Time Domain Feature Extraction Technology of Partial Discharges Based on the Envelope of UHF Signal

Hui HUANG, Feng HUANG, Chunlong LI and Zhen LI

ABSTRACT

This paper proposed a method to extract the time-domain features of ultra-high frequency (UHF) signals regarding the partial discharges (PD). Using the Hilbert transform, the envelope of a PD signal can be solved since the low-frequency signals modulated by high-frequency signals can be demodulated through Hilbert transform. Then the characteristic parameters of some key time domains would be obtained from the extracted envelope signal. An experimental platform for the detection of artificial insulation faults was designed and established. Three types of typical PD signals were generated and used for the verification of our presented algorithm. The result shows that different types of PDs could be accurately recognized.

INTRODUCTION

Partial discharge (PD) monitoring and identification in a power equipment is an important means of finding the incipient insulation faults and preventing the accidents. Among various methods for monitoring the PD signals of power equipment, the ultra-high frequency (UHF) method has high sensitivity and strong anti-interference performance. Moreover, it can identify the fault type and precisely locate the PDs. The UHF method has become a hotspot during the past two decades [1-3]. The insulation defects in a power equipment have different types, such as the floating electrodes, free metallic particles and the contamination on the surface of insulators. Since different defects have various discharge characteristics and impose different degrees of damages on the power equipment, an accurate assessment of the insulation status is of great importance.

Until now, the most used method of PD pattern recognition is based on the phase distribution spectra [4]. However, this kind of method doesn’t take any waveform information of PD pulses into consideration. Besides, the requirement of phase synchronization information of power frequency increases the system complexity and error.
In this paper, we proposed a novel PD recognition method based on the time domain single of PD pulses which requires no phase synchronization information. The main idea of this method is that the UHF signals of PDs are regarded as the low frequency pulse signals modulated by the high frequency signals. Therefore, a Hilbert transform is adopted to demodulate the low frequency signals to form the envelope of detected PD signal. Then the recognition of UHF PD signals can be achieved by extracting their corresponding envelope characteristics.

ENVELOP CHARACTERISTIC EXTRACTION FOR UHF SIGNALS

Enveloping PD signal

Using the UHF method, the effective frequencies of the measured PD signals generally range from 300 MHz to 1.5 GHz, i.e., they can be regarded as the high frequency oscillation signals. To gain an insight into the overall tendency of the high frequency signals in time domain, we should acquire the signal's envelope.

The common methods for extracting the signal envelope include Hilbert transform, demodulation filtering method, high pass absolute value demodulation and spline curve method. Demodulation filtering method extracts the envelope with respect to the middle line of the signal's positive half cycle, while the high pass absolute value method extracts the envelope regarding the signal's middle line. Thus, both methods cannot acquire the actual signal envelope. The principle of the interpolation point selection can hardly be determined for the spline curve method which has poor adaptability to various types of signals. Hence it was not adopted in the present work.

For a signal $x(t)$ with continuous time domain, the Hilbert transform is defined as the convolution of this signal with $h(t)=1/t$, i.e.,

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

(1)

The analytic signal of the original signal $x(t)$ is defined as:

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

(2)

The modulus of the analytic signal can be written as:

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

(3)

which is exactly the envelope of the original signal $x(t)$.

For a discrete signal sequence $x(n)$ with the length of m and the corresponding sequence $X(k)$ after fast Fourier transform (FFT), there is
$$A(k) = \begin{cases} X(k), & k = 0 \\ 2X(k), & k = 1, 2, 3, \ldots, \frac{m}{2} - 1 \\ 0 & k = \frac{m}{2}, \frac{m}{2} + 1, \ldots, m - 1 \end{cases}$$

(4)

where \(A(k)\) denotes the FFT sequence corresponding to the discrete analytic signal \(a(n)\) in \(x(n)\).

After the inverse fast Fourier transform (IFFT) on the acquired \(A(k)\), the modulus was solved. Thus the envelope signal \(E(n)\) can be obtained:

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

(5)

**Characteristic parameters extraction**

After obtaining the envelopes of UHF signals through Hilbert transform, we can observe that the envelopes of different types of PD signals are similar to the double exponential function of an attenuated vibration in waveform, but have obvious differences in oscillation frequency and attenuation time constant. The types of PD signals can then be identified by extracting the data at several key points.

As shown in Fig. 1, we preliminarily extracted five characteristic values of the envelope of UHF PD signals. They are pulse peak \(V_{\text{top}}\), the first wave trough after the peak \(V_{v1}\), the first wave peak after the peak \(V_{p1}\), the second wave trough after the peak \(V_{v2}\) and the second wave peak after the peak \(V_{p2}\).

![Figure 1. Envelope of UHF PD signal and its characteristics.](image)

The differences in the distance between PD source and sensor and in PD type will affect the amplitude of UHF signals. Therefore, the above described original characteristic values should be first normalized, and then can be used as the characteristic parameters of PD signals.

**Feature space construction**

With the computing speed and the algorithm's performance and intuitiveness taken into account, three characteristic parameters with the most favorable discrimination performance were selected to construct the feature space, i.e., to select three parameters with optimal discrimination performance in the set (6) as the \(\{x, y, z\}\) in feature space.

$$\frac{V_{v1}}{V_{\text{top}}}, \frac{V_{p1}}{V_{\text{top}}}, \frac{V_{v2}}{V_{\text{top}}}, \frac{V_{p2}}{V_{\text{top}}}$$

(6)
Then the concept of the differentiability of random variables was introduced. Definition of the differentiability of two random variables, \( a \) and \( b \), at the same dimension:
\[
D_{ab} = \frac{|\bar{x}_a - \bar{x}_b|}{\sigma_a + \sigma_b}
\]  
(7)

Suppose \( \bar{x}_a \) and \( \bar{x}_b \) denote the average values of the samples of two variables, respectively; \( \sigma_a \) and \( \sigma_a \) denote the standard deviations of the unbiased samples. The larger the value of \( D_{ab} \), the less likely the two characteristic parameters, \( a \) and \( b \), are confused.

It should be achieved as far as possible that the constructed 3D feature space is able to differentiate each type of PD signals, i.e., the emphasis should be laid on the global discrimination. Therefore, in the selection of characteristic parameters, we should follow the principle: the combination of the characteristic parameters with the poorest discrimination performance on the PDs of a certain or several types should be excluded. Accordingly, the differentiability of each type of PD signals at each dimension of characteristic parameter was calculated in this paper to select the optimal combination of feature space.

**EXPERIMENTS AND RESULTS**

**Experimental setup**

To examine the effectiveness of the proposed method, an experimental platform was established as shown in Fig. 2. Three defect samples were designed for simulating three types of typical insulation faults, namely, surface discharge, metal particles and floating potential.

![Experimental setup diagram](image)

**Figure 2. Illustration of the experimental system.**

The UHF signals of these three faults were obtained by the experiments as shown in Fig. 3.
According to the proposed method, the characteristic parameters of waveforms were extracted as shown in Fig. 4 where type 1, type 2 and type 3 denote the PD signals of the artificial defects surface discharge, floating potential and metal particles, respectively.

Figure 3. UHF PD signals after preprocessing.

Table 1 lists the statistics of these four characteristic parameters.
Table 1. Characteristic Parameters of Three Types of Typical PDs.

<table>
<thead>
<tr>
<th>Characteristic parameter</th>
<th>Surface discharge</th>
<th>Floating potential</th>
<th>Metal particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Term</td>
<td>$V_{v1}/V_{top}$</td>
<td>$V_{p1}/V_{top}$</td>
<td>$V_{v2}/V_{top}$</td>
</tr>
<tr>
<td>Average value</td>
<td>0.2881</td>
<td>0.5332</td>
<td>0.0638</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.0432</td>
<td>0.0255</td>
<td>0.0237</td>
</tr>
<tr>
<td>Average value</td>
<td>0.1810</td>
<td>0.5214</td>
<td>0.1358</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.0440</td>
<td>0.0431</td>
<td>0.0477</td>
</tr>
<tr>
<td>Average value</td>
<td>0.1133</td>
<td>0.4377</td>
<td>0.2443</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.0597</td>
<td>0.0394</td>
<td>0.0864</td>
</tr>
</tbody>
</table>

Table 2 gives the differentiability of each characteristic parameter of the PD signals of different defects.

Table 2. Differentiability of Characteristic Parameter.

<table>
<thead>
<tr>
<th>Characteristic parameter</th>
<th>Surface discharge floating potential</th>
<th>Floating potential metal particles</th>
<th>Metal particles surface discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{v1}/V_{top}$</td>
<td>1.2285</td>
<td>0.6528</td>
<td>1.6987</td>
</tr>
<tr>
<td>$V_{p1}/V_{top}$</td>
<td>0.1716</td>
<td>1.0149</td>
<td>1.4725</td>
</tr>
<tr>
<td>$V_{v2}/V_{top}$</td>
<td>1.0082</td>
<td>0.8089</td>
<td>1.6389</td>
</tr>
<tr>
<td>$V_{p2}/V_{top}$</td>
<td>1.4932</td>
<td>0.7310</td>
<td>0.0697</td>
</tr>
</tbody>
</table>

Table 3 reports the differentiability of different combinations of characteristic parameters. The bold denotes the poorest discrimination performance.

Table 3. Differentiability of Different Combinations.

<table>
<thead>
<tr>
<th>Differentiability</th>
<th>Surface discharge floating potential</th>
<th>Floating potential metal particles</th>
<th>Metal particles surface discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{v1}/V_{top}$</td>
<td>2.67</td>
<td>2.55</td>
<td>3.18</td>
</tr>
<tr>
<td>$V_{p1}/V_{top}$</td>
<td>3.73</td>
<td>2.89</td>
<td>2.43</td>
</tr>
<tr>
<td>$V_{v2}/V_{top}$</td>
<td>2.89</td>
<td>3.09</td>
<td>2.26</td>
</tr>
<tr>
<td>$V_{p2}/V_{top}$</td>
<td>2.41</td>
<td>3.17</td>
<td>3.83</td>
</tr>
</tbody>
</table>

As shown in Table 3, there is no bold value for $V_{p1}/V_{top}$. Therefore, the characteristic parameters with favorable discrimination performance are $V_{v1}/V_{top}$, $V_{v2}/V_{top}$ and $V_{p2}/V_{top}$. A specific 3D space could be built by these three characteristic parameters as the coordinates.

Using proposed characteristic parameters, even a simple three layers back propagation (BP) neural network can identify these three types of PD signals. The recognition results are shown in Table 4.
Table 4. Confusion Matrix Based on the BP Neutral Network.

<table>
<thead>
<tr>
<th>Output</th>
<th>Surface discharge</th>
<th>Floating potential</th>
<th>Metal particles</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface discharge</td>
<td>42.6%</td>
<td>0.1%</td>
<td>0.0%</td>
<td>98.8%</td>
</tr>
<tr>
<td>Floating potential</td>
<td>0.5%</td>
<td>44.2%</td>
<td>0.5%</td>
<td>97.8%</td>
</tr>
<tr>
<td>Metal particles</td>
<td>0.0%</td>
<td>0.0%</td>
<td>11.7%</td>
<td>100%</td>
</tr>
<tr>
<td>Recognition ratio</td>
<td>98.8%</td>
<td>98.9%</td>
<td>95.8%</td>
<td>(98.5%)</td>
</tr>
</tbody>
</table>

As shown in Table 4, the pattern recognition performance is favorable. Therefore, the selected characteristic parameters in this paper are of great help to effective PD recognitions.

CONCLUSIONS

In this paper, the algorithm for extracting the envelopes of UHF signals is proposed and the corresponding envelope characteristic parameters were investigated. Together with neural network, we also proposed a PD recognition technique based on the envelope characteristics of UHF signals. The experiment proved that the envelopes of UHF PD signals abstracted by Hilbert transform can effectively characterize different types of PDs.

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REFERENCES