Automatic partial discharge detection method of traction transformer based on wavelet transform

Jiyoung Liu*, Xin Wang, Shengchun Yan, Yan Fan, Changjin Hao

1 Shuohuang Railway Development Co, Ltd, Shuozhou 036002, China
2 Institute of Energy Sensing and Information, Sichuan Energy Internet Research Institute, Tsinghua University, Chengdu 610000, China

1981ljy@163.com

Abstract. Partial discharge parameter acquisition and storage of transformer lacks the setting of time threshold, which leads to the low reception rate of transformer discharge signal. An automatic detection method of partial discharge of transformer in substation based on wavelet transform is studied. By analyzing the ultrasonic waveform of discharge signal, the partial discharge parameters of transformer in high voltage substation are extracted. According to the principle of wavelet transform, the time threshold is set, the extracted parameters are collected and stored in sections, and the automatic detection algorithm of partial discharge parameters is established. By deriving the results, the automatic detection of partial discharge is completed. At this point, the design of automatic detection method for partial discharge of transformer in substation based on wavelet transform is completed. Analysis of experimental results: Through comparative experiments, it is found that the highest discharge signal receiving rate of this method is 87.5%, which is superior to other methods and has high application value.

1. Introduction

In the traction power supply system, the transformer plays an important role in the stable output of power, and its stable operation is of great significance to the safety of the power system. Statistics show that transformer faults are mostly caused by insulation problems[1]. Partial discharge of transformer is an important cause of insulation failure. Partial discharge will cause aging or breakdown of transformer insulation parts, which will greatly threaten the service life and operation reliability of transformer, and then affect the stability and reliability of power transmission in the power system. If the partial discharge of the transformer can be found in time, the cause and location of the fault can be determined, and the transformer can be repaired in time, the operation safety and reliability of the transformer can be greatly improved, and the transformer accidents caused by transformer insulation failure can be avoided[2].

At present, there are non-electric measurement and electric measurement methods to locate the discharge position. When partial discharge occurs in the high voltage transformer, it will be accompanied by abnormal phenomena of sound and heat. Parameters can be obtained by ultrasonic sensor, based on which partial discharge location can be carried out[3-4]. Electric measurement method mainly uses pulse current test to locate, although this method has high accuracy but is susceptible to environmental interference[5]. As for the localization algorithm of partial discharge of transformer, literature [6] proposed that in the substation environment with more uncontrollable interference, the optimal identification parameters were obtained by using the node training of network layer to realize
partial discharge identification of substation by utilizing the self-organizing competitive identification and strong anti-interference characteristics of Kohonen network. Literature [7] proposes to use generalized regression neural network and received signal amplitude intensity fingerprint for partial discharge location. Firstly, the fingerprint is established and solved by generalized regression neural network to complete detection and location. However, due to the lack of time threshold for the segmented acquisition of transformer partial discharge parameters, the reception rate of transformer discharge signal becomes low. This paper studies the automatic partial discharge detection method of high voltage transformer, and proposes an automatic partial discharge detection method of transformer using wavelet transform method.

2. Design of automatic partial discharge detection method for transformer

2.1. Partial discharge parameter extraction

There are many partial discharge signal parameters of high-voltage transformer. The amplitude, time interval, energy, frequency and other parameters of parameter waveform can be directly obtained from the ultrasonic waveform of discharge signal [8]. However, the availability of the parameters obtained by the waveform itself is poor. When the partial discharge intensity is large, the time interval of the waveform will be affected. Therefore, this type of parameter has certain limitations. This paper will not consider using this type of parameter for data analysis. Some potential parameters of ultrasonic can also be obtained by indirect means, and the waveform of Partial Discharge Ultrasonic of substation transformer can be converted and calculated to read [9]. For example, through spectrum calculation, parameters such as power spectrum value, frequency of power spectrum, average value of power spectrum, median value of power spectrum and so on of Partial Discharge Ultrasonic of substation transformer can be obtained, Parameter clusters such as square root, square difference and root mean square are obtained by statistical algorithm [10], which can avoid the impact of time interval and improve the availability of data.

By using the principle of wavelet transform, the local discharge times of transformer can be easily extracted. Every impact of ultrasonic wave is caused by discharge [11], the number of discharge times can be counted by counting the impact time of ultrasonic wave. Partial discharge diagram of transformer is shown in Figure 1.

![Partial discharge concept map of transformer](image_url)

Figure 1. Partial discharge concept map of transformer

According to Figure 1, when the impact time of discharge ultrasonic exceeds the pulse cycle of partial discharge, two discharge reactions will occur, but only one set of parameters will be generated. When the impact time of discharge ultrasonic is less than the pulse period of partial discharge, it will also produce two discharge reactions, but two groups of parameters will be generated. Therefore, the same number of discharge signals may contain different groups of parameters, which means that the length of impact time determines the extraction accuracy of ultrasonic parameters, and the less discharge parameters will be obtained with the increase of impact time. Therefore, setting the exact impact time is of great significance to the extraction of discharge parameters. Table 1 shows the
corresponding relationship between the modulation value of wavelet transform and the number of discharges.

### Table 1 Partial discharge times

| Modulation value | Effective discharge times | Invalid discharge times |
|------------------|---------------------------|-------------------------|
| 1                | 324                       | 271                     |
| 2                | 312                       | 254                     |
| 3                | 276                       | 76                      |
| 4                | 259                       | 57                      |
| 5                | 237                       | 21                      |

According to the data in Table 1, the larger the set value of ringing, the greater the proportion of effective discharge. If conditions permit, continue to increase the set value of ringing count, the proportion of effective discharge will continue to increase. However, if the setting of ringing times is too large, it may lead to some unnecessary errors, so the ringing count is modulated to 5. Partial discharge parameters are a relatively stable signal in a small space, but when ultrasonic testing the location of partial discharge, due to the strong variability and randomness of partial discharge, in order to reduce the difficulty of extracting partial discharge parameters, control the spectral distribution of partial discharge and make it tend to a stable state. The partial discharge parameters of transformer in high voltage substation are extracted and processed based on wavelet transform, and then the discharge parameters are stored in sections.

#### 2.2. Partial discharge parameter extraction

The types of signals that can be detected due to partial discharge parameters are called Duoduo, such as ultrasonic signals, high-frequency signals, UHF signals, etc. The above signals have different frequency bands and sampling frequencies. The discharge parameters of these signals are collected and stored. Some signals only need very low sampling frequency, and some signals need very high sampling frequency. Various types of discharge parameters can be processed based on wavelet transform. When collecting discharge parameters at low speed, there is little demand for data storage. At this time, the time threshold can be set. If the sampling time triggers the threshold, the collection will stop. Then it is necessary to process the above collected discharge parameters, continue to collect the discharge parameters, and continue the cycle. Finally, the collection of all partial discharge parameters will stop. Partial discharge will lead to high-frequency electromagnetic wave at the local position of the transformer, up to hundreds of MHz. When the instantaneous voltage to ground in the transformer is generated in the metal enclosure, the electromagnetic wave signal is difficult to capture and collect. Therefore, the signal shall be captured through a special capacitor and detector, and the detector shall be installed on the outer surface of the collector. According to the detector, the transformer discharge signal is captured and the detection medium in the transformer is analyzed.

![Figure 2. Effect of transient on partial discharge](image)

There are two kinds of media in the transformer, I and II. Medium II represents the metal conductor material, and the interior of the transformer is divided into two parts through the metal inner wall. The process of forming transient effect on partial discharge is shown in Figure 2.

In Figure 2, $H^+$ and $H^-$ represents incident electromagnetic wave and reflected electromagnetic wave respectively. The electric field intensity of incident wave and reflected wave is $E$ respectively $^+$ and $E^-$. The two values are opposite in phase and the absolute values are not equal. So we know the critical surface ($X=0$)$E^++E=0$. Magnetic field $H(x, t)$ at position $x$ can be expressed as:
\[ H(x,t) = H^+(x,t) + H^-(x,t) \]  
(1)

Where, \( H^+(x,t) \), \( H^-(x,t) \) respectively represent incident and reflected magnetic fields, and the relationship between them and electric field intensity \( E \) is:

\[
\begin{align*}
H^+(x,t) &= \frac{E^+(x,t)}{Z_{02}} \\
H^-(x,t) &= -\frac{E^-(x,t)}{Z_{02}}
\end{align*}
\]  
(2)

Where, \( Z_{02} \) is the wave impedance of the medium.

The discharge pulse current is:

\[ I = I_0 \exp \left( -\frac{4\pi(t-t_0)^2}{t^2} \right) (H^+(x,t) - H^-(x,t)) \]  
(3)

Where, \( \phi \) is a constant; \( I_0 \) is the pulse peak value, which is the maximum value. At this time, \( t = t_0 \).

Partial discharge signal has periodic characteristics. When the signal period is less than the sampling time, the characteristics of the signal can be fully collected. When the period is greater than the sampling time, the integrity of the collected signal is insufficient. If the partial discharge signal meets the requirements of acquisition frequency, the continuous signal will have a large amount of acquisition data, and has high requirements for the capacity of storage equipment. Its cost will be very high, resulting in lack of economy.

![Diagram](image)

Figure 3. The process of subsection collection and storage of discharge parameters

There are mainly two methods to collect and process partial discharge signals: the first is to collect signals according to the form of signal envelope, so it is necessary to further compress the collected high-frequency signals, so as to obtain the sampled low-frequency signals. Although this method can solve the problem of too low storage capacity, the collected signal is missing some information, that is, after envelope acquisition, it will cause the loss of some important information. The second method is to use ultra-high speed subsection acquisition technology to collect UHF signals in partial discharge. The partial discharge signal obtained by this acquisition method can collect and process the collected matching signal, and then store the partial discharge parameters in this section, which can fully show the characteristics of the original signal. If it is necessary to collect and store segmented data, data can be obtained on a first in first out basis. The implementation process is shown in Figure 3.

2.3. Establish automatic detection algorithm for pd parameters

According to the collected and stored partial discharge parameters, based on wavelet transform and the theory of synchronous acquisition technology, the initial phase can be obtained by automatically detecting and calculating the synchronously collected partial discharge parameters, and the partial discharge parameters can be further obtained. After setting the number of partial discharge pulses of the system, start the synchronous power frequency sampling operation to locate the position of each power frequency sampled partial discharge pulse. Then, the position is used to divide the sampled partial discharge pulses, corresponding to different calculation parts. Calculate the local pulse group of each section according to the phase angle of the first pulse signal, check the time difference between
the first pulse and a single pulse, and select the check standard as the power frequency of the measured pulse group. Calculate the phase value of a single pulse:

$$\varphi_i = 2\pi f (\Delta t) + \varphi_0$$  \hspace{1cm} (4)

Where, $\varphi_i$ is the phase angle of the $i$th pulse signal, $f$ is the actual power frequency voltage frequency of the site, $t_i$ represents the initial moment of the $i$th pulse signal in the paragraph, $t_0$ represents the initial moment of the first pulse signal in the segment, $\varphi_0$ represents the phase angle of the first pulse.

In the low-frequency signal, the power frequency sampling signal is processed by filtering, and the zero crossing detection method is used to detect the zero crossing in ten cycles, and the corresponding zero crossing cycle is obtained. Therefore, the real-time frequency of power frequency signal can be obtained. Finally, according to the principle of wavelet transform, the initial phase value of power frequency signal is obtained. When sampling and processing the voltage value, the voltage function is assumed to be periodic, and only the sinusoidal odd harmonic part is considered. The voltage value is expressed by wavelet transform. Because the voltage value obtained by sampling processing is in a closed linear space, after using the partial discharge parameter self-test method, the above variables become a group of orthogonal bases and are in a closed linear space, that is, the algorithm of automatic partial discharge detection can be obtained. According to the self-test algorithm, the automatic partial discharge detection results are calculated, and the calculated self-test results are derived from the constructed path.

2.4. Build the detection result export path

After the calculation of the automatic calculation algorithm of partial discharge parameters, the calculated automatic partial discharge detection results are exported. Firstly, the result export path should be constructed. It is known that when partial discharge occurs in the transformer, the current is relatively large, resulting in electromagnetic waves and pulse signals generated by partial discharge at each port of the transformer. These signals will propagate in four directions in the complex structure inside the transformer. The electromagnetic waves and pulse signals in the transformer are induced by the propagation law of partial discharge signal. An ultrasonic sensor is installed in the external structure of the transformer to detect the discharge parameters. The discharge parameters, the propagation time of ultrasonic wave and the propagation speed in the transformer shell and medium are counted and calculated, so as to realize the positioning of partial discharge.

Therefore, the propagation characteristics of longitudinal wave and transverse wave of transformer ultrasonic wave are used for detection, combined with the physical properties of propagation medium, the propagation velocity of ultrasonic wave in the inner wall is measured, and the difference between the propagation velocity of longitudinal wave and transverse wave is calculated. According to the signal transmission interval of longitudinal wave and transverse wave, judge the sequence of signals received by the partial discharge sensor outside the transformer. Considering the attenuation effect of propagation in different media and rapid attenuation in the inner wall, combined with this property, the automatic detection of partial discharge can be realized. The export path of partial discharge self-test results is shown in Figure 4.

![Figure 4. Derivation path of partial discharge self test results](image)

When the ultrasonic sensor receives the partial discharge signal, the converter is used to convert the discharge signal into position signal, and the display is used to display the signal and display the partial discharge detection results, so as to realize the purpose of transformer partial discharge self-test.
by wavelet transform, and complete the method and function design of transformer partial discharge self-test based on wavelet transform.

3. Experimental Analysis
The wavelet transform based partial discharge automatic detection method and the traditional method 1 are used respectively[8] and traditional method 2[9]. The advantages of the automatic detection method are verified by comparing the receiving rate of transformer discharge signal between the three.

3.1. Experimental preparation
Velocity of propagation of partial discharge measurement in the first place, and in the complex environment of transformer, the spread of the discharge signals will alternate in solid media and liquid media transmission, the isolation of two kinds of medium stage will cause the change of discharge signal propagation speed, the sound propagation speed is 1.42 km/s discharge signals receiving rate calculation. Since the conversion time of discharge signal between medium and medium can not be calculated accurately, the receiving rate error of discharge signal will be generated. The error range of the positioning method can be calculated by using the positioning equation. The three-dimensional coordinate was established. Assuming the location of partial discharge as the origin, a point in the coordinate was taken as the position of the ultrasonic sensor. The three-dimensional coordinate system was regarded as a cube, and then the cube was divided into 100 equal parts. Establish the function as follows:

$$ V_i = \sum_{l=1}^{10} \left( \frac{\sqrt{S_l - S}}{V} \right)^l $$

Where, $l$ is the point variable, $S_l$ is the right $x$-axis coordinate value of the discharge coordinate point, $S$ is the left $x$-axis coordinate value of the discharge left point, and $V$ is the $Y$-axis coordinate.

The partial discharge phenomenon is detected according to the phase distribution and band characteristics of UHF. When the signal is detected, the interference noise signal needs to be separated. Then UHF and ultrasonic methods are used to accurately determine the receiving rate of discharge signal, or multiple groups of acoustic emission sensors are used to accurately locate the source. The defect type can be determined by using the phase characteristics, and the reception rate of discharge signal can be determined by combining the discharge type, discharge position, signal strength and severity. The automatic detection method proposed in this paper is used to receive and process the same discharge signal respectively as traditional method 1 and traditional method 2, and the reception rate of discharge signal is calculated.

3.2. Comparison of receiving rate of transformer discharge signal
The receiving rate of discharge signal designed by traditional method 1, traditional method 2 and automatic partial discharge detection method of transformer based on wavelet transform is shown in Figure 5.

![Figure 5. Receiving rate of discharge signal of transformer](image-url)
It can be seen from the data in Figure 8 that during the self inspection of transformer discharge signal in traditional method 1, the reception rate of discharge signal is generally above 37.5%, the highest reception rate of discharge signal is 49%, and the lowest reception rate of transformer discharge signal is 37.5%. In traditional method 2, when performing self inspection of transformer discharge signal, the receiving rate of discharge signal is generally above 50%, the highest receiving rate of discharge signal is 62.4%, and the lowest receiving rate of transformer discharge signal is 48%. When the automatic partial discharge detection method of substation transformer based on wavelet transform is used for self inspection of transformer discharge signal, the receiving rate of discharge signal is generally above 75%, the highest receiving rate of discharge signal is 87.5%, and the lowest receiving rate of transformer discharge signal is 68.25%. Therefore, the method designed in this paper has superior performance.

4. Conclusion
The method presented in this paper can fully process the discharge signal data, effectively eliminate the relevant interference on site, and improve the quality and efficiency of partial discharge charged detection. But partial discharge detection is only a means of detection. Based on the theory and standard management method, the abnormal state of the equipment is systematically analyzed, and the important significance of partial discharge detection in the early warning and forecast of power system is realized from the serious influence caused by the abnormal equipment.

References
[1] Hou Rui, Yang Xuebao, Zhao Jianli. On line detection of partial discharge on insulated surface of cables in switchgear[J]. Jiangxi Electric Power, 2020, 44(12): 20-22.
[2] Yan Shuai, Li Pengyu, Wang Gaojie, et al. Discharge location method of open substation based on UHF wireless intelligent sensor array[J]. Electric Power, 2021, 54(02): 52-57.
[3] Zhou Bo, Gao Jun, Yang Hongquan, et al. Case Analysis on Suspension Discharge Defect of 220 kV GIS Disconnecting Switch[J]. High voltage apparatus, 2020, 56(12):313-317.
[4] Wei Wenting, Li Yue, Zhou Yu, Chen Yunfei, Wei Zhanpeng. The Partial Discharge Detection and Failure Analysis of 35 kV XLPE Cable[J]. Shandong Electric Power, 2020, 47(10): 39-44.
[5] Liu Hongliang, Ding Bin, Gao Shuguo, et al. Multi-terminal PD Detection Technology of Transformer Based on Wide Bandwidth Pulse Current Method[J]. High Voltage Apparatus, 2018, 54(11):241-246+252.
[6] Jiang Jiebo, Chen Ke, Shi Yonggui, et al. Partial discharge recognition of typical insulation defect based on Kohonen network[J]. Electric Power Engineering Technology, 2020, 39(05):43-48.
[7] Yu Qichen, Luo Lingen, Wu Fan, et al. UHF Partial Discharge Localization Methodology Based on Generalized Regression Neural Network[J]. Electric Power, 2021, 54(02): 11-17.
[8] Liu Qing, Chang Dingge, Deng Junbo. Optimal Selection on Spatial Spectrum Estimation Algorithms for UHF Direction Finding of Partial Discharge in Substation[J]. Transactions of China Electrotechnical Society, 2020, 35(16): 3551-3560.
[9] Li Ning, Hao Shuxing, Lei Yaoxu, et al. Research on partial discharge detecting repetitive-path problem in robot inspection[J]. Chinese High Technology Letters, 2020, 30(06): 615-625.
[10] Li Jie, Wang Lei, Wang Yingfang, et al. Research on partial discharge monitoring and localization method in an automatic directional way in substations[J]. Electrotechnical Application, 2020, 39(05): 23-28.
[11] Yu Qichen, Luo Lingen, Jia Yanbo, et al. Partial Discharge Positioning Technology in Substation Based on Received Signal Strength Indicator Statistical Analysis of UHF Signal[J]. High Voltage Engineering, 2020, 46(12): 4163-4171.