_{i} of the electric branche is:

$$U_i = \frac{d \times \ln(\frac{2d}{r} + 1 + 2\sqrt{(1+\frac{d}{r})\frac{d}{r}})r}{2.4 \times \sqrt{(1+\frac{d}{r})\frac{d}{r}}e}\sqrt{2\Delta W_0}\sqrt{\frac{m}{\tau}} \tag{7}$$

As for the same kind of materials, the maximum withstand energy ΔW_0 can be considered as a constant. The constructed coefficient A is:

$$A = \frac{d \times \ln(\frac{2d}{r} + 1 + 2\sqrt{(1+\frac{d}{r})\frac{d}{r}})r}{2.4 \times \sqrt{(1+\frac{d}{r})\frac{d}{r}}e}\sqrt{2\Delta W_0} \tag{8}$$

Then the starting voltage U_{i} of the electrical tree can be calculated as follows:

$$U_i = A\sqrt{\frac{m}{\tau}} \tag{9}$$

When the internal space of the micropore is fixed, the average free path of the charged particles can be calculated as follows:

$$\overline{\lambda} = \frac{KT}{\pi r^{\cdot 2} P} = \frac{B}{P} \tag{10}$$

Where, T is the absolute temperature. K is Boltzmann constant. P is the pressure in the micropore. r is the radius of charged particles. Under the same electric field, the velocity obtained by charged particles is almost the same. The average free path time will maintain a positive correlation with the average free path of particles. Therefore, the average free travel can be calculated as follows:

$$\overline{\tau} = \frac{C}{P} \tag{11}$$

Where, C is a constant. Bring expression (8) and expression (11) into expression (7) to get:

$$U_i = \sqrt{\frac{Pm}{C}}A = \frac{d \times \ln(\frac{2d}{r} + 1 + 2\sqrt{(1+\frac{d}{r})\frac{d}{r}})r}{2.4 \times \sqrt{(1+\frac{d}{r})\frac{d}{r}}e}\sqrt{2\Delta\ W_0}\sqrt{\frac{Pm}{C}} \tag{12}$$

From the above formula, it can be seen that the initial voltage of electric treeing is affected by factors such as the radius of curvature of the needle tip, the initial initiation energy of electric treeing, the type of precipitation particles and the pressure of millipore. Assuming that micro pore pressure and the grains colliding with the electrical tree remain unchanged in the experiment, the initialization voltage of the electrical branche is a function of the change of needle curvature. Using the method of experimental test and literature review, determine the parameter size in the relationship, and compare the obtained function image with the test result image, as shown in Fig. 1, it can be analyzed that the test and numerical research results are consistent, identifying that the numerical model is practical, and the needle tip curvature meets a certain positive correlation with the starting voltage of electrical branche.

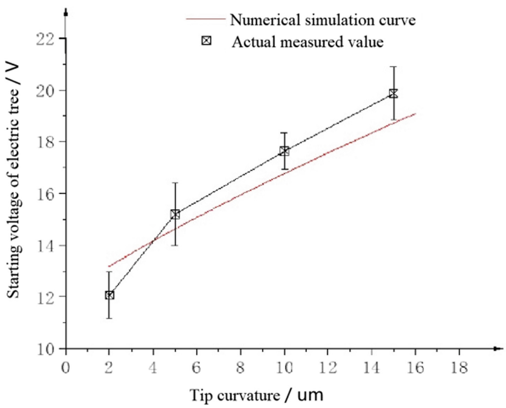


Fig. 1. Comparison between numerical simulation curve and tip curve

According to the established numerical model, when the curvature of the needle tip and the material doesn't change, the initialization voltage of the electrical branche is related to the microporous pressure, and also shows a positive correlation. With the increase (decrease) of the microporous pressure, the higher (decrease) the initial voltage of the electrical branche. Because the test and actual temperature did not exceed the glass transition temperature of XLPE, the material properties remained unchanged. The elastic modulus of cross-linked polyethylene in glass state was large, and the effect of mechanical stress caused by air pressure was small. Air pressure further affected the starting voltage of electrical tree mainly by influencing the process of partial discharge.

The ΔW_0 value mainly represents the energy threshold required for generating branches. This parameter is related to the characteristics, structure and microporous interface of insulating materials. As the process of manufacturing and the curvature of the needle keep the same, the initialization voltage of the electrical branche shows a positive correlation with ΔW_0. The larger the value of ΔW_0, the higher the energy required to generate power branches, and the larger the starting voltage required to generate power branches.

3 Mechanism Research and Analysis

The initiation of electrical branche involves complicated physical and chemical processes, which are affected by external contributor and related to the complex characteristics of insulating materials. As a semi crystalline polymer, cross-linked polyethylene has a high degree of dispersion in the fixed and amorphous regions, and the electrical treeing characteristics have a high dispersion due to the local tensile stress, micropores and inhomogeneous crystallization generated during production. Through experimental simulation and numerical model analysis, this work analyzes the influence of diverse defect characteristics on the starting voltage of electrical tree, and the corresponding influence mechanisms are as follows.

The production of electrical branche involves a variety of physical and chemical phenomena, including charge impact, physical change and chemical oxidation decomposition. The main factors in this process are local electric field concentration and charge injection and extraction. Because of the local high electrical strength and the impact of charged grains, physical and chemical action occur inside the material. As the action intensity overcomes the tolerance of the insulating material, a certain discharge channel will be generated, which is macroscopically manifested as the formation of electrical branches. According to the improved Mason defect curvature radius model established, the distortion degree of the electric field on the tip is deepened, which will enhance the local electric stress. According to the defect model, mainly XLPE and air void are mainly acted by the applied voltage. Under the action of the strong electric field, the gas molecules are strongly accelerated and ionized, and the resulting high-energy particles will hit the material surface, first causing the deterioration of the amorphous area of the material, and further developing, as shown in Fig. 2. When the applied electric strength is lower than the inherent breakdown strength and the local electric stress rises a certain degree, cracks will occur at the interface between the material and the defect. The high temperature generated by the collision will further promote the thermal decomposition, accelerating the initiation of the electric tree and reducing the initial voltage value of the electric branche. Thus, in practice, we can increase the starting voltage of electrical branches by enhancing the curvature of synapses in the semiconductor layer and reducing the number of synapses. For instance, for the actual cable extrusion process, we can set the optimal screw speed based on the material characteristics to improve the extrusion mode of cable insulation layer and semiconductor layer, so as to avoid the problems of material surface roughness and extrusion instability caused by pre crosslinking, so as to produce small bulges and insulation air gaps.

From the mechanism analysis, the influence of micropore pressure on electrical branche initiation is mainly embodied in two aspects: mechanical force stretching and free path of charged grains. The effect of needle tip air pressure makes the interface of cross-linked polyethylene layer bear the effect of radial mechanical stress F_1, and its action diagram is exhibited in Fig. 3. The radial mechanical force will lead to the internal compression of the weak region of the material, which will further cause the generation of tangential stress f_τ, resulting in tangential tensile damage in XLPE, and the crack will develop forward. But due to the fact that the normal operating temperature is lower than 90 °C (the glass transition temperature of XLPE), the movement space of the cross-linked polyethylene chain segment is very small, its own tensile strength is large, and it appears as hard plastic externally. The air void pressure has little influence on the inner wall of the insulation material, and the tensile damage caused by the stress is very small.

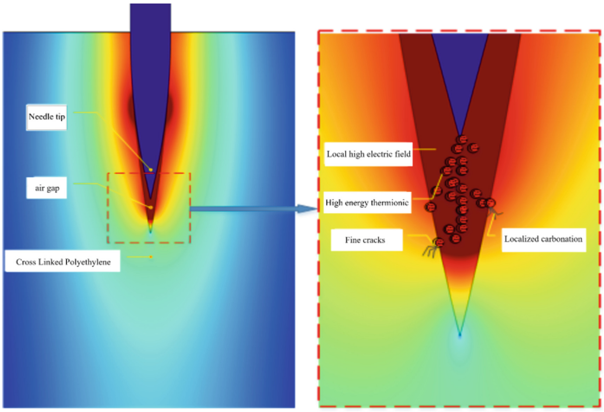


Fig. 2. Hot electron acceleration and material damage under local electric field concentration

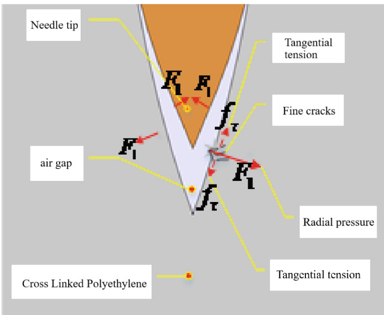
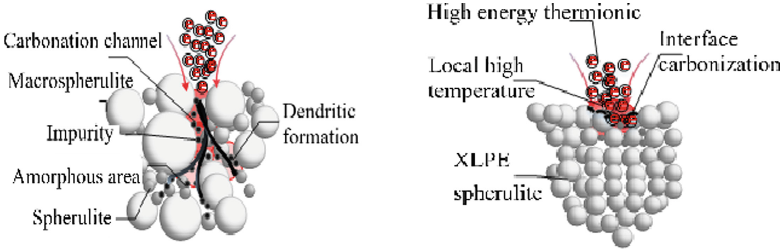


Fig. 3. Stress effect of air gap

From the perspective of particle collision, due to the small micropore gap and pressure of the cable, and the small spacing between particles, the accumulation of energy cannot be completed even under the action of local strong electric field, so sufficient internal electrical stress cannot be generated, and there is no internal discharge, material decomposition and molecular chain fracture in the insulation. By changing the internal pressure of microporous defects to increase the starting voltage of electrical tree, which is mainly carried out from two aspects: ①There are more microholes in cable insulation because of the thermal expansion properties of the material, the non-uniform crystallinity, and the way the material is cross-linked, which mainly reflects that the internal pressure of the micropores in the processing process does not reach the standard value, and the gas cannot be extruded, Improve the extrusion method to reduce the volume of micropores, and increase the pressure of remaining micropores to increase the starting voltage of electric branche; ② The thinner the insulation thickness, the more uniform and concentrated the stress on the material in the pressurization process, and the number of micropores will be reduced, increasing the internal pressure; ③ The dry crosslinking method is selected to replace the wet crosslinking method for polyethylene crosslinking, which avoids causing a large number of micropores in the process of water vaporization and enhances the insulation performance.

Because XLPE is a semi-crystalline polymer compound. Due to certain differences in density and structure between the crystalline region and the amorphous region, their resistance to high-energy particles ΔW_0 and reaction mode are also diverse, and considering the slag removal effect of large grains in the crystalline region and the uneven distribution of the crystalline region caused by it, it also affects the tolerance of materials to electrical tree. In the amorphous region, as shown in Fig. 4a, there are some magazines and small molecular substances. The free movement space of particles is large and the binding effect of materials is relatively small. The collision of high-energy particles is more likely to cause damage to them. At high temperature, the amorphous structure is destroyed and continues to develop along the gap between large crystal regions, and finally forms a dendritic carbonated structure. The introduction of micropores will increase the proportion of amorphous areas and form a weak link in the generation and development of electrical branches. Under the condition of uniform grain distribution (as shown in Fig. 4b), the volume of the amorphous region is small, and the electrons mainly collide with the grains and cause high-temperature carbonization of the interface. Due to the strong damage resistance of the grain structure, the downward development of defects is hindered, thereby improving the resistance ΔW_0. Control the appropriate crosslinking temperature and crosslinking time to obtain the crystal morphology with uniform distribution and high crystallinity, so as to improve the electrical tree resistance of insulating materials, that is, increase the maximum withstand energy value ΔW_0, and then improve the initial voltage intensity of electrical tree.

Inert gas can restrain the ionization degree in micropores, reduce the number of local energetic charged particles, and suppress the local overheating caused by partial discharge, which increases the difficulty of electric tree initiation. At the same time, when manufacturing cables, it is necessary to control the cross-linking process not to occur too early, so as to prevent impurities caused by scorching after the oxidation of the polymer during the early cross-linking, which affect its combination with the normal insulation interface, thus forming bubbles, and reducing the product quality of XLPE. Therefore, changing the crystalline morphology of insulating materials, filling micropores with inert gas and controlling the optimal crosslinking time can improve the size of ΔW_0 and further increase the starting voltage of electrical branche.



(a) (b)

Fig. 4. Target tracking process

4 Conclusion

In this paper, a pin electrode short cable test platform is established. Using this test platform, the growth law of electrical tree under different defects is simulated.

(1) The initial morphology of electrical tree is mainly filiform carbonization, and then gradually develops into the shape of centralized carbonization channel.
(2) There is a positive correlation between the radius of curvature of internal defects in cable insulation and the voltage caused by electrical tree, that is, with the increase of the radius of curvature of defects, the initial voltage of electrical tree increases.

Acknowledgement. This work was financially supported by the science and technology project of State Grid Hunan Electric Power Company Limited (5216A520000H).

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