Partial discharge identification of DC cross-linked polyethylene cables based on GA-BP algorithm

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Abstract. In this paper, XLPE DC cables were used to construct three kinds of defects of inner semiconducting layer breakage, internal air gap defect, and insulating surface scratching defect. And their DC PD characteristics were tested under different voltage amplitudes and polarities. The study found that these three defects exhibit different DC partial discharge characteristics and change with voltage amplitude and polarity. Subsequently, two methods were used to identify the type of defect. The recognition rate of the traditional defect type identification method reached 97.1%, and the recognition rate of the optimized defect type identification method based on GA-BP was increased to 98.9%, which solved the problem that the traditional method was affected by the voltage level and polarity, and improved the recognition rate.

1. Introduction
Cross-linked polyethylene (XLPE) cable has become the mainstream of high-voltage power cables for flexible DC transmission due to its superior electrical performance, excellent heat resistance and mechanical properties, easy installation and environmental protection [1]. Up to now, DC XLPE cables have been accepted by many countries around the world [2-4]. Moreover, with the development of the power industry, high-voltage DC XLPE cables will be more and more widely used in the field of renewable energy grid connection, island power supply, and grid interconnection.

However, various forms of insulation defects of XLPE cables are inevitably produced during manufacturing, installation and operation, such as internal air gaps, scratches on insulating surfaces, and damage to semiconducting layers [5]. At these defects, the electric field is severely distorted, and the insulation is weak, which is prone to partial discharge (PD) [6]. During the long-term operation of the DC XLPE cable, PD will cause deterioration of the surrounding insulation material [7], and even lead to insulation failure, which seriously threatens the safe operation of the flexible DC system. Therefore, in the early stage of large-scale process of DC XLPE cable in power system, it is essential to propose related researches on DC PD mechanism, detection technology [8] and discharge type identification method [9].
At present, some international scholars have begun to pay attention to applying PD for the identification of insulation defect types in DC systems. Wu Guangning et al. from Southwest Jiao Tong University in China proposed a pulse current method to study the discharge time domain waveforms of the air gap discharge model, surface discharge model and corona discharge model under DC voltage. Then they obtained three discharges after Fourier transform. In the frequency domain waveform, there were significant differences between the time domain and the frequency domain waveform of different discharge types, which could distinguish the discharge type as the basis [10]. Sheng Gewei et al. at Shanghai Jiao Tong University in China applied numerical simulation methods to analyze the electric field distribution in the regular XLPE cable model and four typical insulation defects model (corona defect, cavity defect, scratch defect and creepage defect). Furthermore, they established an electrothermal coupling analysis model. Simulation results showed that the four defects caused different electric field distortions. Among them, the deformation of corona defect was the most serious, and the deformation of creepage defect was the slightest [11]. And a new method for feature extraction of partial discharge (PD) image of DC XLPE cable based on non-subsampled contourlet transform (NSCT) was proposed. This method could effectively classify the types of defects in the insulation, and the recognition rate was improved by 16.80%, compared with the traditional wavelet method [12]. Fromm U et al. of the Delft University of Technology in the Netherlands undercharged the defects in gas, liquid and solid insulating media under DC conditions and collected PD data [13]. Then the three-dimensional maps were described and analyzed including the discharge amount, the number of discharges and the time intervals of discharges for the PD phenomenon. It demonstrated that there were differences in PD characteristics under different defect types [14]. Montanari GC et al. at the University of Bologna in Italy studied the insulation properties and PD phenomena of XLPE cables and their insulating materials under DC voltage and discussed the electrical performance and PD characteristics of XLPE cables under different material compositions [15], temperature [16] and pressurization time [17]. In terms of the TF mapping algorithm to extract the PD signal, the statistical parameters of PD were obtained by the amplitude density function and the time interval density function [18], and the defect type was identified by the fuzzy clustering algorithm [19].

The above studies showed that for different insulation defects, the DC PD would be of different statistical characteristics [20]. However, due to the inherent random peculiarity of PD, it would adversely affect the identification of defect type [21], especially when the external conditions for acquiring PD characteristics (such as voltage amplitude, polarity, etc.) changed, it might interfere with the final identification of defect types, and related research was still lacking.

Therefore, PD characteristics induced by typical insulation defects were investigated under DC voltage with different levels and polarities in this paper. Based on traditional identification method, a new identification method can eliminate the influence of test conditions was obtained. As a result, a better defect type recognition effect was obtained.

2. Test system and test methods

2.1. Test system construction

The test system is shown in Figure 1. It mainly consists of two parts: the rectifier circuit and the PD measurement circuit. Among them, the AC voltage generated by the power frequency test transformer (maximum output voltage 50kV, capacity 100kVA) is half-wave rectified by the high voltage silicon reactor Ds and the filter capacitor Cm, and a DC high voltage (with a ripple coefficient of 0.98%) is applied to the sample. AC and DC high voltage is measured by capacitor divider and resistor divide, respectively. R1 and R2 are protection resistors, which can limit the breakdown of the sample and the current through the high voltage silicon reactor and transformer when the power supply is suddenly charged to the capacitor Cm, to avoid the damage to high voltage silicon reactors and transformers [22]. Once PD is generated, the pulse current method is used to obtain its discharge intensity. Cm is the coupling capacitor, Zm is the measured impedance, and the voltage pulse crosses Zm during discharge is recorded by the oscilloscope, and the apparent discharge amount can be obtained after calibration.
The oscilloscope used was the Tektronix 5100 with a bandwidth of 2 GHz, a maximum sampling rate of 20 GS/s, and a memory depth of 10 MS. The sampling rate was set to 50 MS/s during the test. Since the oscilloscope is capable of triggering peak and locating the discharge pulse in time series, continuously sampling of the discharge signal can be realized in a long time. The measurement system has a maximum resolution of 1.0 pC and an ambient temperature of 293±5K.

Figure 1. Partial discharge test system under DC voltage.

2.2. Defect model design
The test chose a copper core XLPE insulated non-armored PVC sheathed flame-retardant power cable with a nominal cross-section of 150 mm², an inner shield thickness of 1.2 mm, an XLPE insulation thickness of 10.5 mm, and an outer shield thickness of 1.2 mm. Before the insulation defects were processed, the outer shielding layer at both ends of the cable was stripped, and the cut surface of the insulating layer was smoothed and put into the pressure-equalizing ball. Then, a DC high voltage was applied to any end of the cable, and the cable sheath was grounded through the wrapped copper skin. If no PD was generated within the test voltage range, an insulation defect could be formed later, which ensured the unity of the power supply.

(a) inner semiconducting layer breakage; (b) internal air gap defect; (c) insulating surface scratching defect.

Figure 2. Sketch maps of insulation defect models of cable: (a) inner semiconducting layer breakage; (b) internal air gap defect; (c) insulating surface scratching defect.

The three typical defects are: 1) inner semiconducting layer breakage. Because it is necessary to restore the inner semi-conductive layer of the conductor portion of the crimping tube when making the cable joint, and the inner semi-conductive layer of the cable portion cannot be connected when the reserved length is insufficient. The semiconducting layer in the connector on the tube is connected, destroying the continuity of the inner semiconducting layer, and this insulating defect occurs, and its size is about several hundred micrometres to several millimetres [23]. Circular damage with a diameter of 1 mm is done on the layer material; 2) internal air gap defect, which is mostly due to the uneven gas foaming reaction of the XLPE insulation material during the extrusion process, and concentrated gas by-products. Further, an internal air gap of the insulating material is formed, and the diameter of such defects is mostly concentrated on several micrometres to several hundred micrometres [24]. In the test, an air gap of 0.3 mm in diameter is formed at a distance of 6 mm from the surface of the core; 3) insulating surface scratching defect, it is necessary to peel off the outer semi-conductive layer of the insulating layer when making the cable joint. Since the outer semi-conductive layer is tightly combined with the cross-linked polyethylene, the insulating surface is easily scratched during peeling. It should be mentioned that the defective measurement typically a few millimeters to a few centimeters is in the range form [25], and the test processed 3cm, 1mm deep scratches in the surface of the insulating layer of a length of the sample. A schematic diagram of the structure of three typical defects is shown in Figure 2.
2.3. Test procedure
When the applied voltage was higher than 40.0 kV, PD was generated, and thus the highest test voltage was determined to be 40.0 kV. The partial discharge inception voltage (PDIV) of the samples with different insulation defects was then tested as shown in Table 1. Among them, the PDIV of the insulation surface scratch defect at the positive polarity voltage was higher than 40.0 kV, so it is pointless to do the partial discharge experiment of the insulation surface scratch defect under the positive polarity voltage. According to PDIV, the test voltage of each sample was set as shown in Table 2.

| Table 1. PDIV of different defects. |
|-------------------------------------|
| Defect type                         | inner semi-conducting layer breakage | internal air gap defect | insulating surface scratching defect |
| Voltage polarity                   | +                                   | -                       | +                                     |
| PDIV (kV)                           | 16.7                                | 18.3                    | 16.9                                  |
|                                     |                                     |                         | 15.7                                  |
|                                     |                                     |                         | —                                     |
|                                     |                                     |                         | 21.3                                  |

| Table 2. Test voltage for insulation defects. |
|-----------------------------------------------|
| Defect type                                 | Voltage polarity (kV)                 |
| Inner semiconducting layer breakage          | ±20.0, ±22.0, ±24.0, ±26.0, ±28.0     |
| Insulated internal air gap                  | ±17.5, ±20.0, ±22.5, ±25.0, ±27.0     |
| Insulation surface scratch                  | -22.0, -23.5, -25.0, -26.5, -28.0     |

During the PD test, the voltage was gradually increased to the set voltage, and 3000 PD data were continuously acquired. In order to balance the repeatability of the test results, three PD tests were performed on each sample. It should be noted that only typical test results were listed in this paper.

**Figure 3.** H (n, q, Δt) maps of inner semiconducting layer breakage defect under different negative voltages: (a) -20.0kV, (b) -22.0kV, (c) -24.0kV, (d) -26.0kV, (e) -28.0kV.
3. Test results

3.1. Discharge characteristics under different voltage amplitudes

Unlike the AC voltage, the PD signal has no phase information under DC, so the DC PD cannot be analysed using the PRPD spectrum commonly used in AC. Under the DC voltage, the $H(n, q, \Delta t)$ map can be constructed using the apparent discharge amount $q$, the discharge time interval $\Delta t$, and the number of discharges $n$ [26].

The $H(n, q, \Delta t)$ maps of the inner semiconducting layer breakage defect at the negative polarity were shown in Figure 3. A significant main peak could be observed in the range of -20.0kV~24.0kV, and after the voltage was boosted to -26.0kV and -28.0kV voltage levels, the main peak of the partial discharge $H(n, q, \Delta t)$ spectrum was no longer obvious, and the spectral dispersion was gradually enhanced. The corresponding discharge repetition rates of the internal semiconducting layer damage defects at the five test voltages was 11 times/s, 57 times/s, 104 times/s, 118 times/s, 224 times/s; The average discharge amounts were 301 pC, 401 pC, 480 pC, 640 pC, and 808 pC.

The $H(n, q, \Delta t)$ maps of the internal air gap defect of the negative polarity insulation were shown in Figure 4. Similar to the defect of inner semiconducting layer breakage, the $H(n, q, \Delta t)$ maps of the internal air gap defect of the insulation also exhibited a single main peak. As the amplitude of the test voltage increased, the discharge pattern gradually shifted toward a larger discharge amount and a shorter discharge time interval, and the discharge peak tended to concentrate. The corresponding discharge repetition rates of the internal air gap defects of the insulation at the three test voltages was 13 times/s, 21 times/s, 34 times/s, 63 times/s, 84 times/s, corresponding to the five test voltages. The average discharge amount was 244 pC, 326 pC, 375 pC, 417 pC, and 433 pC.

The $H(n, q, \Delta t)$ maps insulation surface scratch defect under negative polarity were shown in Figure 5. At -22.0kV and -23.5kV, the discharge amount of defects was concentrated in the range of 10pC~20pC, and the discharge amount $q$ at different $\Delta t$ changed little; when the voltage rose to -25.0kV and -26.5kV, the discharge time interval distribution tended to be concentrated, and the
discharge peaks were located at 8.0ms and 6.0ms respectively. The $\Delta t$ corresponding to different q did not change much; when the voltage continued to rise to -28.0kV, the discharge peaks became more dispersed, and the discharge amount was distributed in the range of 139pC to 2000pC, and was distributed in the range of 0.3ms to 1.5ms. The corresponding discharge repetition rates of the insulating surface scratch defects at the five test voltages was 38 times/s, 568 times/s, 1036 times/s, 1285 times/s, and 1429 times/s, corresponding to the five test voltages. The discharge capacity was 85pC, 558pC, 1035pC, 1295pC, 1428pC.

3.2. Discharge characteristics under different voltage polarities

The change in voltage polarity had a certain effect on the PD characteristics. Figures 3 and 4 depicted the PD characteristics of the inner semi-conducting layer breakage and internal air gap defect under the negative polarity. For comparison, Figures 6 and 7 list the $H(n, q, \Delta t)$ maps of these two defects under positive polarity conditions. Differing from the negative polarity condition, the $H(n, q, \Delta t)$ maps of the damage of the inner semiconducting layer under the positive polarity did not change much at different q, and in 20.0kV, 22.0kV, 24.0kV, a significant main peak of discharge can be observed, and the $\Delta t$ value at different q did not change a lot. When the voltage rose to 26.0kV and 28.0kV, there were two obvious discharge levels in the maps. 26.0kV is set as an example, there were two sets of concentrated discharge peaks at $\Delta t$ of 3.2ms and 1.0ms, and the discharge amount $q$ was distributed in the range of 63pC~960pC.

![Figure 5](image)

**Figure 5.** $H(n, q, \Delta t)$ maps of insulating surface scratch defect under different negative voltage: (a) -22.0kV, (b) -23.5kV, (c) -25.0kV, (d) -26.5kV, (e) -28.0kV.

As the positive polarity voltage increases, the time interval of the PD gradually decreased, and the discharge amount gradually increases. The $H(n, q, \Delta t)$ maps steadily changed from a single discharge peak to multiple sets of discharge peaks. The discharge repetition rates of the inner semiconducting layer damage defect under positive polarity were 3 times/s, 21 times/s, 35 times/s, 54 times/s, 76 times/s, and at the same voltage level, the positive discharge polarity repetition rate was higher than the negative polarity, additionally, the positive charge dissipation rate was higher than the negative charge, which led to the occurrence of this test phenomenon [26]; the average discharge capacity at the
positive polarity were 185pC, 377pC, 586pC, 753pC, 952pC, respectively. Compared with the negative polarity, the average discharge amount $q$ varied over a broader range.

**Figure 6.** H ($n$, $q$, $\Delta t$) maps of inner semiconducting layer breakage defect under different positive voltage: (a) +20.0kV, (b) +22.0kV, (c) +24.0kV, (d) +26.0kV, (e) +28.0kV.

**Figure 7.** H ($n$, $q$, $\Delta t$) maps of internal air gap defect under positive voltage: (a) +17.5kV, (b) +20.0kV, (c) +22.5kV, (d) +25.0kV, (e) +27.0kV.

Figure 7 showed H ($n$, $q$, $\Delta t$) maps of the inner air gap defect under the positive polarity. Similar to the negative polarity, the H ($n$, $q$, $\Delta t$) maps of the inner air gap of the positive polarity exhibited a single discharge peak. As the test voltage increasing, the discharge peak distribution became more
dispersed, the amount of discharge increases and the discharge time interval decreases. The discharge repetition rates of internal air gap defect under the positive polarity was 3 times / s, 21 times / s, 35 times / s, 54 times / s, 76 times / s, and at the same voltage level, the repetition rate of the positive discharge was lower than that of the negative polarity. The average discharge capacities under positive polarity was 210pC, 250pC, 295pC, 350pC, 413pC, which was basically consistent with the negative polarity.

4. Defect type identification

4.1. Traditional defect type identification method

The traditional defect type identification method is obtained by extracting the feature values of the distribution parameter images of the PD maps and applying them to PD types’ recognition [27]. Introducing the maximum discharge amount $q_{\text{max}}$, the average discharge amount $q_{\text{avg}}$, the discharge repetition rate $N$, the previous discharge time interval $\Delta t_{\text{pre}}$, and the subsequent discharge time interval $\Delta t_{\text{suc}}$ to derive the distribution parameters of the PD signal, including $H_{q_{\text{max}}} (\Delta t)$, $H_{q_{\text{avg}}} (\Delta t)$, $H_N (\Delta t)$ and $H_N (q)$, and the like. Among them, $H_{q_{\text{max}}} (\Delta t)$ characterizes the correlation between the maximum discharge and before and after discharge interval; $H_{q_{\text{avg}}} (\Delta t)$ characterizes the correlation between the average discharge and before and after discharge interval; $H_N (\Delta t)$ represents the distribution density of the discharge time interval; $H_N (q)$ represents the distribution density of the discharge amount.

After obtaining the above distribution relationship, different feature parameters are extracted, including skewness $S_k$, kurtosis $K_u$, correlation coefficient $CC$, peak $P_{ks}$, etc. [28]. On this basis, 18 parameters under different defects could be obtained by calculation.

4.2. Optimization of defect type identification method

Aiming at the problem that the traditional defect type identification method was susceptible to voltage amplitude and polarity, the GA-BP algorithm filters and combines the characteristic parameters to obtain the optimised parameters, thus eliminating the interference of the test conditions. The basic idea is to encode the typical PD characteristic parameter sets by GA algorithm, and train such a set of DNA as the input parameters of the neural network [29] to realise the optimisation of parameters acquisition. The objective function is used to solve the fitness of different combination parameters, and high-quality individuals are selected. The objective function value of each group of DNA is the proportion of correctly identified fault types obtained by the DNA training in the neural network. Based on this, the DNA is scored and sorted, and the optimal combination is obtained through multiple generations of genetic screening [30].

The parameters of the GA-BP algorithm model set in this paper are shown in Table 3. The initial population size is 50, the crossover probability is 0.7, and the mutation probability is 0.01. A total of 500 sets of partial discharge data were collected, so the total number of samples was $N=500$.

| Parameter name                      | Parameter value |
|-------------------------------------|-----------------|
| Population size (G)                 | 50              |
| Maximum evolution (MAXGEN)          | 100             |
| Individual length (L)               | 10              |
| Selection probability ($p_s$)       | 0.95            |
| Cross probability ($p_c$)            | 0.7             |
| Variation probability ($p_m$)        | 0.01            |

Table 3. GA-BP algorithm model parameters.

With the calculation by genetic algorithm, the value of the specific gravity of the characteristic parameters containing less defect type information declined. On the contrary, the value of the specific
gravity corresponding to the parameter including the information of the effective defect type gradually increases. The K-fold cross-validation method was used to train and test the neural network after the samples were divided. The three groups of DNA used in the neural network corresponded to the inner semi-conducting layer breakage (F1), the internal air cavity defect (F2) and the insulating surface scratching defect (F3) defect. By the calculation of GA-BP algorithm of the three defects’ DNAs, the parameters that were greatly affected by the voltage levels and polarities were excluded, which would greatly improve recognition efficiency.

4.3. Impact of two methods on defect type identification
In order to compare the impact of two methods on the identification of defect types, the recognition rates of the traditional defect type identification and the defect type identification optimized by GA-BP algorithm were calculated respectively. There were 5 data groups of experimental conditions, each of which contains 3 defect types, and each kind collected partial discharge data under a single test condition, that was, a fixed voltage condition.

The recognition results in Table 4 were obtained. It could be seen that the recognition rates of the two methods had reached 97.12% and 98.91%, respectively. The recognition rate of the optimized identification method had been greatly improved compared to the traditional identification method. It also showed that the optimized defect type identification could effectively suppress the influence of changes in voltage factors and improved defect type recognition efficiency.

| Table 4. Comparison between traditional identification and optimized identification. |
|----------------------------------------|------------------------|------------------------|
|                                       | traditional identification  | optimized identification |
| recognition rates                      | 97.12%                  | 98.91%                 |

5. Conclusions
1) Both of the DC PD repetition rate and average discharge of the three insulation defects have an upward trend with the increase of the voltage levels. At the same voltage level, the PD of the inner semiconducting layer breakage defect was more severe in the positive polarity, and the discharge repetition rate and average discharge were higher than the corresponding values in the negative polarity; the discharge repetition rate of the air gap defect under negative polarity was higher than it under the positive polarity, and the average discharge amount was basically the same. The discharge repetition rate and the average discharge of insulating surface scratch defects varied within a wide range, and the discharge repetition rate was significantly higher than the other two defects.

2) The GA-BP algorithm was used to optimize the traditional identification method. By performing GA-BP calculations on the three types of defect discharge data, the influence of voltage level and polarity on the recognition effect was gradually reduced, which effectively suppressed the influence of changes in voltage factors. The recognition rate of the optimized recognition method reached 98.91%, which was greatly improved compared with the traditional method.

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