Partial discharge detection and type identification of typical defects of XLPE cables under AC voltage

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\textbf{Abstract}—According to the discharge characteristics of the typical defects of power cables, four common physical models of cable simulation defects are designed and produced under laboratory conditions. The high-frequency current method is used to measure the discharge signals of the four common cable simulation defect models, the data is collected and stored, a two-dimensional discharge map is drawn, and the support vector machine method (SVM) is used for classification. The results show that: the signal distribution range of levitation discharge is the widest, and the signal distribution is long; the tip discharge only generates the discharge signal in the negative half of the cycle; the negative half of the creeping discharge is more dense than the positive half of the cycle; the number of discharges in the positive and negative half of the internal air gap discharge is roughly the same; discharge of different types of defects is obviously different. Extracting statistical features from its two-dimensional spectrogram for identification, the identification accuracy rate is above 90%, and different types of defects can be effectively identified.

1. Introduction

With the rapid development of my country's power grid and the continuous advancement of science and technology, the development prospects of my country's power industry are prosperous, which is followed by a surge in electricity consumption and lengthening of transmission lines\cite{1}. Cables have the characteristics of corrosion resistance, environmental impact friendliness, and strong safety, and underground cables are widely used\cite{2}. Cross-linked polyethylene (XLPE) cables are widely used in distribution networks, especially in high-voltage and ultra-high-voltage lines, due to their excellent insulation properties, good heat resistance, strong mechanical properties and chemical resistance\cite{3}.

It is generally believed that in a normal environment, the average life of power cables is about 20 to 30 years\cite{4}. However, cross-linked polyethylene power cables are affected by factors such as fine processing, specific use environment, mechanical damage, and overload operation. The insulation of the cable is damaged, and even the insulation is broken down from time to time. The insulation defect of the cable middle joint and terminal head accessories is the main reason for the cable accident\cite{5}. In recent years, relevant domestic and foreign studies have shown that the insulation defects of cables will cause irreversible damage to their insulation properties. After analysis, it can be seen that partial discharges, electrical tree branches and water tree branches are the most important causes of insulation defects, and their occurrence frequency is relatively high\cite{6}. Because the discharge signal caused by cable insulation damage is very weak, the probability of detecting partial discharge signals in traditional preventive experiments is relatively low, so traditional test methods can no longer meet the requirements of cable safe operation\cite{7}. Measuring the change of partial discharge is one of the methods...
to analyze the degree of damage to the cable insulation. Therefore, international power authorities such as IEC, IEEE, and CIGRE unanimously recommend partial discharge experiments as the best method for evaluating the insulation condition of XLPE power cables [8].

This paper takes the typical defects of XLPE power cable accessories as the research object. Under laboratory conditions, four kinds of simulated defect experimental models of internal air gap, tip, creeping and suspension discharge are designed and manufactured [9]; based on high-frequency current

2. Typical defect model and measurement platform

2.1. Typical defect model types and production

The types of cable accessory defects are prominently manifested as defects caused by partial discharge caused by discharge at different interfaces, insulation damage of accessory materials, and floating electrodes. The main defects of the XLPE power cable body are caused by the air gap inside the insulator, the gap between the insulator and the semiconductor, and the sharp corners formed by the semiconductor protruding into the insulating layer. Table 1 lists the causes and relationships of these defects and corresponds to them one by one.

| Type of defect               | Type of discharge      | Experimental defect model |
|-----------------------------|------------------------|---------------------------|
| Rubber and cable interface  | Air gap discharge       | Internal discharge         |
| Internal air gap            | Air gap discharge       | Internal discharge         |
| Surface air gap             | Air gap discharge       | Internal discharge         |
| Tip                         | Corona discharge        | Tip discharge              |
| Rubber and epoxy interface  | Creeping discharge      | Creeping discharge         |
| Suspended metal particles   | Suspended electrode discharge | Suspended discharge |

![Internal air gap discharge model](image.png) ![Tip discharge model](image.png)

(a) Internal air gap discharge model (b) Tip discharge model

![Creeping discharge model](image.png) ![Suspended discharge model](image.png)

(c) Creeping discharge model (d) Suspended discharge model

Fig.1 Construction and geometrical dimensions of specimens

2.2. Experiment platform

Partial discharge experiment platform is shown in Figure 2. The instruments used are: autotransformer, high voltage transformer, R protection resistor, C1 and C2 in parallel, the partial discharge is obtained through the voltage waveform of C2 Signal phase, Cx typical defect experimental model, D is a high-frequency current sensor, the frequency range is between 300K-30MHz, FPGA acquisition card Communicate and transmit data, store the collected partial discharge signals and complete subsequent data processing.
3. Experiment results and analysis

3.1. Internal air gap discharge
The internal air gap discharge is caused by damage to the insulation inside the joint or tiny bubbles inside the insulation.

![Internal air gap PRPD pattern](image)

According to the figure, the internal air gap partial discharge signal has roughly the same discharge intensity and number of discharges in the positive half cycle and negative half cycle, and the positive and negative half cycles are symmetrically distributed in phase.

3.2. Tip discharge
The tip discharge is a partial discharge phenomenon caused by the small sharp corners inside the connector.

![Tip discharge PRPD pattern](image)

When the spike discharges, the discharge signal does not appear in the positive half of the cycle, but only appears in the negative half of the cycle.
3.3. Creeping discharge
Creeping discharge is a discharge phenomenon between interfaces, which occurs at the interface between rubber and epoxy resin inside the joint.

Fig. 5 Creeping discharge PRPD pattern

According to the figure, because of the polarity effect of the partial discharge signal of creeping discharge, the discharge intensity of the positive half cycle is smaller than that of the negative half cycle.

3.4. Suspended discharge
Suspended discharge is caused by conductive metal particles in the cable conductor layer or accessories.

Fig. 6 Suspended discharge PRPD pattern

According to the figure, the discharge density of the positive half cycle of the suspension discharge is smaller than that of the negative half cycle, and the signal distribution phase is symmetrical.

4. Feature selection and defect type recognition

4.1. Feature selection
Partial discharge is a direct manifestation of the failure of electrical equipment. Partial discharge statistical parameters are obtained by data statistics on a large amount of data and can improve the accuracy of recognition. This article introduces the following feature quantities.

1) Skewness
It is used to describe the degree of skew between the distribution of a certain shape and the normal distribution.

\[
S_k = \sum_{i=1}^{W} (x_i - \mu)^3 \cdot p_i \Delta x / \sigma^3
\]

Where \( W \) is the number of phase windows in a half-period; \( x_i \) is the phase of the \( i \)-th phase window; \( \Delta x \) is the width of the phase window; \( p_i \), \( \mu \) and \( \sigma \) regard the spectrogram as a probability
density distribution diagram, and taking $x_i$ as a random variable is the probability, mean and standard deviation of the event in the phase window $i$.

2) Steepness
Used to describe the convexity of a shape to the shape of a normal distribution.

$$K_u = \left[ \sum_{i=1}^{n} (x_i - \mu)^4 p_i \Delta x / \sigma^4 \right] - 3$$  \hspace{1cm} (2)

3) Initial discharge phase
Phase of the first discharge in the positive and negative half cycle.

$$\Phi = \frac{\phi}{360}$$  \hspace{1cm} (3)

4) Correlation coefficient
The degree of similarity between the positive and negative half cycles of the plane of the discharge spectrum.

$$C_c = \frac{\sum_{i=1}^{n} q_i q_i' - \left( \sum_{i=1}^{n} q_i \right)^2 / W}{\left( \sum_{i=1}^{n} (q_i)^2 \right)^{1/2} \left( \sum_{i=1}^{n} (q_i')^2 \right)^{1/2} / W}$$  \hspace{1cm} (4)

4.2. SVM defect type recognition
Support Vector Machines (SVM) is a machine learning algorithm proposed by Vapnik et al. based on statistical learning theory.[10] SVM aims to find an optimal hyperplane to make the model's data classification error as small as possible.

The original problem uses the kernel function $K$ of the transformation $\Phi$. By introducing Lagrangian multipliers and optimality conditions, the above original problem can be transformed into a dual problem:

$$\max \sum_{i=1}^{n} a_i - \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} a_i a_j y_i y_j \left( x_i \cdot x_j \right)$$  \hspace{1cm} (5)

s.t. $\sum_{i=1}^{n} a_i y_i = 0$  \hspace{1cm} (6)

$C \geq a_i \geq 0, \hspace{0.2cm} i = 1, 2, \cdots, n$  \hspace{1cm} (7)

Where $a_i$ is the Lagrange multiplier. Find the optimal solution as $\alpha^* = (\alpha_1^*, \cdots, \alpha_n^*)^T$, then we can get $\omega^*, b^*$:

$$\omega^* = \sum_{i=1}^{n} \alpha_i^* y_i x_i$$  \hspace{1cm} (8)

$$b^* = y_j - \sum_{i=1}^{n} y_i \alpha_i^* \left( x_i, x_j \right)$$  \hspace{1cm} (9)

This results in the nonlinear classification decision function:
This paper adopts RBF kernel function for multi-class recognition. It can be seen in Table 3 that the accuracy of identifying different types of defects is above 90%, where A, B, C, and D are internal air gap discharge, tip discharge, creeping discharge and suspended discharge respectively.

Table 2. Accuracy of different defect recognition

| Type of defect | A  | B   | C  | D  |
|----------------|----|-----|----|----|
| Accuracy/%     | 90 | 96.67 | 95.5 | 93.33 |

5. Conclusion

Based on the results and discussions presented above, the conclusions are obtained as below:

1. The discharge characteristics of different defect types show the phase distribution and discharge density.
2. After extracting its statistical feature value as the feature to be identified, the differentiation of different types of discharge data is more obvious.
3. Training and testing in SVM show that SVM recognition accuracy is high and can effectively identify different types of defects.

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