Graphical Characteristics Analysis of PD Signals Phase Distributions of XLPE Cables

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Abstract. Aiming at analysing the graphical characteristics of PD signals of XLPE cables, this paper introduced the methods of constructing four graphs of phase distribution: \( \phi \)-Q-N distribution map, maximum discharge quantity phase distribution \( H_{Q_{\text{max}}}(\phi) \), the mean of discharge quantity phase distribution \( H_{Q_{\text{mean}}}(\phi) \) and the discharge frequency phase distribution \( H_{S}(\phi) \). An experimental platform in laboratory was established to acquiring PD signals of four typical insulation defects of XLPE cables. The results show that different insulation defects leads to the PD signals which have distinct graphical characteristics. Corona discharge and surface discharge are asymmetrical in phase distribution while suspended electrode discharge and internal air gap discharge are symmetrical. The amplitudes of corona discharge are concentrated while the amplitudes of surface discharge vary greatly. The amplitudes of internal air gap discharge in two half-cycle are almost the same level while the amplitudes of suspended electrode discharge in positive half-cycle exceed that in negative half-cycle. According to these characteristics, it can be inferred which type of discharge the PD signals belongs to.

1. Introduction

The partial discharge (PD) is a phenomenon that reflects the insulation of power equipment. To some extent, if the PD quantity of electric power cable varies, it is possible that there exist some insulation defects threatening the operation safety [1]. The variation tendency of PD is a better indict than PD quantity which reflects the insulation aging degree of electric power cable [2]. At present, the PD is mainly analysed by means of evaluating the variation tendency, including the numerical and graphical analysis [3-4]. The numerical analysis usually studies the statistical parameters such as skewness, steepness, number of peaks, discharge factor, asymmetry, cross-correlation factor, etc [5]. The graphical analysis usually studies the pulse waveform in time or frequency domain and the PD signals phase distribution [6].

Based on the above articles, this paper selected four phase distributions including \( \phi \)-Q-N distribution map, maximum discharge quantity phase distribution \( H_{Q_{\text{max}}}(\phi) \), the mean of discharge quantity phase distribution \( H_{Q_{\text{mean}}}(\phi) \) and the discharge frequency phase distribution \( H_{S}(\phi) \). In this paper, different defect models of XLPE cables were designed to generate PD signals in laboratory, and the above selected PD signals phase distributions were graphically analysed to study the characteristics of the XLPE cables PD signals.
2. PD Signals Phase Distribution

The PD signals phase distributions can be divided into two types: three-dimensional pattern and bidimensional pattern. The three-dimensional pattern is the distribution of discharge frequency (N) with respect to discharge quantity (Q) and phase (φ), drawn by φ-Q-N matrix. Bidimensional pattern can be extracted from the φ-Q-N matrix.

2.1. φ-Q-N pattern

The φ-Q-N matrix can be obtained by counting the pulse numbers of each discharge quantity interval and phase interval from the PD phase resolved pulse sequence (PRPS). PRPS is the PD pulses sampled in 50 consecutive power frequency periods, and the phase in every period is uniformly divided into 360 portions.

2.2. $H_{Q_{\text{max}}}(\phi)$

The construction of maximum discharge quantity phase distribution $H_{Q_{\text{max}}}(\phi)$ needs calculate the discharge quantity $q_s$ at first. $q_s$ is equivalent to the cumulation of PD quantity in a phase interval:

$$q_s = \sum q_i$$  \hspace{1cm} (1)

where, $q_i$ represents the quantity of a single pulse marked with i in a phase interval. After obtaining $q_s$, $H_{Q_{\text{max}}}(\phi)$ can be plotted as the distribution of the maximum of $q_s$, noted as $Q_{\text{max}}$, with phase.

2.3. $H_{Q_{\text{mean}}}(\phi)$

Similar to the method in section 2.2, the mean of discharge quantity phase distribution $H_{Q_{\text{mean}}}(\phi)$ firstly needs obtain $q_s$, then calculate the average of $q_s$, noting as $Q_{\text{mean}}$, and finally reflecte the distribution of $Q_{\text{mean}}$ with phase.

2.4. $Q_N(\phi)$

The construction of the discharge frequency phase distribution $H_N(\phi)$ needs calculate the discharge frequency $N$ at first. $N$ is equivalent to the cumulation of PD pulse numbers in a phase interval:

$$N = \sum i$$  \hspace{1cm} (2)

where, i represents the $i^{th}$ PD pulse in a phase interval. After obtaining $N$, $H_N(\phi)$ can be plotted as the distribution of $N$ with phase.

3. The design of experiment

3.1. Detection system

This paper adopted YJV-8.7/15 3×35mm² 10kV three-phase XLPE cable with the length of 30 meters as the experiment object. Select phase-A cable and make the oil terminal at both ends to execute a single phase test. A PD detection system was established in laboratory whose structure is shown in Figure 1.

![Diagram of PD detection system for XLPE cable](image)
As Figure 1 shows, the detection system is composed of two main parts: the non-PD high voltage power supply and PD detecting device. The non-PD high voltage power supply consists of 380V/50Hz power supply, voltage regulator, auto-transformer, and step-up transformer. The power supply capacity is 50 kVA. The output voltage is adjustable with the range of 0~150 kV. The PD detecting device consists of current-limiting resistance, coupling capacitor, measuring impedance and detecting apparatus. The background noise of the whole system is less than 2 pc.

3.2. Defect models
In order to study the PD characteristics of XLPE cables under different insulation defects, this paper designed four types of defect models according to the production mechanism:

3.2.1. Corona discharge. The metal protrusions on the surface of the high-voltage conductor will lead to the partial electric field enhancement near the protrusions, thus causing a flow-injection corona discharge similar to the needle plate electrode. The designed model is a steel tip with the curvature radius of 50um fixed at the high-pressure end of the oil terminal, shown as Figure 2.

3.2.2. Suspended electrode discharge. The suspended electrode discharge is mainly due to the failure of cleaning the cable accessories during the process of making the cable terminal or intermediate joint, and the introduction of metal impurities between the winding insulation of the accessories and the main insulation of the cable. The defect model is designed by wrapping the copper wire as cylinder. The diameter of the copper wire and the length of cylinder are respectively 4mm and 13mm. The copper cylinder is fixed around the semiconductor outside the cable conductor, shown as Figure 3.

3.2.3. Internal air gap discharge. The cable air gap discharge is caused by the air bubble inside the main insulation or the insulation damage of external shield. The real internal air gap is difficult to be made by hand, so this paper adopted the tip damage at external shielding and main insulation as this defect model. Strip the outer sheath and fill of the cable, spin the steel needle inward from the copper shield outward insulation, and the tip penetrates the outer semiconductor layer into the insulation layer. The curvature radius of steel needle front end is 0.5 mm, the diameter of back end is 2 mm, and the penetration depth is 4 mm. The model is shown as Figure 4.

3.2.4. Surface discharge. The surface discharge is mainly caused by the discharge between the surface and the crack of the cable insulation, mainly due to the moisture of water bubbles and gas impurities between the insulation and the conductor. The defect model is designed by wrapping the metal foil around the cable conductor, shown as Figure 5.
3.2.4. Surface discharge. The surface discharge mainly occurs between the main insulation in the cable accessories and the winding insulation interface of the accessories. In most of situations, it is caused by improper installation of cable accessories or unreasonable design of cable accessories structure. This paper inserted a needle into the junction of the outer semiconductor layer and the insulation layer, with the depth of 1 mm. Besides, a copper wire was adopted. One end was twined around the high-voltage conductor, while another end was stretched toward the tip of the needle along the XLPE insulation. The shortest distance between copper wire and the needle tip is about 2mm. This defect model is shown as Figure 5.

4. Result analysis

4.1. Corona discharge
When the exerted voltage rised to 2.5kV, the PD took place with a capacity of 21pC. The phase distributions were plotted as shown as Figure 6.

![Figure 6](image)

**Figure 6.** Phase distribution of surface discharge

As Figure 6 exhibit, the PD pulses of corona discharge occur in negative half-cycle, mainly near 90° of power frequency, so this defect leads to the discharge which is very asymmetric in positive and negative half-cycle. The discharge amplitude and phase distribution are very concentrated, and the amplitude is the smallest among four types of defects.

4.2. Suspended electrode discharge
When the exerted voltage rised to 20kV, the PD took place with a capacity of 130pC. The phase distributions were plotted as shown as Figure 7.
Figure 7. Phase distribution of suspended electrode discharge

The phases of the suspension electrode discharge are distributed within 0–90° in the positive and negative half-cycle of the power frequency, however, the amplitude in positive half-cycle is larger than the amplitude in negative half-cycle, so this defect leads to the discharge which is kind of symmetric in phase distribution. The discharge amplitude is larger and less concentrated than that of corona discharge.

4.3. Internal air gap discharge

When the exerted voltage rised to 3kV, the PD took place with a capacity of 117pC. The phase distributions were plotted as shown as Figure 8.
Figure 8. Phase distribution of internal air gap discharge

The phase distribution of internal air gap discharge is near 90° in both positive and negative half-cycle of power frequency, and the amplitudes in two cycles have no great difference, so this defect leads to a very symmetric discharge. The overall amplitude is between the amplitude of corona discharge and suspended electrode discharge.

4.4. Surface discharge

When the exerted voltage rose to 12kV, the PD took place with a capacity of 1600pC. The phase distributions were plotted as shown as Figure 9.

Figure 9. Phase distribution of surface discharge
The PD pulses of surface discharge corona occur both in positive and negative half-cycle of power frequency. However, there exist much more pulses in negative half-cycle than positive half-cycle. As a result, this defect leads to the discharge which is less symmetric in positive and negative half-cycle. As for the amplitude, this type of discharge is composed of a small number of large pulses and dense small pulses, and the large pulses concentrated in negative half-cycle. The overall amplitude is the largest among the four types of defects.

5. Conclusion
This paper acquired PD signals of four typical insulation defects of XLPE cables by the detection system in laboratory. According the methods introduced in the second section, four kinds of phase distributions: \( \phi-Q-N \), \( H_{Q\max}(\phi) \), \( H_{Q\text{mean}}(\phi) \) and \( H_{N}(\phi) \) were constructed in order to be graphically analysed. The results show that corona discharge and surface discharge are asymmetrical in phase distribution while suspended electrode discharge and internal air gap discharge are symmetrical. As for an asymmetrical graph, if the amplitudes are concentrated, it is more possible to be corona discharge; if the amplitudes vary greatly, it is more possible to surface discharge. As for a symmetrical graph, if the amplitudes in two half-cycle are almost the same level, it is more possible to be internal air gap discharge; if the amplitudes in positive half-cycle exceed amplitudes in negative half-cycle, it is more possible to be suspended electrode discharge.

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