Evaluation of insulation condition detection methods applied to DC XLPE cable

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Abstract. At present, with the construction and operation of new energy grid-connected and offshore wind power projects in China, DC XLPE cables have been widely used. Under the operating conditions, there are mainly two feasible technical means of DC cable insulation state detection, partial discharge (PD) and leakage current. However, it is still a blank in the world to apply it to the validity and condition of DC cable operation detection. Based on the semi-conductive layer residual defect model of XLPE cable, the characteristics of PD and leakage current under different voltage values and polarities are studied by setting up an experimental platform for detecting PD and leakage current of DC XLPE cable. The results show that both PD and leakage current can detect cable defects, among which PD is easier to detect cable defects under negative polar voltage and higher voltage. Leakage current characteristics change obviously under positive polar voltage. When applied voltage is lower than rated voltage, obvious changes can also be measured. In this paper, the feasibility of live detection of leakage current of DC cables under operating conditions is proposed, which is of great value to improve the detection capability of DC XLPE cables.

1. Introduction

Many DC cable lines have built in Shanghai, Zhejiang and Fujian, China. And it is expected that the first ±535kV DC cable and accessories will be used in the Zhangbei flexible DC transmission project in 2019. The above cable projects all use the XLPE insulated cables. With the development of the new energy grid and offshore wind power, the application of DC XLPE cables will become more and more extensive in the future [1-2]. At present, a lot of work in the basic research of DC cables has been done at home and abroad, including: nano material [3], cable accessory [4], space charge [5], operating temperature [6] and other factors can cause electric field distortion and insulation aging of DC cables. However, how to effectively detect and evaluate the operating state of the DC cable are still blank in the world [7-8]. Therefore, it is of great significance to carry out the research on DC cable state detection technology, which can verify the operating reliability and improve the online monitoring level of DC cables.

Currently, XLPE DC cable has a short running time. The failure mechanism and development rule of XLPE DC cable and XLPE AC cable are different. Compared with the AC cable system, the DC cable system lacks the phase information, thus the tanδ detection method is not suitable for the DC cable system. It is not advisable to simply transplant the AC cable state detection method to the DC
cable field. Partial discharge (PD) detection [9] and leakage current detection [10] are two technical means to evaluate the insulation condition of cables. In particular, PD detection has been unanimously recommended by the international power authorities such as IEC, IEEE and CIGRE as the best method for the insulation state evaluation and early fault diagnosis of high voltage XLPE cables [11-15]. The leakage current can reflect the overall moisture and deterioration state of the insulating medium. At the same time, by measuring the variation law of the leakage current of the cables under different voltage levels and voltage polarities, it can be judged whether there is a defect in the cables.

Therefore, this work proposes to evaluate the usage of AC cable test on DC cable test in order to overcome the lack of studies on DC cable operation condition. In this paper, a joint test platform for PD and leakage current detection of XLPE DC cable was built, and a semi-conductive layer residual defect model of the cable was fabricated. PD and leakage current tests were carried out under different voltage levels and voltage polarities. The cable PD characteristics, the cable leakage current variation characteristics and the correlation relationship between them were analyzed. The effective detection method of XLPE DC cable insulation state was explored.

2. Test model and test platform

2.1. Defect model

The structure and parameters of the cable defect model are shown in Table 1. In order to prevent the cable creepage discharge, the outer shield layer at both ends of the cable sample is stripped 0.2m. The section of the cable insulation layer is smoothed with sandpapers and the cable core is placed into a voltage equalizing ball. The end of the cable with the defect is inserted into a silicone rubber terminal. The copper shield of the cable is reliably grounded.

| Table 1. The cable defect model. |
|----------------------------------|
| Type                            | 8.5/15kV YJV-120mm² |
| Core diameter                   | 13.2mm               |
| Inner semi-conductive shield layer thickness | 1.0mm         |
| Insulation layer thickness      | 4.2mm               |
| Outer semi-conductive shield layer thickness | 1.0mm         |
| PE sheath thickness             | 1.5mm               |

In this paper, the residual defect of the semi-conductive layer is taken as the research model. The defect model is as follows: during the manufacture of the cable terminal joint, an outer semi-conductive layer with a width of 3mm and a length of 30mm is stripped on the main insulating surface. The residual defect of the simulated outer semi-conductive layer is shown in Figure 1.

![Figure 1. The residual defect of the outer semi-conductive layer.](image)

2.2. Test platform

DC cable PD and leakage current detection test wiring is shown in Figure 2. The test platform is mainly composed of a DC test transformer (DC: 5kVA/200kV), a resistive voltage divider \( \left( R_2/(R_1+R_2) = 1/10000 \right) \), a protective resistor \( R_3: 10k\Omega \), a DC PD detector \( E_1: \text{Haeftely DDX 9121b} \), a coupling capacitor \( C_k: 200kV/100pF \), a non-inductive detection impedance \( Z_m: 50\Omega \), a XLPEDC
cable (as shown in Table 1), a leakage current detector (E2: 6485 Picoammeters) and a digital storage oscilloscope (DSO: WavePro 7100XL).

![Diagram of test setup](image)

**Figure 2.** DC cable PD and leakage current detection test wiring.

![Installation diagram](image)

**Figure 3.** Cable defect model test site installation diagram.

### 2.3. Test procedure

The test platform is connected as shown in Figure 3. The PD quantity correction is performed by a DC PD signal generator, and the background noise of the test system is ensured below 0.5pC. Slowly increase the test voltage until PD is detected, and record the current voltage value, picoammeters output waveform, and PD signal. Then, the test is carried out by the voltage step-up method, and the leakage current data and PD data are recorded at each voltage level.

### 3. Test results analysis

The variation characteristics of the PD and leakage current under positive and negative voltages are studied by the repeated tests. The results of the repeated tests maintain a good consistency, and the results of one test are shown in Table 2 and Table 3.

**Table 2.** PD parameters and leakage current values of XLPE DC cable under negative voltage.

| Negative voltage(kV) | PD quantity(pC/pulse)/PD repetition rate(pulse/min) | Leakage current(nA) |
|----------------------|----------------------------------------------------|----------------------|
|                      | Normal cable Defective cable                        | Normal cable Defective cable |
| –2.2                 | / /                                                  | 0.1 14.6             |
| –4.8                 | / /                                                  | 7 14.7               |
| –7.6                 | / /                                                  | 11 15.0              |
| –13.3                | / /                                                  | 127 256              |
| –14.4                | / /                                                  | 159 278              |
| –16.0                | / /                                                  | 185 356              |
| –18.3                | / 40/1400                                            | 192 386              |
| –19.8                | / 40/1200                                            | 206 420              |
| –21.2                | / 52/650                                             | 209 440              |
| –24.2                | / 64/1160                                            | 227 460              |
| –25.2                | / 70/1080                                            | 238 480              |
Table 3. PD parameters and leakage current of XLPE DC cable under positive voltage.

| Positive voltage (kV) | PD quantity (pC/pulse) | PD repetition rate (pulse/min) | Leakage current (nA) |
|---------------------|-----------------------|-------------------------------|---------------------|
|                     | Normal cable | Defective cable | Normal cable | Defective cable |
| +3.1                | /              | /                             | 29                  | 171                |
| +6.2                | /              | /                             | 134                 | 356                |
| +10.1               | /              | /                             | 174                 | 507                |
| +12.0               | /              | /                             | 204                 | 602                |
| +14.4               | /              | /                             | 280                 | 664                |
| +17.4               | /              | /                             | 463                 | 716                |
| +19.7               | /              | /                             | 489                 | 762                |
| +21.3               | /              | /                             | 528                 | 735                |
| +24.0               | /              | /                             | 654                 | 890                |
| +26.7               | /              | 179/510                       | 763                 | 902                |

The recording data of the DC PD detector under the applied voltage of –25.2kV is shown in Figure 4.

Figure 4. The recording data of the DC PD detector under the applied voltage of –25.2kV.

The recording data of the DC PD detector under the applied voltage of +26.7kV is shown in Figure 5.

Figure 5. The recording data of the DC PD detector under the applied voltage of +26.7kV.
By analyzing the test data in Table 2 and Table 3, the following main conclusions can be drawn:

(1) With the increase of the test voltage, the PD parameters (discharge quantity and discharge repetition rate) and leakage current values increase to different degrees, but there is no strong correlation between PD and leakage current. The picometers can still detect stable leakage current when there is no discharge, and the leakage current value may be large when the discharge quantity is small. Because PD reflects the insulation state of the defect in the cable insulation layer. Applying the DC voltage to the cable sample, the charge is continuously accumulated in the defect area in the cable insulation layer. When the voltage across the defect exceeds its initial breakdown voltage, the PD occurs. However, the leakage current characterizes the overall insulation state of the cable insulation layer, which has a good linear relationship with the DC resistance of the insulation material. Therefore, the correlation between these two detection methods is not strong from the detection mechanism.

(2) The DC PD characteristic parameters, including the discharge quantity and the discharge repetition rate, can reflect the defect state of the XLPE cable to some extent. Compared with applying positive voltage across the cable, applying negative voltage across the cable is more likely to cause PD, and the PD repetition rates is larger under negative voltage. When the high voltage (HV) electrode is negative polarity, the electron collapse develops outward from the surface of HV electrode. Since the movement speed of electron is faster than that of positive ion, a large number of positive ions remain near the HV electrode, and these positive ions will strengthen the electric field near the HV electrode. Which causes the self-sustaining discharge to be easily formed. Therefore, the corona starting voltage is low, and PD is likely to occur\cite{12-13}.

(3) Whether the cable sample is normal cable or defective cable, their leakage current values vary significantly under different voltage levels. When the absolute value of the applied negative voltage is higher than 13.3kV, the leakage current value increases sharply, and the leakage current value is less than 500nA when the absolute value of the applied negative voltage is lower than 25kV. When the positive voltage is applied across the cable, the leakage current value increases with the voltage. The leakage current value increases sharply when the positive voltage is higher than 6.2kV, and which is around 902nA when the applied voltage is +26.7kV.

4. Conclusions

In the paper, a joint test platform for the PD and leakage current detection of XLPE DC cable was built, and the detection tests were carried out by a residual defect model of the cable semi-conductive layer under different voltage levels and voltage polarities. The effective detection method of XLPE DC cable insulation state was explored. The general conclusions are as follows:

(1) The PD detection and leakage current detection used in AC cable tests also can be performed on DC cable tests.

(2) There is no strong correlation between the PD and leakage current, and the stable leakage current also can be detected even there is no discharge.

(3) The insulation defect of XLPE DC cable is easily detected by the PD detection method under negative voltage, and the insulation state of the cable can be evaluated by PD quantity and PD repetition rate.

(4) The leakage current value changes significantly under positive voltage, and the obvious changes also can be measured even when the applied voltage is lower than the rated voltage, which is beneficial to the running state detection and evaluation of the XLPE DC cable.

In the next step, we will focus on the study of the PD and leakage current characteristics based on the cable samples of different insulation defect types, different defect severity degrees, and different aging degrees.

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