Defect simulation and state characteristic analysis of cable joints with tip defects

Hang Jiang1,4, Junping Cao1, Shuyang Wang2, Li Tong1, Weijie Zhou3 and Yong Yang1

1 State Grid Zhejiang Electric Power Research Institute, Hangzhou, China
2 Shanghai survey and Design Research Institute Co., Ltd. Shanghai, China
3 State Grid Hangzhou power supply company, Hangzhou, China
4E-mail: jhshiep@163.com

Abstract. In recent years, the breakdown of the body and accessories of high voltage cables has increased gradually. Taking the tip defect of 110 kV high voltage cable joint as an example to carry out electric field simulation analysis, the distribution and change law of electric field under this defect are put forward. Based on full working condition detection platform of high voltage cable, the simulation test of the defect is carried out. The effectiveness of various charged detection methods and on-line monitoring methods has been studied, and the variation rules of cable state under different working conditions have been obtained. The results show that, when tip defect is between stress cone silicon rubber and main insulation of cable body, electric field distortion around the tip shows discharge, and the breakdown potential is 83 kV. The high frequency partial discharge detection method and ultrasonic partial discharge detection method can detect the defects effectively, among which anti-interference ability of high frequency partial discharge detection at the capacitive arm is the best, and detection sensitivity of the grounding current is higher in the on-line monitoring. The thermal efficiency of load current has little effect on development of tip defects. But with the increase of test voltage, the high frequency emission volume increases obviously and breakdown occurs easily at higher voltage.

1. Introduction

As an important equipment of urban power supply, the utilization rate of cable is increasing day by day. At the same time, the failure of cable body and accessories is also common [1]. For the high-voltage cable under different working conditions, the analysis of the causes of typical defects and the law of state quantity change can be used as the technical basis of the cable state evaluation [2], which is of great significance to the overall guarantee of the safe and stable operation of the high-voltage cable line.

Cable defect simulation is an important basis for studying the development law of cable defects, finding defect detection means and establishing cable state evaluation system [3, 4]. Most of the existing defect simulation methods are under voltage condition [5-7]. For example, in Literature [8], infrared imaging and partial discharge monitoring are used to study the damage degree of various typical defects under different voltage levels. In Reference [9], defects such as main insulation dent, main insulation knife wound, main insulation metal tip and main insulation surface impurity are constructed by using the cable body, and the above defects are tested by partial discharge. In Reference [10], based on the simulated defect test platform of 110 kV real XLPE cable, two kinds of
discharge models of suspension and sliding flashover are made at the cable terminal, and the development process of two kinds of discharge types is studied by step-up method. However, none of the above defect simulation methods can simulate the load current condition of the actual cable line, which has certain limitations in the study of the influence of load current thermal effect on cable defects [11, 12].

In this paper, 110 kV high-voltage cable joint tip defects are taken as an example to carry out electric field simulation analysis. The full working condition and combined state detection platform of high-voltage cable are used to carry out live detection and online monitoring of defect circuit, and the effectiveness of detection method is studied. Based on this, the change rule of cable state characteristic quantity under different load conditions is obtained.

2. Electric field simulation analysis of defects at the tip of high voltage cable joint

In the process of cable joint installation, it is easy to have semi-conductive exploitation irregularity, water and metal left at the interface, and the surface of conductor connector for wire core crimping is not smooth, resulting in defects at the joint tip [13]. The field strength at the conductor tip is distorted, resulting in partial discharge, which eventually leads to the gradual deterioration of internal insulation.

Taking YJLW03-(Z), 64/110 kV, 1×800 mm² cable as an example, this paper uses COMSOL Multiphysics software to set the tip defect as the combined model of cylinder and cone with the bottom radius of 5mm. The overall length of the defect is 20 mm, 30 mm, 40 mm, 50 mm, 60 mm, 70 mm, 80 mm, 90 mm, 100 mm, 110 mm, 120 mm, 130 mm, 140 mm, 150 mm, whose location is shown in Figure 1.

The voltage levels selected in the simulation are 16 kV, 32 kV, 38.4 kV, 44.8 kV, 51.2 kV, 57.6 kV and 64 kV. The maximum electric field intensity of the defect is shown in Figure 2.

![Figure 1. Model diagram of joint tip defect.](image)

In the figure, when the tip is located on the external semiconducting layer or the main insulation interface, (between the cut-off 1 and 3), the electric field intensity around the tip is small, which has
no effect on the electric field distortion of the cable, and no discharge occurs. When the tip is located on the interface between the stress cone and the main insulation, the electric field strength around the tip increases, but it does not reach the main insulation and the breakdown field strength of the stress cone 22 kV/mm. When the tip is located at the interface between the preform silicone rubber and the XLPE of the cable body, (between the cut-off 3 and 4), the electric field around it is seriously distorted, and the longer the conductor length is, the greater the electric field strength of the tip is. When the potential of the cable core is 83 kV, because of the air gap around the tip, the electric field strength of the air gap is far less than that of the silicone rubber insulation, and the breakdown potential will be lower than 83 kV.

3. Research on the different characteristics of tip defect detection
The tip thin iron sheet is used to trial produce the joint defect sample. The width of the iron sheet is 5mm, which is inserted from the end of the bell mouth of the rubber part in the intermediate joint, with the depth of 150 mm from the end, exceeding the semi conductive shield port of the bell mouth, as shown in Figure 3.

![Figure 3. The setting of tip defect.](image)

The joint tip simulation test is carried out by using the high voltage cable full working condition and combined state detection platform. By increasing the test voltage step by step, the defect characteristics of the intermediate joint are detected by means of live detection and on-line monitoring. High frequency partial discharge and ultrasonic partial discharge are used for live detection, and online monitoring means include high frequency partial discharge, temperature and grounding current monitoring.

![Figure 4. The local spectrogram at capacitive arm side.](image)

3.1. Live detection

3.1.1. High frequency partial discharge detection. Channel 1, channel 2 and channel 3 of high frequency partial discharge live detection are respectively arranged on the capacitance arm at the
direct grounding side, the grounding cable at the direct grounding side and the grounding cable at the protective grounding side of the intermediate joint. When the test voltage is gradually increased to 33 kV, the center frequency is 4.5 MHz, and the discharge signal can be detected in three ways of high-frequency partial discharge. When the voltage rises to 55 kV, the partial discharge signal atlas is shown in Figures 4, 5 and 6.

![Figure 5. The local spectrogram at direct ground side.](image)

![Figure 6. The local spectrogram at protective earthing side.](image)

In the figure, the maximum discharge amplitudes detected by capacitance arm detection, direct grounding and protection grounding side high-frequency partial discharge are 175 PC, 85 PC and 70 PC respectively. The characteristics of discharge spectrum are obvious, which are mainly concentrated in the peak value of positive and negative voltage values, in the shape of symmetrical mushroom on both sides, with clear separation of signal interface. Comparing the three detection results, it can be seen that the anti-interference ability of detection at the capacitor arm is the best, the detection sensitivity at the direct grounding is in the middle, and the detection sensitivity at the protective grounding is the lowest.

3.1.2. Ultrasonic partial discharge detection. The probe of the ultrasonic partial discharge charged detection sensor is installed on the surface of the rubber part of the joint. When the test voltage is gradually increased to 33 kV, the ultrasonic partial discharge can detect the discharge signal. When the
voltage rises to 40 kV, the detection diagram is shown in Figure 7. It can be seen that under the 40 kV test voltage, the obvious discharge signal is detected by the ultrasonic partial discharge detection method, with component 1 reaching 0.3 MV and component 2 reaching 0.7 MV.

![Continuous spectrogram of ultrasound placement](image1)

(a) Continuous spectrogram of ultrasound placement

![Phase spectrogram of ultrasonic partial discharge](image2)

(b) Phase spectrogram of ultrasonic partial discharge

**Figure 7.** Ultrasonic local spectrogram of tip defect.

3.2. On-line monitoring

3.2.1. On line monitoring of high frequency partial discharge. On line monitoring of high frequency partial discharge adopts two methods: polarity identification on both sides of the joint and grounding cable monitoring on the direct grounding side. When the test voltage is gradually increased to 40 kV, the local discharge signal will be detected first in the monitoring mode of the grounding cable at the direct grounding side. When the voltage is increased to 45 kV, the discharge signal can be detected in both monitoring modes. The map of local discharge signal is shown in Figure 8 and Figure 9.

In the figure, under the test voltage of 45 kV, the characteristics of the partial discharge map at the direct grounding side are obvious, and the first and third quadrant signals are symmetrical; the defects that can be located by the body polarity identification method belong to the internal discharge of the joint, and the signals exist continuously during the test process, and the discharge pulses are generated continuously at a certain interval.
Figure 8. Direct grounding side spectrogram of tip defect.

Figure 9. Polarization identification of tip defects.

3.2.2. **On line monitoring of temperature and grounding current.** Online temperature monitoring includes temperature measurement optical fiber arranged on the cable body and temperature measurement module arranged on the conductor of the defective sample joint. Under the current condition, the on-line monitoring of cable skin and conductor body temperature is carried out; the on-line monitoring of grounding current is carried out at the GIS terminal of cable. Under the defect of
joint tip, no abnormality was found in temperature measurement and on-line monitoring of grounding current.

4. Research on electrical characteristics of defects under multiple working conditions
On the basis of the research on the different characteristics of the detection methods of the defects at the tip of the high voltage cable joint, further research on the change law of the state characteristics under different working conditions for a long time is carried out. The trends of partial discharge, temperature and ground current were analyzed, and the discharge path and channel characteristics after breakdown were observed.

4.1. Current operating mode
Firstly, increase the test voltage to 45 kV. When a stable discharge signal appears in the high-frequency partial discharge detection, apply a test current of 1200 A, and record the partial discharge amplitude and temperature changes of the direct grounding side and the protective grounding side every 1 h. The results of high frequency partial discharge are shown in Table 1.

**Table 1. Partial discharge in 1200 A current condition.**

| Time | Test voltage (kV) | Test current (A) | Live partial discharge detection (Pc) |
|------|------------------|------------------|---------------------------------------|
|      |                  |                  | Capacitor arm mode | Direct grounding | Protective earthing |
| 0    | 0                | 0                | 25                  | 30              | 15                  |
| 1    | 45               | 1200             | 75                  | 45              | 30                  |
| 2    | 45               | 1200             | 85                  | 55              | 35                  |
| 3    | 45               | 1200             | 80                  | 53              | 33                  |
| 4    | 45               | 1200             | 85                  | 53              | 33                  |
| 5    | 45               | 1200             | 90                  | 57              | 37                  |
| 6    | 45               | 1200             | 85                  | 55              | 35                  |
| 7    | 45               | 1200             | 80                  | 50              | 30                  |
| 8    | 45               | 1200             | 85                  | 55              | 35                  |
| 9    | 45               | 1200             | 85                  | 55              | 35                  |
| 10   | 45               | 1200             | 85                  | 55              | 35                  |

With the increase of current rising time, the amplitude of high frequency partial discharge of capacitor arm, direct grounding side and protection grounding side does not change much in 1200 A and 0 ~ 10 h. In addition, there is no obvious abnormal temperature rise at the defect of the joint tip. Therefore, the duration of current has little effect on the development of tip defects.

4.2. Voltage condition
Gradually increase the test voltage to observe the changes of partial discharge, grounding current and contact voltage.

4.2.1. High frequency partial discharge. Under voltage condition, high frequency partial discharge detection is shown in Table 2.

In Table 2, the initial discharge voltage of high-frequency partial discharge is 33 kV, and the partial discharge signal of capacitor arm mode and direct grounding side is more obvious than that of protection grounding side. With the increase of test voltage, the amplitude of partial discharge signal increases gradually. When the test voltage rises to 75 kV, the discharge amplitude of capacitor arm mode reaches 405 PC. When the voltage continues to rise, the partial discharge increases rapidly, and the breakdown occurs when the test voltage rises to 87 kV. The characteristics of partial discharge patterns of the defective capacitor arm, the direct grounding side and the protective grounding side at
the tip of the joint are obvious. The discharge signals are concentrated at the peak of the positive and negative values of the voltage, which is symmetrical on both sides.

Table 2. Partial discharge under different test voltages.

| Working condition | Test voltage (kV) | Live partial discharge detection (pC) |
|-------------------|------------------|--------------------------------------|
|                   |                  | Capacitor arm mode | Direct grounding | Protective earthing |
| 1                 | 0                | 25                  | 30               | 10               |
| 2                 | 33               | 50                  | 30               | 15               |
| 3                 | 40               | 60                  | 40               | 20               |
| 4                 | 45               | 75                  | 55               | 30               |
| 5                 | 50               | 120                 | 70               | 45               |
| 6                 | 55               | 175                 | 85               | 70               |
| 7                 | 65               | 260                 | 180              | 130              |
| 8                 | 75               | 450                 | 300              | 250              |
| 9                 | 80               | 800                 | 550              | 400              |
| 10                | 83               | 1300                | 900              | 700              |
| 11                | 86               | 1800                | 1250             | 1000             |
| 12                | 87               | Breakdown            |                  |                  |

4.2.2. Ultrasonic partial discharge. Under voltage condition, the amplitude of ultrasonic partial discharge detection is shown in Table 3.

Table 3. Detection results of ultrasonic local discharge.

| Voltage (kV) | RMS (mV) | Per (mV) | Component 1 (mV) | Component 2 (mV) |
|--------------|----------|----------|------------------|------------------|
| Background   | 0.18     | 0.7      | 0                | 0                |
| 33           | 0.5      | 3.3      | 0.1              | 0.43             |
| 40           | 1        | 6.2      | 0.3              | 0.7              |
| 45           | 2        | 12       | 0.9              | 2.1              |
| 50           | 4        | 22       | 1.4              | 3.2              |
| 55           | 5        | 25       | 1.8              | 4.1              |

It can be seen that the initial discharge voltage of ultrasonic partial discharge is 33 kV, and the amplitude of partial discharge signal increases obviously with the increase of test voltage. Under different test voltage, the characteristics of ultrasonic partial discharge spectrum are more obvious, the amplitude of each component signal of continuous spectrum increases obviously with the rise of voltage, and the discharge signal of phase spectrum is mainly concentrated in the first three quadrants, which is symmetrical on both sides.

To sum up: under the current condition, the amplitude of partial discharge in the detection of high-frequency partial discharge is basically unchanged, the characteristics of partial discharge spectrum are basically the same, and the temperature rise at the defect is normal; under the voltage condition, the amplitude and spectrum characteristics of high-frequency partial discharge and ultrasonic partial discharge are obvious, and the amplitude of partial discharge signal increases significantly with the increase of test voltage, and the grounding current has no abnormal change.

5. Conclusions

(1) The prefabricated intermediate joint of high-voltage cable needs to peel off the cable body in the construction process, which is easy to leave a conductive tip on the interface between the prefabricated joint and the cable body. With long-term operation, it may lead to the breakdown of the outer sheath of the cable, and ultimately affect the service life and personal safety of the cable.
(2) Through the electric field simulation, it is found that the discharge occurs when the tip defect is between the stress cone silicone rubber and the main insulation of the main body.

(3) Both high frequency PD and ultrasonic PD can get obvious discharge signal for conducting tip defect detection. Among them, the high-frequency partial discharge detection method has the best anti-interference ability at the capacitor arm, the detection sensitivity at the direct grounding is in the middle, and the detection sensitivity at the protective grounding is the lowest. In the field application, the sensitivity, operation convenience and anti-interference ability should be considered, and the appropriate detection location should be selected.

(4) The on-line monitoring method of high frequency partial discharge has obvious characteristics in the first three quadrant symmetrical partial discharge spectrum of the direct grounding side; the defects that can be located by the body polarity identification method belong to the internal discharge of the joint.

(5) For tip defects, the amplitude of the high-frequency partial discharge keeps constant with the increase of the current rising time. Under voltage condition, the high-frequency partial discharge increases with the increase of test voltage, and it is easy to break down under high voltage; the ultrasonic partial discharge signal increases obviously.

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