Study on Insulation Characteristics of Scratch Defects in 35kV XLPE Cable Terminals

Wei Jiaxiang¹, Wang Chong², Gan JianWen³, Lu Zhengxu³, Liang Dawei⁴, Li Lini⁵

¹ Guangxi Power Grid Power Dispatching Control Center, Guangxi, China
² Beijing Urban Construction Design and Development Group Co., Ltd., Beijing, China
³ Guangxi Power Grid Materials Co., Ltd., China
⁴ State Grid Zhejiang Electric Power Co., Ltd. Construction Branch, Zhejiang, China
⁵ College of Electrical Engineering Southwest Jiaotong University, Sichuan China

475857275@qq.com

Abstract. In order to study the influence of different ring-shaped scratches on the insulation characteristics of 35kV Crosslinked polyethylene (XLPE) cable terminations, the model of air-gap defects caused by ring-shaped scratches was introduced at the end of the outer semiconductor shielding layer, and the finite element simulation calculation was used to calculate the model. The electric field distribution characteristics inside the cable terminal were simultaneously made into cable end samples of different types of scratch defects, and the discharge characteristics were tested by a partial discharge test circuit. The results show that the air gap defect caused by the annular scratch defect increases the degree of electric field distortion. The maximum electric field strength is much larger than the breakdown field strength of the air, and it is prone to partial discharge activity. The Phase Resolved Partial Discharge (PRPD) of the cable terminal with ring scratch defects shows a typical "rabbit ear" shape. As the scratch defects deepen, the PRPD spectrum begins to gradually transition to a short-feeling "cat ear" shape.

1. Introduction

The 35kV XLPE cable terminal is an important device for transmission lines, which is used to connect the cable body and other electrical equipment, and is responsible for the transmission of electrical energy [1]. Due to the particularity of the cable termination structure, the probability of failure is much greater than that of the main body. It is the weak link of the transmission line insulation, and its safe operation directly affects the effective operation of the transmission system. The XLPE cable terminal needs to be cut off part of the semiconductor layer during the installation of the field terminal, and the stress tube and the heat shrinkable tube are installed layer by layer, which causes the difference of the material parameters of the interlayer and the difference of the structure, resulting in uneven distribution of the internal electric field, and due to the immature manufacturing process, it is easy to cause scratch defects on the XLPE insulation surface of the cable terminal, and air gap defects are formed after the fabrication, so that the uneven distribution of the electric field is further deepened, and the insulation performance of the cable terminal is further weakened [2].
At present, domestic and foreign scholars have conducted some research on the defects of cable terminals. Yang Fengyuan of Shanghai Jiaotong University studied the cables of different defect types by partial discharge. The research shows that the partial discharge characteristics of cables with different defect types have significant characteristics, and the partial discharge information can be used as an important means of defect research \(^3\); HA Illias and Lee ZH use finite element analysis software to simulate the different defect sizes, locations and different insulation thicknesses of medium voltage cable joints, the main factors affecting the electric field strength distribution in cable joints are studied \(^4\); Sichuan University scholars use electric field simulation and aging experiments. In a combined way, the characteristics of the discharge at the air gap defect are explored. It is believed that the concentration of the electric field at the air gap defect is an important cause of the continuous ablation of the insulation and the final breakdown \(^5\).

Based on previous research, due to the special materials and structures between the 35kV XLPE cable termination layers, when the scratch defects are introduced, the air gap is present, which has an important impact on the insulation performance of the cable termination. Through the finite element simulation analysis and partial discharge test of cable terminals with different air gap defects caused by different scratch depths, the electric field distortion and partial discharge characteristics are explored, which can provide an important basis for cable terminal fault diagnosis.

2. Simulation analysis

2.1. Model building.

According to the investigation, the 35kV XLPE cable terminal needs to cut off the water blocking layer and the outer semiconductor layer. Because the cable is a cylindrical structure and the thickness of the outer semiconductor layer is small, when the cutting is performed, the depth and strength of the feeding are difficult to control. The ring scratch defect is caused, and at the same time, due to the process reason, the treatment for the scratch defect is rough, and the scratch defect cannot be filled, thereby causing the existence of the air gap defect.

It is found through experiments that the annular scratch defect at the cut-off is most likely to occur. To study the insulation characteristics of the scratch defect of the 35kV XLPE cable terminal, according to the actual structure, the cable terminal model is built according to the 1:1 ratio. The simulation model is shown in Figure 1. The circular scratch defect is set with three parameters, which are circular scratch defects with a depth of 0.5mm, 1mm, 2mm and a thickness of 1mm at the cut. At the same time, considering the shape of the cut-off position, the material cannot be completely fitted, so that there is an air gap at the joint between the cut-off portion of the outer semi-conductor layer and the stress tube, and a triangular air gap with a height of 0.5 mm is provided at the joint of the cut-off portion and the stress tube.

![Figure 1. Simulation model diagram](image)
2.2. Simulation results.

The 35kV XLPE cable terminal runs under power frequency. The electric field under the power frequency voltage changes slowly with time. The electric field can be solved according to the electrostatic field. According to the material test and literature, the material parameters are set. The air gap parameter is set to air and the metal shield is set. Layer grounding, electric field simulation for no scratch defects and three ring scratch defects respectively. Since the cable end is an axisymmetric structure and the defect is a circular scratch defect, the electric field distribution of the entire cable terminal can be characterized by studying a horizontal plane. The cross section of the maximum value of the electric field strength in the spatial region is studied, and the simulation results are shown in Figure 2.

![Figure 2](image)

**Figure 2.** Cable terminal simulation results

It can be seen from Figure 2 that when the XLPE cable terminal does not introduce a scratch defect, the electric field strength is at a maximum of 6.88 MV/m, which does not reach the breakdown field strength of the cross-linked polyethylene, and the maximum value is at the junction of the outer semiconductor layer cutoff and the insulating layer. The electric field strength at other locations is relatively evenly distributed; When the annular scratch defect is introduced, the air gap defect is caused, as shown in Figure 2(b), the scratch depth is 0.5mm, and the air gap depth is 1mm. The maximum electric field strength is 12.55MV/m, the breakdown field strength exceeding air [6] is 66.5% higher than the maximum terminal electric field strength when no scratch defect is introduced. It can be seen from the local electric field distribution magnified view that due to the abrupt change of the interlaminar material parameters and the junction structure, the electric field distortion is very serious, the air gap electric field strength is greater than the electric field of the surrounding insulating layer; As shown in Fig. 2(c), the scratch depth is 1mm at this time, and the formed air gap depth is 1.5mm. At this time, the maximum electric field strength is 10.56MV/m, which exceeds the breakdown field strength of air by 3 MV/m. It can be seen from the enlarged view of the local electric field distribution that although the scratch depth is deepened by 0.5 mm, the electric field intensity maximum is smaller than the scratch depth of 0.5 mm, but the electric field strength is small in the air gap region, especially in the insulating portion. The electric field distortion at both ends of the area is particularly serious; As shown in Fig. 2(d), the scratch depth is 2mm at this time, and the formed air gap depth is 2.5mm. At this time, the maximum electric field
strength is 9.51MV/m, which is still higher than the breakdown field of air. It can be seen from the enlarged view of the electric field distribution that as the depth of the scratch is deepened, the maximum value of the electric field strength decreases at this time. The reason for the analysis is that the increase of the air gap defect region weakens the abrupt change of the junction structure, so that the electric field intensity is gradually distributed uniformly [7], but the electric field strength of the entire air gap region is still stronger than the electric field strength around the insulating layer.

It can be seen from Figure 2(b)-(d) that the introduction of scratch defects has a great influence on the electric field distribution inside the cable terminal, especially in the air gap portion, the maximum electric field strength is higher than the air breakdown field strength, which is extremely easy. Partial discharge occurs and the surrounding insulating material is burned. At the same time, the deepening of the scratch defect causes the thickness of the insulating layer to be drastically reduced, which reduces the insulation performance of the cable. Under the intense discharge activity and low insulation performance, the entire cable terminal’ electrical performance will be greatly affected. At the same time, it can be seen from the comparison that the smaller the defect is, the more severe the electric field distortion is. Therefore, the extremely small air gap defect is also an extremely weak part of the cable terminal, and needs to be focused.

3. Study on the characteristics of partial discharge
The electric field simulation analysis of the 35kV XLPE cable terminal scratching defect can characterize its internal insulation characteristics, but there is no instrument to effectively detect the electric field distribution inside the cable terminal. Currently, the test for the insulation state of the cable terminal is generally through partial discharge. The parameters related to the partial discharge test are closely related to the insulation state performance of the cable. The partial discharge quantity characteristic can be used to initially detect the insulation of the test cable, provide reference for the tester, and master the insulation state of different operating periods to reduce the operation. The sudden accident of the line provides great help [8,9].

As shown in Figure 3, it is a partial discharge test loop, in which the Partial Discharge (PD) uses JF2006. After the partial discharge signal is processed by the amplification module and the filter module in the signal conditioning module, the data is collected using DPO-5024B, finally transferred to the PC to achieve partial discharge data processing and display [10].

![Partial discharge test circuit diagram](image)

Figure 3. Partial discharge test circuit diagram
In order to fit the simulation experiment and the actual situation, this study carried out the production of four cable terminal samples. First, the water blocking layer and the outer semiconductor layer of the four cable bodies were cut off. No. 1 was no scratch defect, No. 2 is to make a circular scratch depth of 0.5 mm at the cutoff of the outer semiconductor layer, No. 3 is to make a circular scratch depth of 1mm at the cutoff of the outer semiconductor layer, No. 4 is to make a circular scratch depth of 2 mm at the cutoff of the outer semiconductor layer. Scratch defects are produced as shown in Figure 4. After the scratch is made, the stress tube, the heat shrinkable tube, and the shed are sequentially mounted in the specified order to form 4 cable termination samples.
Firstly, the partial discharge system is calibrated, the background noise is controlled to be less than 10pC, and then the terminal sample of the No. 1 cable is connected to the partial discharge test circuit. The partial discharge signal is not detected at the rated working voltage of 35kV for 15 minutes to ensure the test, that the system is normal and noise interference is minimized. Through the test, record the initial discharge voltage of each test and pressurize to 35kV, the time to form a stable PRPD spectrum, take the average of five tests of each cable terminal sample, and the terminal sample of 2-4 cable The initial discharge voltages were 7.8kV, 10.5kV, 11.2kV, respectively, and the stable discharge time were 75min, 64min, 60min respectively. After testing, the most representative PRPD of the five test samples of each cable terminal was selected. The spectrum is shown in Figure 5.

Fig. 5(a) is a PRPD spectrum of a circular scratch defect depth of 0.5 mm. It can be seen from the figure that the discharge phase is concentrated between 45°-100° and 225°-270°, and the positive and negative half-cycle discharge shapes are relatively thin and long, the whole discharge process presents a typical "rabbit ear" shape; the positive half cycle discharge is dense, the discharge amount is distributed at 10-1000pC; for the negative half cycle, the discharge amount is concentrated at 500-1000pC, and the discharge amount is less in the interval below 500pC, discharge The shape presents a floating state.

Fig. 5(b) is a PRPD spectrum of a circular scratch defect depth of 1 mm. It can be seen from the figure that the discharge interval is increased and the discharge phase is concentrated between 30°-100° and 225°-280°. The shape of the "rabbit ear" is relatively short and thick; the discharge trend is similar in the positive and negative half cycles, and the discharge area of each half cycle forms a "M" shape discharge shape, the discharge amount fault appears at about 252pC, and the high discharge amount is concentrated between 252-750pC. The discharge in the low discharge area is very dense.

Fig. 5(c) is a PRPD spectrum when the depth of the annular scratch defect is 2 mm. It can be seen from the figure that the discharge interval is increased, and each phase has a relatively obvious discharge activity, and the entire discharge process still exhibits "rabbit ear" shape, but has gradually transitioned to the "cat ear" shape; positive and negative half cycles exhibit different discharge characteristics, the discharge phase of the positive half cycle is concentrated at 75° -105°, the discharge distribution is relatively uniform; the discharge phase of the negative half cycle is concentrated at 225° - 300°, the discharge intensity of the negative half cycle is greater than that of the positive half cycle, and the discharge amount is concentrated between 10-600pC, and the discharge in the low discharge region is relatively dense.

According to the partial discharge test, as the scratch defect deepens, the air gap region increases, so that the electron dispersion in the air gap region is relatively stable, and the partial discharge activity is relatively stable, however, the deepening of the scratch defect causes the thickness of the insulating layer to be lowered, the insulation performance is greatly impaired, and the breakdown failure of the cable terminal is extremely likely to occur.
Figure 5. Partial discharge results
4. Conclusion
Based on the defects caused by the 35kV cable termination, the finite element simulation analysis and partial discharge test of the circular scratched cable terminal are carried out, and the following conclusions are obtained:

(1) When the cable terminal contains a circular scratch defect, it is easy to cause distortion of the internal electric field. The maximum electric field strength of the air gap defect area far exceeds the breakdown field strength of the air, which is easy to cause partial discharge activity;

(2) The simulation results of three types of cable terminations with ring-shaped scratch defects show that due to the sudden change of the material parameters of the interlayer and the sudden change of the structure of the interface, the depth of the scratched air gap is shallow, and the degree of electric field distortion is more serious, so even small defects need to be focused;

(3) The partial discharge test results of the cable terminations with different types of scratch defects indicate that the shape of the partial discharge of the cable terminal with scratch defects is "rabbit ear" shape. As the depth of the scratch deepens, the shape of the discharge begins to transition from a "rabbit ear" shape to a short and fat "cat ear" shape, its partial discharge characteristics can be used as an important basis for insulation diagnosis.

(4) By studying the electric field and partial discharge characteristics of the cable termination with scratch defects, it can provide a good data foundation for the next cable fault insulation diagnosis.

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5. References
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