Research on GIS partial discharge light measuring method based on Fluorescent fiber sensing system

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Abstract. In order to accurately detect the partial discharge information inside GIS, this paper proposes a PD measurement method based on fluorescent fiber sensing system. Firstly, the typical physical model reflecting four typical insulation defects in GIS is perfected. The PD optical signal is obtained through the detection system, and the corresponding 3D map and its gray image are constructed. At the same time, for the simple fractal is not enough to accurately describe the characteristics of PD discharge mode, a multi-fractal spectrum algorithm for partial discharge gray image is proposed. Then, based on the extraction of each feature information in the multifractal spectrum, BP neural network based on improved conjugate gradient algorithm is selected as the classifier for feature recognition. The results show that the multifractal spectrum can effectively describe the degree of PD gray image inhomogeneity and its different levels of geometric structure, and can accurately identify the PD phenomenon caused by four typical insulation defects.

1. Introduction
With the increasing demand for electricity in society, the power industry needs to develop toward ultra-high pressure and large capacity. However, due to the shortage of urban land resources, it is more difficult to establish large-scale open-type ultra-high voltage substation in cities. Compared with open transmission equipment, gas-insulated combined electrical equipment has the advantages of small footprint, low external interference, safe and stable operation, environmental protection, long maintenance period and small maintenance workload. It has solved the traditional open transmission. The problem of large area of equipment and other issues has alleviated the problem of tight urban construction land. Although GIS has the above advantages, it still inevitably has defects in inducing insulation faults, and will gradually expand, and once an insulation fault is formed, it will cause a major accident [1-2]. According to the data provided by the CIGRE23.10 working group international investigation report, GIS insulation faults occur mostly in high-voltage equipment. Once the fault occurs, the economic loss is immeasurable, so it is of great significance to ensure the safe and reliable operation of GIS. Partial discharge is a precursor to the degradation of equipment insulation and an important feature to characterize the degree of insulation degradation. Since the GIS accident is mainly caused by insulation degradation, the on-line monitoring of GIS for PD can find many internal defects and prevent the formation of insulation faults [6-9], which can reduce the economic loss caused by GIS insulation faults.

At present, for the PD phenomenon occurring inside GIS, the main detection methods include pulse current method, radio frequency detection method, ultra-high frequency method, ultrasonic detection...
method, chemical detection method and optical measurement method. Among them, because the optical measurement method is less affected by external interference, the sensitivity of measurement is relatively high, and it has gradually replaced the traditional ultra-high frequency method and ultrasonic method to obtain wide application. The optical measurement method is a non-destructive on-line detection method for partial discharge. The pattern recognition and fault diagnosis of PD are realized by detecting the optical signals released by PD caused by different types of insulation defects. Compared with other methods, the optical measurement method directly measures the optical signal generated by the PD inside the GIS, and can detect the PD in real time, can determine the position of the PD, and can be used for online PD monitoring in the GIS.

The key to pattern recognition of PD is to effectively extract the feature quantity that reflects the difference in discharge characteristics between various defects. At present, PD signal feature extraction is mainly divided into two categories: time domain analysis and statistical analysis. The former is to extract the characteristics of a single PD signal directly or through corresponding mathematical methods, for example, using wavelet transform or complex wavelet transform to extract a single PD signal feature for pattern recognition, but the characteristics of a single PD signal are greatly affected by the type of the sensor, and Distortion and serious disturbances occur in the transmission process, so it is difficult to extract the feature quantity that effectively describes the PD, so that the recognition effect obtained by the method in practical applications is not ideal. The latter is the feature of extracting the statistical map of PD signal, has strong pattern description ability, and is widely used in practice. Commonly, there are moment features, fractal features, Weibull features, morphological features and statistics extracted by mathematical methods [10-14]. But the existing feature quantity still has insufficient problem to describe the PD feature, resulting in low recognition rate. Therefore, it is necessary to explore a more excellent PD feature quantity to improve the PD pattern recognition rate.

Compared with single fractal, multifractal can accurately describe the characteristic information inside complex systems, and has been applied to scientific fields such as information, medical, finance, geology, etc., and has achieved certain results [15-16].

In this paper, the method of detecting PD optical signal by fluorescent fiber is used to obtain the corresponding 3D map and gray image. The multi-fractal spectrum algorithm of PD gray image is proposed. The results show that the multifractal spectrum can accurately describe the complex geometric features of PD gray image. On the basis of analysing the physical meaning of each feature quantity of multifractal spectrum, the feature quantity used for PD pattern recognition is extracted, and the BP neural network with improved conjugate gradient algorithm is selected as the classifier for feature recognition. The results show that the correct rate of PD pattern recognition is improved.

2. GIS partial discharge simulation experiment and signal acquisition

Among the various faults in GIS, insulation faults are the most common and the most concerned. At present, the artificial simulated insulation defect model for PD generated in laboratory GIS devices does not have a completely uniform standard. According to the PD characteristics induced by typical insulation defects of GIS equipment, four typical insulation defects for simulating internal PD of GIS are constructed. ①Fixed metal protrusion defects: simulated by aluminum needle-stainless steel plate electrode model, the radius of curvature of the needle electrode is about 0.3mm, the diameter of the plate electrode is 120mm, the thickness is 10mm, and the spacing of the needle plate can be adjusted between 1-20mm. ②Free metal particle defects: The bowl electrode is used to simulate PD that occurs under a slightly uneven electric field. The high-pressure ball electrode and the grounding bowl electrode are made of stainless steel. The diameter of the small ball is 30mm. The diameter of the bowl electrode is 120mm. The free metal particles are simulated by tiny rectangular aluminum foil. The size of the aluminum foil particles is about 2mm×2mm. ③ Metal particle defects on insulator surface: Two circular plate electrodes are used to simulate the uneven electric field in the GIS cavity. The high voltage plate electrode is made of aluminum, and the ground plate electrode is made of stainless steel. Both plate electrodes are 120 mm in diameter and adopt a cylindrical ring. The oxygen resin block is used to simulate the supporting insulator of GIS. The epoxy resin block has a diameter of 60 mm and a thickness
of 25 mm. Metal contamination of the surface of the basin insulator was simulated by attaching a certain amount of copper scrap on the surface of the epoxy block. Air gap defect between insulator and high voltage guide rod: Two circular plate electrodes are used to simulate the uniform electric field inside GIS. The electrode material of high voltage plate is aluminum, the electrode material of ground plate is stainless steel, the diameter of both plates is 120mm, and it is cylindrical. The epoxy block is used to simulate the supporting insulator inside the GIS. The epoxy block is 60mm in diameter and 20mm thick. An air gap of about 1 mm is left between the upper surface of the epoxy block and the electrode of the high voltage plate to simulate the air gap defect formed after the connection between the GIS high voltage conductive rod and the basin insulator is loose.
3. System topology based on fluorescent fiber sensor
The fluorescent fiber sensing system is used to detect the internal PD signal of GIS. Specifically, the fluorescent fiber sensor is placed in an appropriate position inside the GIS to sense the micro-light signal generated by the PD caused by the insulation fault, and converted into a fluorescent signal, and then the fluorescent signal is coupled and the optical signal is transmitted to the photodetector using a common optical fiber. The photodetector converts the fluorescent light signal into a current signal, and finally converts the current signal into a voltage signal, and transmits it to a digital oscilloscope through a coaxial cable for signal display, acquisition, processing, and storage. The schematic diagram of the fluorescent fiber sensing system is shown in Figure 5. It mainly includes five parts: optical sensor unit, optical transmission unit, photoelectric conversion unit, power module and electrical signal transmission and acquisition unit.

The optical test method for detecting the internal PD experiment system of GIS is shown in Figure 6. It consists of a power supply, an insulation defect model, a simulated GIS cavity, and a fluorescent fiber sensing system. The insulation defect model is placed in the center of the simulated GIS cavity. The bottom surface of the cavity is 200mm in diameter and 270mm in height. In order to effectively avoid the interference of external light, the experimental device is placed in a metal light shielding room, and the size of the shielding room is 3m×2.4m×2m. The system introduces a power frequency test voltage signal to describe the phase at which the PD occurs.
4. Gray image acquisition of PD optical signals
The PD optical signal samples collected by the fluorescent fiber sensing system are subjected to statistics of phase $\phi$, amplitude $u$, and number of discharges $n$ to form an $\phi$-$u$-$n$ three-dimensional spectrum of the PD optical signal [17]. The gray image of the PD optical signal is directly projected from the $\phi$-$u$-$n$ map to the $\phi$-$u$ plane. The gray level of the gray image is 0~255, and the $\phi$-$u$-$n$ three-dimensional spectrum is regarded as the $Hn(\phi, u)$ spatial surface. In this paper, the power frequency phase $\phi$ axis is divided into 256 intervals according to 0~360°, and the amplitude $u$-axis of the optical pulse signal is divided into 128 cells according to 0~0.1V, which is divided into planes of 128×256 cells. Count the number of discharges in each cell on the $\phi$-$u$ plane, that is, obtain the $\phi$ spatial surface. The $\phi$-$u$-$n$ spatial surface constructed by the article is obtained from 200 power frequency signals.

The $\phi$-$u$-$n$ three-dimensional map and gray image constructed by the PD optical signal samples from the four kinds of insulation defect models collected are shown in Figure 7.

![Experimental system](image)

**Figure 6.** Experimental system

![Three-dimensional spectrum of partial discharge generated by four typical defects in GIS](image)

**Figure 7.** Three-dimensional spectrum of partial discharge generated by four typical defects in GIS
The three-dimensional spectrum of $\phi-u-n$ constructed by the PD optical signal under the defects of metal protrusions shows that the repetition rate of the optical pulse is high, the average amplitude is large, and the range of amplitude variation is small, and both are symmetrically distributed around the phase 270° of the negative half cycle of the power frequency. It is found that the PD generated by the metal protrusion is a typical corona discharge, and the light signal generated by the discharge is relatively stable, and the light intensity generated by the single discharge is large. Therefore, the average amplitude of the light pulse detected by the photometric method is large, and the amplitude is large. The range of variation is small. The initial discharge voltage of the positive half cycle of the corona discharge power frequency is higher than the negative half cycle of the power frequency, and the space charge generated by the discharge diffuses rapidly in the gas, the space charge has little influence on the external electric field, and the corona discharge starting voltage is almost extinguished. The voltages are equal, so the light pulse distribution has the above characteristics.

The three-dimensional spectrum of $\phi-u-n$ constructed by the PD optical signal under the defect of free metal particles shows that the repetition rate of the optical pulse is low, the average amplitude is large, the range of amplitude variation is large, and the optical pulse distribution has no phase characteristics. The analysis shows that the free metal particles obtain an induced charge under the action of an external electric field and move under the action of the electric field force. The degree of movement of the metal particles depends on the induced charge of the particles, the shape of the particles, the direction of movement of the particles, and whether the particles collide with other objects during the movement, and the PD generated by the defects of the free metal particles is caused by the movement of the metal particles. Therefore, the PD generated by the defect of the free metal particles is very unstable, and the intensity of light generated by each PD is also greatly different, and the phase of the PD is also irregular.

The $\phi-u-n$ three-dimensional spectrum constructed by the PD light signal on the surface of the insulator shows that the repetition rate of the light pulse is low, the amplitude of the average light pulse is small, the range of amplitude variation is large, and the light pulses are distributed around the phases 90° and 270°. And distributed in 90°–180° phase width greater than 0°–90°, distributed in 270°–360° phase width more than 180°–270°. The reason for this is that the PD generated by the defect of the metal contaminant on the surface of the insulator will generate electric branches on the surface of the insulator, affecting the insulation state of the surface of the insulator, thereby making the PD phenomenon unstable, and the intensity of light generated by a single discharge is not First, the light intensity generated by the discharge is generally small, so the average amplitude of the light pulse obtained by the photometric method is small, and the amplitude varies widely.

From the three-dimensional spectrum of the $\phi-u-n$ constructed by the optical signal of the air gap between the insulator and the high-voltage conductor, it can be seen that the optical pulse repetition rate is high, the average amplitude is small, the amplitude variation range is large, and the light pulses are distributed at a phase of 90° and near 270°, and distributed in the range of 90°–180°, the phase width is greater than 0°–90°, and the phase width is more than 270°–360° in the range of 180°–270°. The reason is that the PD caused by the air gap defect between the insulator and the metal conductor is unstable, and the intensity of the light generated by the single discharge is different, but the light intensity generated by the discharge is generally small, so the average amplitude of the detected light pulse is small. The amplitude varies widely. Since the insulator hinders the diffusion of the space charge, the space charge causes distortion of the external electric field, so that the initial discharge voltage of the pd caused by the air gap defect between the insulator and the metal conductor is higher than the extinction voltage, and thus the above-mentioned optical pulse distribution is obtained.
Figure 8. Metallic protrusion defect PD grayscale image

Figure 9. Free-metal particle defect PD grayscale image

Figure 10. Insulator surface metal particle defect PD grayscale image

Figure 11. Gray-scale image of air gap defect between insulator and high-voltage conductor
Figure 8-11 shows the $\varphi-u-n$ grayscale image obtained by the photometric method to detect the PD signal structure generated by four typical defects in GIS. It is not difficult to see that the $\varphi-u-n$ grayscale images under different defects have large differences. A large number of experiments have shown that the grayscale images of PD produced by different defects have obvious characteristics. The same type of PD grayscale images have the same spectrum measured at the same voltage. As the voltage increases, the PD discharge intensity of each defect increases, but the distribution of grayscale images remains basically the same. The similarity between PD grayscale images produced by different defects at different voltages is much greater than that of different types. The degree of similarity between PD grayscale images produced by defects.

In short, the $\varphi-u-n$ three-dimensional spectrum and the gray-scale image feature of the PD optical signal constructed by different insulation defects are significantly different, so the PD optical signal can be used to distinguish the internal discharge type of the GIS.

5. Multifractal spectrum of partial discharge gray image and its feature extraction

PD has randomness, so each discharge mode of PD has very complex graphic features, but a large number of studies have shown that various discharge modes of PD have fractal features, and the fractal characteristics of PD discharge mode can be extracted by fractal theory. Multifractal is a set of singular measures of multiple scale indices based on simple fractals. It is based on the singular measure divided into different fractal subsets. It can describe different regions and different levels of conditions of the research object. The resulting complex fractal structure is comprehensive and detailed. It can be seen from the PD grayscale image that the grayscale pixel points are unevenly distributed and complex, and are not a simple fractal. Describe the PD grayscale image with a single fractal dimension and ignore many details. Multi-fractal description of PD gray the characteristics of the graph are more accurate.

5.1. Probability algorithm for multifractal spectrum of Pd gray image

Multifractal is generally described by the $\alpha \sim f(\alpha)$ function, which is the multifractal spectrum [18]. The following two-dimensional research object is taken as an example to explain the meanings of $\alpha$ and $f(\alpha)$.

Using the box number method to divide the fractal set into $N$ boxes of $r \times r$, the probability distribution function $P_{ij}$ of the $(i, j)$ boxes is:

$$P_{ij}(r) \sim r^\alpha$$  \hspace{1cm} (1)$$

$\alpha$ is a singularity index, which reflects the physical quantity of the singularity of each small box on the fractal. According to the value of $\alpha$, it can be divided into simple fractal and multi-fractal. The number of small boxes with the same alpha value is denoted as $N_\alpha(r)$, which is related to $r$ and can be written as:

$$N_\alpha(r) \sim r^{-f(\alpha)}$$  \hspace{1cm} (2)$$

$F(\alpha)$ represents the fractal dimension of a fractal subset with the same $\alpha$ value and the fractal properties of this series of subsets.

Statistical physics gives the construction principle of statistical fractal multifractal spectrum, which defines a partition function $\chi(q, r)$ to perform q-th power weighted summation on the distribution probability $P_{ij}(r)$. The mathematical expression is:

$$\chi(q, r) = \sum P_{ij}(r)^q = r^{q(\alpha)} - \infty < q < +\infty$$  \hspace{1cm} (3)$$
9

\[ T(q) \] becomes the mass index and can be obtained from the slope of the \( \ln \chi(q, r) \sim \ln r \) curve, ie:

\[ \tau(q) = \frac{\ln \chi(q, r)}{\ln r} \quad (r \to 0) \quad (4) \]

According to the distribution probability \( P \), the binomial summation is obtained. From equation (3), \( \chi(q, r) \) can be expressed as:

\[ \chi(q, r) = \sum N(P)P^q \quad (5) \]

Combined equation (2), equation (3), equation (4) and equation (5), \( \chi(q, r) \) can be expressed as:

\[ \chi(q, r) = \sum r^{-f(\alpha)} r^q = \sum r^{\alpha q - f(\alpha)} = r^{\tau(q)} \quad (6) \]

Dividing both sides of equation (6) by \( r^{\tau(q)} \), you can get:

\[ \sum r^{\alpha q - f(\alpha) - \tau(q)} = 1 \quad (7) \]

Because of \( r \to 0 \), only the item of \( \alpha q - f(\alpha) - \tau(q) = 0 \) remains during the summation of equation (7), ie:

\[ f(\alpha) = \alpha q - \tau(q) \quad (8) \]

\( \alpha \) is defined as:

\[ \alpha = \frac{d\tau(q)}{dq} \quad (9) \]

According to formula (8) and formula (9), the multifractal spectrum \( \alpha \sim f(\alpha) \) of the fractal set can be obtained.

5.2. Construction of Multifractal Spectrum of Pd Gray Image

First, the PD grayscale image is divided into small boxes of scale \( r \times r \). And define the distribution probability of the \((i, j)\) box discharge:

\[ P_{ij}(r) = \frac{S_{ij}(r)}{\sum S_{ij}(r)} \quad (10) \]

Where \( S_n(r) \) is the sum of the gray values of all the pixels in the \((i, j)\) box, and \( \sum S_n(r) \) is the sum of the gray values of all the pixels in the PD gray map. Through a large number of calculations, it is found that the linear region of the \( \ln \chi(q, r) \sim \ln r \) curve is almost constant under different weight coefficients \( q \), indicating that the fractal scale-free region of the PD gray image is determined by the characteristics of the graph itself, independent of the weight coefficient. It can be seen from the above analysis that the
PD gray image only maintains self-similarity in the fractal scale-free region. Therefore, constructing the multi-fractal spectrum of the PD gray image requires first determining the fractal scale-free region of the PD gray image. In this paper, we use the piecewise linear fitting method to determine the fractal scale-free area. The algorithm flow is as follows:

1) Starting from the smallest division scale, the \([ln r, ln \chi(q, r)](i=1,2,3,\ldots,n)\) curve is divided into \(n-m+1\) segments of length \(m\), where \(m\) is taken as 2.

2) The slope of each small region after division is calculated by linear fitting method, and sequentially labeled in order, so that the slope set \(k_i\) corresponding to the divided region can be obtained \((i=1, 2, 3, \ldots, n-m+1)\).

3) The search method can be used to find the largest subset of the slope set \(k_i\) with a fluctuation range less than 10%, and the corresponding region is the fractal scale-free region.

In theory, the partition function \(\chi(q, r)\) is obtained by summing the \(q\)-th power of the distribution probability. The partition function calculated by different \(q\) reflects the properties of different fractal subsets. The value of \(q\) is \(-\infty\sim+\infty\). The range of \(Q\) values is too large or too small to fully and accurately analyze the probability distribution characteristics of the research object. Therefore, calculating the multifractal spectrum of the PD gray image requires determining the appropriate value range of \(q\). The parameter \(\beta\) that defines \(f(\alpha, q)\) as a function of \(q\) is:

\[
\beta = \left| \frac{f (\alpha, q) - f (\alpha, q - \text{step})}{f (\alpha, q) - f_{\max}(\alpha)} \right| \tag{11}
\]

\(F_{\max}(\alpha)\) is the maximum value of the multifractal spectrum, and \(\text{step}\) is the difference between the two adjacent weight coefficients \(q\). The value range of \(q\) obtained by \(\beta<0.01\) is used as the reference value for constructing the multifractal spectrum.

5.3. Pd gray image multifractal spectrum

Figure 12 shows the multifractal spectrum of different defect PD gray image images calculated by the above construction algorithm. It can be concluded from the figure that the multi-fractal spectrum of PD gray image under different insulation defects is different, and the multi-fractal spectrum can be used to describe PD features effectively.

From equations (1) and (2), it can be seen that \(\alpha\) and \(f(\alpha)\) respectively represent the magnitude of the discharge distribution probability and the number of boxes with the same fractal characteristics in the fractal structure. The larger the \(\alpha\), the smaller the distribution probability, the larger the \(f(\alpha)\) The more the number of boxes. The physical meanings of the characteristic parameters of the multi-fractal spectrum of PD gray image are as follows: the parameters \(\alpha_{\max}\) and \(f(\alpha_{\max})\) reflect the properties of the
fractal subset of the minimum distribution probability of PD. The parameters \( a_{\text{min}} \) and \( f(a_{\text{min}}) \) reflect the nature of the fractal subset of the maximum distribution probability of PD. \( a(0) \) and \( f(a(0)) \) reflect the properties of the PD maximum likelihood distribution probability fractal subset. The spectral width \( \Delta a = a_{\text{max}} - a_{\text{min}} \), \( \Delta a \) reflects the degree of fluctuation of the PD distribution probability, and the larger \( \Delta a \) indicates that the PD distribution is more uneven. \( \Delta f = f(a_{\text{max}}) - f(a_{\text{min}}) \), \( \Delta f \) reflects the ratio of the number of PD minimum and maximum distribution probability fractal subset boxes.

The above eight characteristic parameters of the multi-fractal spectrum of PD gray image under different defects are shown in Tables 1 and 2. It can be seen from the table that the characteristics of multi-fractal spectrum of PD gray image under different defects are different. Using them as the recognition feature quantity, the PD characteristics under different insulation defects can be more fully described. In this paper, the above eight parameters of \( H_q^- (\phi, u) \) multi-fractal spectrum are taken as feature components \( x_1 \sim x_8 \), and the above eight parameters of \( H_q^+ (\phi, u) \) multi-fractal spectrum are used as feature components \( x_9 \sim x_{16} \), and \( x_1 \sim x_{16} \) are combined to form the feature vector of PD pattern recognition.

### Table 1. Main features of multifractal spectrum of PD negative half-cycle gray image

| Defect type                        | \( a_{\text{min}} \) | \( f(a_{\text{min}}) \) | \( a_{\text{max}} \) | \( f(a_{\text{max}}) \) | \( a(0) \) | \( f(a(0)) \) | \( \Delta a \) | \( \Delta f \) |
|------------------------------------|------------------------|--------------------------|------------------------|--------------------------|-----------|----------------|----------------|----------------|
| Metal protrusion                   | 0.89                   | 0                        | 2.23                   | 0.86                     | 1.55      | 1.47           | 1.34           | 0.86           |
| Insulator surface air gap          | 0.60                   | 0.30                     | 2.25                   | 0.25                     | 1.66      | 1.45           | 1.65           | -0.05          |
| Insulator surface metal particles  | 0.81                   | 0.04                     | 3.31                   | 0.98                     | 2.13      | 1.56           | 2.50           | 0.94           |
| Free metal particles               | 0.94                   | 0.00                     | 3.64                   | 0.37                     | 2.25      | 1.94           | 2.70           | 0.37           |

### Table 2. Main features of multi-fractal spectrum of PD positive half-cycle gray image

| Defect type                        | \( a_{\text{min}} \) | \( f(a_{\text{min}}) \) | \( a_{\text{max}} \) | \( f(a_{\text{max}}) \) | \( a(0) \) | \( f(a(0)) \) | \( \Delta a \) | \( \Delta f \) |
|------------------------------------|------------------------|--------------------------|------------------------|--------------------------|-----------|----------------|----------------|----------------|
| Metal protrusion                   | 0                      | 0                        | 0.00                   | 0.00                     | 0.00      | 0              | 0              | 0              |
| Insulator surface air gap          | 0.57                   | 0                        | 1.77                   | 0.50                     | 1.37      | 1.29           | 1.20           | 0.50           |
| Insulator surface metal particles  | 0.62                   | 0                        | 2.04                   | 0.51                     | 1.62      | 1.31           | 1.38           | 0.51           |
| Free metal particles               | 1.00                   | 0.31                     | 3.07                   | 0                        | 2.16      | 1.96           | 2.07           | -0.31          |

### 5.4. Feature Extraction of Multifractal Spectrum of PD Gray Image

The gray image is constructed by acquiring the PD photometric signal. The total number of grayscale images is 480, and there are 120 PD grayscale images under each insulating defect. Extracting the Characteristics of Multifractal Spectrum of PD Gray Image by Using the above Method. In order to compare the difference of the multifractal spectrum characteristic parameters of PD gray image under different insulation defects, the relevant parameters are normalized by the formula (12), as shown below.

\[
L_i = \frac{|x_{i\text{max}} - x_{i\text{min}}|}{x_{i\text{max}}}
\]  

The characteristic parameter distribution interval of the multi-fractal spectrum of PD gray image under the insulation defect after normalization is shown in Figure 13. It can be seen from Fig. 12 that the characteristic parameters of the multi-fractal spectrum of PD gray image under different insulation defects are distributed within a certain interval, indicating that the probability distribution characteristics of PD in the \( \phi-u \) plane vary within a certain range. Although there are overlapping regions of single characteristic parameters under different insulation defects, the distribution intervals of 16 characteristic parameters under different insulation defects are different, indicating that the probability distribution
characteristics of PD under different insulation defects are different. According to the feature quantity selected in this paper, different insulation can be distinguished. The PD under the defect, which is again experimentally verified that the feature quantity selected for PD pattern recognition is feasible.

![Characteristics of PD under different insulation defects](image)

**Figure 13.** Characteristic parameter distribution interval of multifractal spectrum of PD gray image

After the feature quantity selection is completed, it is important to design a classifier with strong approximation and strong generalization ability. Because artificial neural network has the characteristics of information distribution storage, strong adaptive processing capability, high fault tolerance and generalization performance, it has been widely used as a recognition classifier in various fields in recent years. In this paper, BP neural network is used as the recognition classifier. The multi-fractal spectrum of PD gray image extracted in the previous paper is characterized by feature quantity, and the PD discharge type is identified. The results show that BP neural network as a classifier has a higher recognition rate for PD pattern recognition.

6. Pattern Recognition Based on BP Neural Network

Taking the multi-fractal spectrum feature sample data of gray image extracted from this paper as the feature quantity, BP neural network is used as the classifier to identify the PD type caused by different insulation defects inside the GIS equipment. The 480 sets of PD gray image multifractal spectrum feature sample data extracted in the previous paper are divided into two categories: $S_1$ is the training sample and $S_2$ is the test sample. The specific number of each sample is shown in Table 3.

In order to verify the superiority of the improved conjugate gradient algorithm, BP neural network based on gradient descent algorithm, conjugate gradient algorithm and improved conjugate gradient algorithm are used as recognition classifiers. The multi-fractal spectrum features are extracted as feature quantities, and three kinds of features are compared. The performance of the classifier. In this paper, there are 16 nodes in the BP neural network input layer, 33 nodes in the hidden layer, and 4 nodes in the output layer. Table 4 and 5 respectively give the comparison results of training time and recognition effect of three different algorithms. It can be seen from Table 4 that BP neural network based on improved conjugate gradient algorithm has the fastest convergence speed and the shortest training time. It can be seen from Table 5 that the BP neural network based on the improved conjugate gradient algorithm has the highest recognition rate. Therefore, the BP neural network based on the improved conjugate gradient algorithm is a better PD pattern recognition classifier.
Table 3. sample attributes

| Defect type                                      | S1 | S2 |
|-------------------------------------------------|----|----|
| Metal protrusion                                | 20 | 100|
| Air gap between insulator surface and high voltage conductor | 20 | 100|
| Metal particle defects on insulator surface     | 20 | 100|
| Free metal particles                            | 20 | 100|

Table 4. GIS PD three identification methods identify training time

| Algorithm type                  | Gradient descent | Conjugate gradient method | Improved conjugate gradient method |
|---------------------------------|------------------|---------------------------|-----------------------------------|
| Number of training              | 29400            | 684                       | 17                                |
| Training time                   | 246s             | 1.2s                      | 0.1s                              |

Table 5. Comparison of recognition methods of three identification methods of GIS PD

| Defect type                                      | Gradient descent | Conjugate gradient method | Improved conjugate gradient method |
|-------------------------------------------------|------------------|---------------------------|-----------------------------------|
| Metal protrusion                                | 88.3%            | 97.5%                     | 97.5%                             |
| Air gap between insulator surface and high voltage conductor | 84.1%          | 90%                       | 91.7%                             |
| Metal particle defects on insulator surface     | 79.2%            | 83.3%                     | 87.5%                             |
| Free metal particles                            | 85%              | 93.3%                     | 95.8%                             |

Table 6. Comparison of GIS PD recognition effects based on different characteristics

| Defect type                                      | Single fractal feature | Multifractal spectrum |
|-------------------------------------------------|------------------------|-----------------------|
| Metal protrusion                                | 91.7%                  | 97.5%                 |
| Air gap between insulator surface and high voltage conductor | 74.2%                | 91.7%                 |
| Metal particle defects on insulator surface     | 76.7%                  | 87.5%                 |
| Free metal particles                            | 93.3%                  | 95.8%                 |

Single fractal feature is one of the commonly used recognition features of PD pattern recognition. In order to further study the ability of multifractal spectrum to distinguish PD discharge type, it is compared with a single fractal feature, so the features extracted in this paper and the method according to the literature [19] The extraction box dimension and information dimension are used as the feature quantities to identify the PD discharge type, and the improved conjugate gradient method BP neural network is used as the classifier. The recognition results are shown in Table 6. It can be seen from the table that the multi-fractal spectrum of the PD gray image extracted from this paper is better than the single fractal feature, so the characteristics of the multi-fractal spectrum can better describe the PD characteristics under different insulation defects. Since the original grayscale image used in the PD pattern recognition is constructed by the photometric signal, it is also verified that different types of discharge can be identified by using the PD photometric signal.

7. Conclusion

(1) Four typical insulation defect models are constructed, which can be used to analyse the mechanism and conditions of PD generated by GIS internal insulation defects, and enhance the understanding and understanding of GIS internal defects.
(2) A partial discharge (PD) fluorescent fiber sensing system was developed. Through the simulation of four typical insulation defect models, the PD optical signals under different defects were obtained, and the corresponding $\phi-u-n$ three-dimensional map and its gray image were constructed. The results show that there are significant differences in PD optical signal characteristics under different insulation defects, so the PD optical signal can be used to distinguish the internal discharge type of GIS.

(3) Aiming at the fact that simple fractal is not enough to accurately describe the characteristics of PD discharge mode, a multi-fractal spectrum algorithm for partial discharge gray image is proposed. The multi-fractal spectrum features of gray image of PD light signal are extracted by each insulation defect model. The comparison of multi-fractal spectrum features of gray image under different PD shows that multi-fractal spectrum can effectively describe the geometric features of PD gray image, which can be used for Identify different insulation defects.

(4) Based on the analysis of the physical meanings of the multi-fractal spectrum of PD gray image, the main features are extracted as the feature quantity of PD pattern recognition. By using BP neural network classifier based on improved conjugate gradient algorithm, the optical method is obtained. The PD signals generated by the four typical physical models of insulation defects are classified and identified, and all defects can be accurately identified.

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