A Study on the Extraction Method of Partial Discharge Features in Gas Insulated Switchgear Based on Ultra-High Frequency Signal Envelope

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Abstract. Because the UHF detection method has the advantages of wide detection range and high sensitivity, it is of great significance for partial discharge detection and defect type identification in gas insulated electrical equipment. Therefore, this paper proposes a new type of partial discharge UHF signal pattern recognition algorithm, which can effectively identify the type of partial discharge defects. The low frequency signal modulated by high frequency signal is demodulated by Hilbert transform. This paper presents a method to extract the time domain characteristics of UHF signals emitted by gas insulated switchgears (GIS) partial discharge (PD). By using the Hilbert transform, the envelope of partial discharge signal can be obtained, and then the key points related to features in time domain can be obtained. The artificial insulation fault test platform is developed. Experimental data of three typical partial discharge signals are obtained, and the algorithm is analyzed and verified. The result shows that the method can recognize different types of PD well. So it is practical and effective.

1. Introduction

Gas insulated switchgear (GIS) has the advantages of small occupancy space and high reliability, and has been widely used in the electric power system [1]. However, the consequences of a GIS failure can be quite severe.

Partial discharge (PD) monitoring is an important method to detect early insulation defects in GIS and prevent serious accidents. Among many monitoring methods of GIS partial discharge [2], the UHF (Ultra-High Frequency) method has the advantages of high sensitivity, strong anti-interference, fault identification and accurate localization of partial discharge. In the past 20 years, it has become a hot topic of research in the world [3], [4].

Currently, the partial discharge identification methods which commonly used are mainly based on PRPD [5], [6], which contains no PD pulse waveform pattern and needs the synchronization signal of power voltage.

In this paper, a PD type identification method based on PD pulse waveform pattern is proposed. This method does not need the synchronous signal. The main idea of this method is to regard the PD UHF signal as a low frequency pulse signal modulated by high frequency signal. Then we use the envelope signal feature extracted before to identify uhf partial discharge signal with the pattern recognition tool.
2. Extraction of UHF Signal Envelope Features

The process of extracting envelope characteristics of UHF signals mainly includes three steps:

1) Waveform filtering and noise reduction, 2) Acquisition of signal envelope, 3) Envelope characteristic parameter extraction.

2.1. Waveform Filtering and Noise Reduction

Spectral analysis of three typical PD signals (creep discharge, floating electrode and free metal particles) is performed, as shown in figure 1.

![Figure 1](image_url)

(a) Creeping discharge  (b) Floating electrode  (c) Free metal particles

**Figure 1.** Typical discharge signal spectra

It can be seen from figure 1, the spectral distribution of several typical discharge signals has the following characteristics:

1) The frequency composition of PD signals of each types is similar below 300MHz, thus it cannot be used to distinguish PD types.

2) According to the experiments, the maximum spectrum amplitude (about 870MHz) of PD signals generated by free metal particles and floating electrode corresponds to the noise band;

3) The influence of frequency component at 900MHz or higher on the envelope of time-domain waveform is not obvious, thus it cannot be used to distinguish PD types.

2.2. Signal Envelope Acquisition [7], [8]

The effective spectral range of PD signals detected by UHF method is 300MHz-1.5GHz. The envelope line is needed to represent the overall trend of high-frequency signals in the time domain [9].

The commonly used envelope signal acquisition methods include Hilbert transform, detection-filtering method, high-pass absolute value demodulation method and spline curve method. This paper adopts Hilbert transform to obtain UHF signal envelope. Hilbert transform is a kind of transformation from time domain to time domain. It is widely used in signal processing.

Consider a continual time domain signal \( x(t) \). Its Hilbert transform \( H[x(t)] \) is defined as the convolution of \( x(t) \) and function

\[
h(t) = \frac{1}{\pi t}
\]

that is

\[
\hat{x}(t) = H[x(t)] = x(t) \ast h(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} x(\tau) \cdot \frac{1}{t - \tau} d\tau
\]

(1)
The analytical signal of the original signal \( x(t) \) is defined by formula:

\[
a(t) = x(t) + j\hat{x}(t)
\]

The modulus of analytical signal

\[
E(t) = |a(t)| = \sqrt{x^2(t) + \hat{x}^2(t)}
\]

is also the envelope of \( x(t) \).

For a discrete sequence \( x(t) \) with a length of \( m \) and its FFT sequence \( X(k) \), we have

\[
A(k) = \begin{cases} 
X(k), & k = 0 \\
2X(k), & k = 1, 2, 3, \ldots, \frac{m}{2} - 1 \\
0 & k = \frac{m}{2}, \frac{m}{2} + 1, \ldots, m - 1
\end{cases}
\]

where \( A(k) \) is the FFT sequence of discrete analytical signal \( a(n) \) of \( x(n) \).

The envelope \( E(n) \) can then be obtained by calculating the modulus of \( A(k) \)'s IFFT sequence, IFFT[•] perform the inverse fast Fourier transform.

\[
E(n) = |a(n)| = |\text{IFFT}[A(k)]|
\]

2.3. Extraction of Envelope Features

The UHF signal envelope is obtained by Hilbert transform. As figure 2 shows, this paper is extracting 5 featuring voltage values of UHF PD envelope: the pulse peak \( V_{\text{top}} \), the first trough after the peak \( V_{t1} \), crest after the peak \( V_{p1} \), the second trough after peak \( V_{t2} \) and the second crest after peak \( V_{p2} \).

![Figure 2. UHF PD Envelope and Its Features](image)

2.4. Extraction of Envelope Features

Considering the calculation speed, algorithm efficiency and intuitiveness, the three optimal differential features are used to establish the feature space. That is, 3 variates in the set \( \{V_{\text{top}}, V_{p1}, V_{t1}, V_{p2}, V_{t2}\} \) will be chosen as axes \( \{x, y, z\} \) of a 3-dimensional feature space.

Now we introduce the “difference” of two scalar random variables \( a \) and \( b \) in a same dimension:

\[
D_{ab} = \frac{\hat{\lambda}_a - \hat{\lambda}_b}{\sigma_a + \sigma_b}
\]
Where $\bar{\lambda}_a$ and $\bar{\lambda}_b$ are respectively the expectations of $a$ and $b$; $\sigma_a$ and $\sigma_b$ are respectively standard deviations of them. The larger the $D_{ab}$ is, the less $a$ and $b$ are overlapped.

3. Experiments and Results

3.1. Experiment Design

In order to verify the effectiveness of our method, a PD detection platform is built in GIS to simulate three kinds of insulation defects: creep discharge, free metal particles and floating electrode. In this experiment, UHF PD signals with the above defects are sampled.

The experiment platform consists of a power unit, an experimental model and a PD detection device. The system structure is shown in figure 3.

![Figure 3. Diagram of Experiment System](image)

The power supply unit consists of console, voltage regulator, test transformer and protective resistor. The testing transformer is a 50Hz PD-free testing transformer; the protection of resistance is 5kΩ, used to limit the current flashover; the capacitance of the coupling capacitor is 1000pF. The PD electromagnetic signal sensor adopts a double helix Archimedes antenna with a bandwidth of 300MHz-1.5GHz. PD signal samples with three artificial insulation defects are obtained, namely creep discharge, floating electrode and free metal particles. The filtered waveforms are shown in figure 4.

![Figure 4. UHF PD signal examples](image)

Using the algorithm introduced above to treat these signals. The features are extracted, as shown in figure 5. Type 1, type 2 and type 3 defects in the figures are respectively creeping discharge, floating electrode and free metal particles. The statistical parameters of the four features are shown in Table 1.

The “differences” of each feature for different PD signal pairs are calculated in Table 2. Then we can discard one of the features and calculate several sums of “differences”. The minimums of the sums can be considered to have "worst differentiation" and is highlighted by the parentheses in Table 3.
Figure 5. Feature Distributions of UHF PD envelopes

Table 1. Feature Distributions of UHF PD envelopes

| PD Type          | PARAMETER    | $V_{v1}/V_{top}$ | $V_{p1}/V_{top}$ | $V_{v2}/V_{top}$ | $V_{p2}/V_{top}$ |
|------------------|--------------|------------------|------------------|------------------|------------------|
| Creeping Discharge| Mean         | 0.2881           | 0.5332           | 0.0638           | 0.3303           |
| Discharge         | Std. Dev.    | 0.0432           | 0.0255           | 0.0237           | 0.0227           |
| Floating Electrode| Mean         | 0.1810           | 0.5214           | 0.1358           | 0.3874           |
| Electrode         | Std. Dev.    | 0.0440           | 0.0431           | 0.0477           | 0.0156           |
| Free Metal Particles| Mean         | 0.1133           | 0.4377           | 0.2443           | 0.3237           |

Table 2. The “Differences” Of Each Feature For Different PD Pairs

| PD Pair                        | $V_{v1}/V_{top}$ | $V_{p1}/V_{top}$ | $V_{v2}/V_{top}$ | $V_{p2}/V_{top}$ |
|-------------------------------|------------------|------------------|------------------|------------------|
| Creeping discharge & Floating electrode | 1.2285           | 0.1716           | 1.0082           | 1.4932           |
| Floating electrode & Free metal particles | 0.6528           | 1.0149           | 0.8089           | 0.7310           |
| Free metal particles & Creeping discharge | 1.6987           | 1.4725           | 1.6389           | 0.0697           |

Table 3. “Difference” Sums With Different Features Discarded

| PD Pair                        | $V_{v1}/V_{top}$ | $V_{p1}/V_{top}$ | $V_{v2}/V_{top}$ | $V_{p2}/V_{top}$ |
|-------------------------------|------------------|------------------|------------------|------------------|
| Creeping discharge & Floating electrode | 2.67             | 3.73             | 2.89             | (2.41)           |
| Floating electrode & Free metal particles | (2.55)           | 2.89             | 3.09             | 3.17             |
| Free metal particles & Creeping discharge | 3.18             | 2.43             | (2.26)           | 3.83             |

*Bracketed: “worst differentiation” in feature pair (row).
$V_{v1}$ and $V_{v2}$ are respectively the voltage of the first trough and second through after peak of an oscillating pulse, $V_{p1}$ and $V_{p2}$ are respectively the voltage of the first crest and second crest after peak of an oscillating pulse, $V_{top}$ is the peak voltage of an oscillating pulse. It is obvious from Table III that the only column without any parentheses is the second column, i.e. the $V_{p1}/V_{top}$ column. This means that with feature $V_{p1}/V_{top}$ discarded, the combination of $V_{v1}/V_{top}$, $V_{v2}/V_{top}$ and $V_{p2}/V_{top}$ better differentiates the PD types. Take these three features as the coordinates of a three-dimensional space and collect the PD signals into three distinct clusters [10], as shown in figure 6.

**Figure 6.** Distribution of data points in 3-dimensional space

Using three-layer BP neural network (NN) can identified three types of PD. The identification result is in the form of NN confusion matrix, as shown in table 4.

**Table 4.** Confusion Matrix Of The BP Network

| Predicted       | Creeping discharge | Actual Floating electrode | Free metal particles | Correct rate |
|-----------------|--------------------|----------------------------|----------------------|--------------|
| Creeping discharge | 42.6%              | 0.1%                       | 0.0%                 | 98.8%        |
| Floating electrode | 0.5%              | 44.2%                      | 0.5%                 | 97.8%        |
| Free metal particles | 0.0%              | 0.0%                       | 11.7%                | 100%         |
| Recognition Rate | 98.8%              | 98.9%                      | 95.8%                | 98.5%        |

Abbreviations: CD – Creeping Discharge; FE: Floating Electrode; FMP: Free Metal Particles.

4. Conclusion

This paper uses neural network to analyze GIS partial discharge identification technology based on UHF signal envelope features. The following conclusions can be drawn:

(1) The Hilbert transform can obtain the envelope of UHF PD signals in GIS. The PD types can be distinguished effectively by the envelope features extracted in this article.

(2) The experiment shows that the feature extraction proposed in this paper can accurately identify three typical insulation defects in GIS by using neural network.

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