Multifractal Spectrum Identification of Partial Discharge in GIS Based on Optical Detection

R Xie¹, X Y Ge¹, J P Zhu¹, R P Hu¹, F K Zhou¹ and X X Zhang¹, ²

¹Guangzhou Power Supply Bureau Co., Ltd, Guangzhou 510000, Guangdong Province, China
E-mail: xiaoxing.zhang@outlook.com

Abstract. Partial discharge (PD) pattern recognition is an effective means to accurately obtain the correspondence between PD features and insulation defects. Optical detection for PD has strong anti-interference ability. Therefore, this paper carried out research on the pattern recognition of PD optical signal. In this paper, the PD optical signal under four typical defects of gas-insulated switchgears (GIS) are obtained by fluorescent fiber sensing system, and the four kinds of grayscale images are established. The multifractal spectrum features of the grayscale images of the optical signals are extracted. By analysing the physical meaning of each feature information in the multifractal spectrum, the feature components for PD pattern recognition are extracted, and the improved conjugate gradient back propagation (BP) neural network algorithm is selected as the classifier. This paper show that the multifractal spectrum can effectively describe the degree of unevenness of PD grayscale images and the geometric features of different level. The correct recognition rate of all kinds of defects by the multifractal spectrum is more than 87%, which is better than the identification of the box dimension and information dimension as the feature components. It lays the foundation for the future application of the optical detection.

1. Introduction
SF₆ gas insulted switchgear (GIS) is widely used in urban power grids due to its unique advantages such as small footprint, safe operation and low electromagnetic pollution. However, during the transportation, installation, operation, maintenance, various types of insulation defects will inevitably appear inside the GIS. The types of partial discharge (PD) are different, the severity of equipment failure [1-2] and the risk of operational failure [3-6] are also different. Therefore, identifying the type of insulation defects in GIS by identifying PD pattern has been a research hotspot in this field.

One of the keys to pattern recognition of PD is the efficient extraction of feature that reflect differences in discharge characteristics in various defects [7-10]. At present, the extraction of PD signal feature is mainly divided into two categories: time domain analysis method and statistical analysis method. The former is to extract the characteristics of the single signal directly or through corresponding mathematical methods [11], for example, using wavelet transform or complex wavelet transform to extract single signal features for pattern recognition [12-13]. However, the characteristics of single signal are greatly affected by the type of the sensor. Due to distortion in the transmission process, it is difficult to extract the feature to effectively describe the PD, the recognition effect in practical application is unsatisfactory [14-15]. The latter is to extract the feature of statistical map of PD signal, and it has strong pattern description ability, which is widely used in practice [16-23]. However, the existing feature is not sufficient to describe the PD feature and the recognition rate is low. Therefore, it
is necessary to explore more excellent PD feature components to improve the PD pattern recognition rate.

Multifractal theory can divide it into different regions according to the singularity of the internal geometry of complex systems, so as to obtain many feature information that is ignored by simple fractals. It has become an effective means to quantitatively describe the characteristics of complex systems. And it has been successfully applied in scientific fields such as chemical engineering, finance, geology, meteorology and fault diagnosis [24-25].

In this paper, multifractal spectrum is used to analyze rich feature information of PD grayscale image, and the probability calculation method of multifractal spectrum of PD grayscale image is proposed. The results show that the multifractal spectrum can describe the degree of unevenness of PD grayscale images and the geometric features of different levels. Based on the analysis of the physical meaning of each feature of multifractal spectrum, the feature components for PD pattern recognition that can describe multifractal spectrum is extracted. The improved conjugate gradient back propagation (BP) neural network algorithm is used as the classifier to identify the optical signal of PD. Compared with the commonly used box dimension and information dimension feature [26-27]. The results show that the correct rate of PD pattern recognition is improved.

2. Partial discharge experiment and grayscale image acquisition

2.1. Experimental part

Currently, there is no uniform standard for artificially simulated insulation defect models for PD generation in laboratory. According to the PD characteristics caused by the typical insulation defects in GIS, the four insulation defect models introduced in the literature [28-30] are used: 1) metal protrusion defect, called type N (Needle), using needle-plate electrode, the space of needle and plate is 5 mm; 2) the air gap defect is called type G (Gap), it is simulated by the gap between the electrode and the epoxy insulator, the distance is 1mm; 3) the metal particle defect is called type M (Metal), simulated by attaching a copper wire with diameter of 1 mm and length of 5 mm to the surface of the insulator; 4) the free metal particle defect, called the type P (Particle), simulated by placing 30 2mm×2mm aluminum foils between the electrodes.

![Figure 1. Experiment system](image)

The artificial defect model is placed in the simulated cavity, and the cavity is repeatedly washed with SF$_6$ gas for 3 times, then charging with 0.3 MPa of SF$_6$ gas; slowly increasing the test voltage, recording initial discharge voltage $U_0$, continue to increase the test voltage ($>1.2U_0$), and collecting PD signals at different discharge intensities.

2.2. Grayscale image

The PD optical signal samples collected by the fluorescent fiber sensing system are used to calculate the phase $\phi$, the amplitude $u$, and the number of discharge $n$ to form the $\phi$-$u$-$n$ three-dimensional spectrum. The grayscale image of the PD optical signal is directly obtained by projecting the $\phi$-$u$-$n$ map onto the $\phi$-$u$ plane, and the gray level of the grayscale image is in range of 0 to 255. The $\phi$-$u$-$n$ three-dimensional spectrum is regarded as the $H_d(\phi, u)$ spatial surface. In this paper, based on the maximum and minimum
values of $H_d(\varphi, u)$ to determine the maximum and minimum gray level of grayscale image, the grayscale image of $H_d(\varphi, u)$ [32] is constructed. The calculation method of pixel gray value is

$$m_{ij} = \frac{n_{ij}}{n_{\max}} \times 255$$  \hspace{1cm} (1)

Where $m_{ij}$ is the pixel gray value of the $i$-th row and the $j$-th column; $n_{ij}$ is the number of discharges on $H_d(\varphi, u)$ spatial surface; $n_{\max}$ is the maximum number of discharges on the $H_d(\varphi, u)$ spatial surface. The resolution of the grayscale image is 256 pixels x 128 pixels. The $\varphi$-$u$-$n$ three-dimensional spectrum and its grayscale images under the four insulation defect models are shown in figure 2, that is, the PD grayscale image is the projection of the three-dimensional spectrum in $\varphi$-$u$ plane. It shows that the grayscale image features constructed by PD optical signals with different insulation defects are significantly different, so the PD optical signal can be used to distinguish the internal discharge type of GIS.

![Figure 2](image)

**Figure 2.** The four typical $\varphi$-$u$-$n$ three-dimensional spectrum and its grayscale images of the optical signal samples of PD

3. **Multifractal spectrum**

It can be seen from figure 2 that the PD grayscale image under AC voltage usually has two discharge-dense regions, which are located near the positive half cycle and negative half cycle. The two half cycles have different features. Therefore, the multifractal spectrum of grayscale image in the two half cycles are extracted, respectively.

3.1. **Multifractal spectrum of PD grayscale image**
Figure 3 shows the multifractal spectrum of PD grayscale images are extracted by the probability algorithm [33]. It can be seen that the PD grayscale images with different insulation defects have different multifractal characteristics, so the multifractal spectrum can effectively describe the PD features. However, if the multifractal spectrum is directly used as the feature component, the dimension of feature component is too high, which is not conducive to the identification of the discharge type. The multifractal spectrum can describe the details of the research object and has the following properties: 1) \( f(\alpha) \) is the unimodal curve which has the maximum value; 2) \( f(\alpha) \geq 0 \); 3) the multifractal spectral function \( f(\alpha) \) is the convex function with respect to \( \alpha \). From the property of the multifractal spectrum, the multifractal spectrum can be described by the main feature \( \alpha_{\text{max}}, f(\alpha_{\text{max}}), \alpha_{\text{min}}, f(\alpha_{\text{min}}), \alpha(0), f(\alpha(0)) \), \( \Delta \alpha(\Delta \alpha=\alpha_{\text{max}}-\alpha_{\text{min}}) \), \( \Delta f(\Delta f=f(\alpha_{\text{max}})-f(\alpha_{\text{min}})) \).

![Figure 3. The multifractal spectrum under the different defects](image)

The physical meanings of the main features of multifractal spectrum are as follows: \( \alpha_{\text{max}} \) and \( f(\alpha_{\text{max}}) \) reflect the properties of the fractal subset of PD minimum distribution probability; \( \alpha_{\text{min}} \) and \( f(\alpha_{\text{min}}) \) reflect the properties of the fractal subset of PD maximum distribution probability; \( \alpha(0) \) and \( f(\alpha(0)) \) reflect the properties of the fractal subset of PD maximum likelihood distribution probability; \( \Delta \alpha(\Delta \alpha=\alpha_{\text{max}}-\alpha_{\text{min}}) \), \( \Delta f(\Delta f=f(\alpha_{\text{max}})-f(\alpha_{\text{min}})) \) reflects the fluctuation of the PD distribution probability; \( \Delta f=f(\alpha_{\text{max}})-f(\alpha_{\text{min}}) \), \( \Delta f \) reflects the number ratio of the boxes in the fractal subset of PD minimum distribution probability to PD maximum probability distribution.

The main feature parameters of the multifractal spectrum of the grayscale image are shown in table 1 and table 2. It can be seen that the parameters under different insulation defects are different, which indicates that they have different degrees of unevenness and different geometric features at different fractal levels. Therefore, the feature parameter listed in tables 1 and 2 can be used as feature components for PD pattern recognition. In this paper, the parameters in the negative half cycle are taken as feature components \( x1, x2, \ldots, x8 \), the parameters in the positive half cycle are taken as the feature components \( x9, x10, \ldots, x16 \). Combine \( x1, x2, \ldots, x16 \) to form the feature components for the recognition.

### Table 1. The multifractal feature parameters in the negative half cycle

| Type   | N    | G    | M    | P    |
|--------|------|------|------|------|
| \( \alpha_{\text{min}} \) | 0.89 | 0.6  | 0.81 | 0.94 |
| \( f(\alpha_{\text{min}}) \) | 0   | 0.3  | 0.04 | 0    |
| \( \alpha_{\text{max}} \) | 2.23 | 2.25 | 3.31 | 3.64 |
| \( f(\alpha_{\text{max}}) \) | 0.86 | 0.25 | 0.98 | 0.37 |
| \( \alpha(0) \) | 1.55 | 1.66 | 2.13 | 2.25 |
| \( f(\alpha(0)) \) | 1.47 | 1.45 | 1.56 | 1.94 |
| \( \Delta \alpha \) | 1.34 | 1.65 | 2.5  | 2.7  |
| \( \Delta f \) | 0.86 | -0.05 | 0.94 | 0.37 |
Table 2. The multifractal feature parameters in the positive half cycle

| Type   | N  | G   | M   | P   |
|--------|----|-----|-----|-----|
| $\alpha_{\min}$ | 0  | 0.57| 0.62| 1   |
| $f(\alpha_{\min})$ | 0  | 0   | 0   | 0.31|
| $\alpha_{\max}$ | 0  | 1.77| 2.04| 3.07|
| $f(\alpha_{\max})$ | 0  | 0.5 | 0.51| 0   |
| $\alpha(0)$ | 0  | 1.37| 1.62| 2.16|
| $f(\alpha(0))$ | 0  | 1.29| 1.31| 1.96|
| $\Delta \alpha$ | 0  | 1.2 | 1.38| 2.07|
| $\Delta f$ | 0  | 0.5 | 0.51|-0.31|

3.2. Feature extraction

In order to compare the characteristics of the multifractal spectrum, the feature parameter of the extracted multifractal spectrum is normalized by equation (2):

$$L_i = \frac{|X_{i_{\max}} - X_{i_{\min}}|}{X_{i_{\max}}}$$

Figure 4 shows the distribution interval of multifractal spectrum feature parameter $L_i$ after normalization. It can be seen that the feature parameters under different insulation defects are distributed in the certain region, indicating that the probability distribution characteristics of PD on the $\varphi$-$u$ plane are varied.

![Figure 4](image_url)

**Figure 4.** The distribution interval of multifractal spectrum feature parameter

4. Pattern recognition

The multifractal spectrum feature components $L_1, L_2, ..., L_{16}$ are extracted as the identification feature, and the BP neural network with 16 input nodes and 4 output nodes (4 internal PD types of GIS) is used as classifier to identify the PD types caused by different insulation faults. The learning algorithm uses the improved conjugate gradient algorithm.

The feature samples extracted from the experimental data of the original PD grayscale image are screened to form the sample library. Each mode sample is composed of feature samples of the multifractal spectrum under different test voltages, and a total of 120 samples are obtained. Then, 100 samples from each defect database are selected to form the training sample to train the algorithm, and the remaining 20 samples are used to test the algorithm. To obtain better recognition effect, the selected
training samples need to be representative, and each mode needs to select certain number of training samples under the test voltage at all levels.

The feature recognition effect of multifractal spectrum and simple fractal is shown in Table 3. The simple fractal feature uses fractal theory to extract various fractal dimensions of PD grayscale image, which is one of the commonly used recognition features of PD pattern recognition. Multifractal spectrum employ the features of PD grayscale image.

It can be seen from Table 3 that the recognition rate of the four defects using multifractal spectrum is more than 87%, the recognition effect is favorable, indicating that the pattern recognition method proposed in this paper can effectively distinguish PD types. Compared with simple fractal, multifractal spectrum has higher recognition rate. For the similar grayscale images like G-type and M-type defects have significantly higher recognition rate by multifractal spectrum. In addition, the identification method of multifractal spectrum can be used not only for PD original grayscale image constructed by optical signal, but also for PD original grayscale image constructed by electrical signal.

Table 3. Comparison of PD recognition results based on different method

| Type | Simple fractal | Multifractal spectrum |
|------|----------------|-----------------------|
| N    | 91.7%          | 97.5%                 |
| G    | 74.2%          | 91.7%                 |
| M    | 76.7%          | 87.5%                 |
| P    | 93.3%          | 95.8%                 |

5. Conclusions
The optical signals of PD under four typical defects of GIS are obtained by fluorescent fiber sensing system, and the four kinds of grayscale images are established. The difference of optical signal is significant under the four different insulation defects. So the optical signal can be used to distinguish the PD types. The multifractal spectrum feature parameters of the grayscale images are extracted. The BP neural network is used to identify the PD types. The recognition rate of all kinds of defects by multifractal spectrum is more than 87%, and it is favorable. The ability of distinguish PD types by multifractal spectrum is stronger than simple fractal features.

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