Research on PD monitoring and location method of automatic directional substation

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Abstract. The accurate positioning of partial discharge can effectively avoid the occurrence of insulation failure of power equipment, but most of the existing positioning devices are fixed antenna array, which is difficult to achieve multi angle discharge monitoring in space, and the positioning method is single and the positioning accuracy is not high. Therefore, this paper proposes an automatic directional monitoring device for partial discharge source, and proposes a precise positioning method based on fixed point iteration method. With this positioning method as the main method and the automatic directional device as the auxiliary method, the spatial multi angle positioning of partial discharge source is realized. Firstly, PD signal recognition algorithm is used to identify the fault of PD signal, and then the steering gear rotation angle is determined by the angle correlation calculation formula, so as to accurately identify the position and direction of PD source. On this basis, four antenna array positioning algorithm is used to accurately locate PD source. Finally, through the field simulation test, it is found that the angle error of automatic orientation is 3°. The position error of PD source is 0.19m, which verifies the feasibility of the proposed method and device.

1. Introduction
If the equipment has insulation defects and is not repaired in time, it will eventually lead to insulation breakdown, sudden power failure of equipment, resulting in power interruption and great loss. Moreover, data show that 90% of the power failure is originally caused by insulation defects of different reasons[1], and all insulation defects caused by partial discharge will occur. Therefore, partial discharge monitoring is conducted for the operating equipment, it is effective to avoid the occurrence of insulation breakdown fault by finding partial discharge signal in time and repairing the defect as soon as possible.

In recent years, the proposed partial discharge monitoring methods mainly include arc detection by optical fiber sensor[2], acoustic emission (AE) method and ultra high frequency (UHF) method[3], which are widely used to monitor partial discharge by detecting ultra high frequency (300 ~ 3000MHz) electromagnetic wave signal of partial discharge radiation, and studies have proved that it has good monitoring effect[4]. On line monitoring often uses "time difference of arrival (TDOA) method for PD location[5]. Its main idea is to compare the time of signals received by sensors installed in different positions to determine the location of PD. The difference of research lies in the installation of sensors and how to obtain and process the obtained time difference signals to locate the PD source. Relevant scholars propose to use the four channel antenna array as the sensor, and then use Newton iterative
method, lattice search method and other methods to solve the time difference equation\cite{6}. Among them, the essence of solving the TDOA equation by lattice search method and particle swarm optimization algorithm is to solve the minimum value of the corresponding error equation and search the corresponding coordinates in the preset range, but this method has low computational efficiency\cite{7}. Plane intersection location method is proposed, which can also be used for PD Location: firstly, the time difference between antenna arrays is obtained by interpolation cross-correlation method, then the time difference equation is solved by plane intersection method, and the location with the highest probability in the location result is selected as the final result by statistics. However, this method to achieve high-precision monitoring needs to meet certain limited conditions: the distance and angle between PD source and antenna array need to be small\cite{8}.

In the above PD monitoring methods of UHF method, most of the sensors are installed with fixed antenna array, and the device can only realize the monitoring in the plane where the antenna array is located, which limits the monitoring range of PD monitoring, which also leads to some high-quality algorithms to achieve high-precision PD monitoring under certain conditions\cite{9}.

Therefore, this paper proposes a local discharge source location method which is mainly based on the positioning algorithm and the automatic orientation device as the auxiliary. The automatic directional device can be written into the positioning algorithm, which can monitor the multi-dimensional signals of antenna array by the steering gear and stepper motor. At the same time, the direction of local discharge source can be determined by UHF signal discrimination algorithm and local discharge source direction determination algorithm. On this basis, a precise localization algorithm of local amplifier source based on four antenna array is proposed. The algorithm has small error and is easy to realize. Finally, through the field simulation experiment, it is found that the angle error of the positioning device is less than 2° in scope, and the error of the simultaneous positioning algorithm is about 0.19m, which verifies the feasibility of the orientation device and the positioning algorithm.

2. Design of automatic orientation device

Figure 1 is the schematic diagram of the partial discharge monitoring and positioning device in the substation. $t_1$~$t_4$ are the time required for the electromagnetic signal from the partial discharge source to be received by four antennas. The steering gear, stepping motor and antenna array are the main components of the automatic directional device. When the electrical equipment in the substation produces partial discharge, the radiated UHF signal can be received by the four antennas of the antenna array. The signal acquisition controller synchronously collects the four channel signals after signal amplification and filtering, converts the collected electromagnetic wave signals into corresponding digital waveforms, and then identifies the UHF signals. When the UHF signals generated by defects are identified, the signal acquisition controller controls the alarm circuit to give an alarm. According to the time difference of the same PD signal arriving at each antenna, the PD monitoring and positioning algorithm is used to obtain the control signal transmitted to the stepper motor and steering gear, so as to make the antenna array rotate to the position directly opposite to the PD source, and the laser head is used to indicate the direction of the PD source, so as to realize the function of PD direct positioning. The structure block diagram of the device is shown in Figure 2.

Fig.1. Structure Diagram of Automatic Orientation Device in Substation
Fig. 2. Structure Block Diagram of Partial Discharge Monitoring and Positioning Device in Substation

Stepping motor and steering gear are the key mechanical structures to realize the multi-directional detection of UHF signal by antenna array. The stepper motor can rotate 360 degrees, and the steering gear fixed on the output shaft of the stepper motor can rotate with the output shaft of the stepper motor. By adding a mechanical lever to the swing arm of the steering gear, the steering gear can turn 180 degrees longitudinally. The rotation of the two in the three-dimensional coordinate system is shown in Figure 3, and the stepper motor is realized on the XOY plane $\alpha$ Rotation of angle $0^\circ < \alpha < 360^\circ$. The steering gear is realized on the XOZ plane $\beta$ Rotation of angle $0^\circ < \beta < 180^\circ$. So the antenna array can point in any direction.

Fig. 3. Rotation Effect Drawing of Stepping Motor and Steering Gear

3. Monitoring and location algorithm

The system positioning algorithm flow is shown in Fig. 4. The signal acquisition controller converts the signal after signal amplification and signal filtering into digital waveform, and analyzes and judges the time difference of four channel digital waveform: if the time difference between any two digital waveforms is zero, the zero described here is the time difference under ideal conditions, in fact, it can be controlled within the allowable error range. If the time difference is within $t$, it can be said that the PD signal reaches the four antennas at the same time within the allowable error range, then turn on the laser head, and the place where the laser irradiates is the place where the PD occurs; If the time difference is greater than $t$, the signal acquisition controller transmits the control signal to make the stepper motor and steering gear rotate respectively $\Delta \alpha$, $\Delta \beta$. The position of the driving PD source is close to the center of the antenna array. After repeated sampling, analysis, calculation and transmission of the control signal until the time difference of UHF signal is within $t$, the laser head is controlled to turn on and point to the position of PD, so as to realize the orientation of PD source.
3.1 UHF signal recognition
Because the pulse type random interference signals collected by antenna array are difficult to distinguish and eliminate, in the partial discharge pattern analysis mode, a variety of interference signals are fully displayed in a graphical way, and the two are distinguished according to the characteristics of various interferences and real partial discharge pulses. As shown in Figure 5, the signal acquisition controller converts the electromagnetic wave signals collected by the four omni-directional antennas into various digital waveforms, and judges whether the collected pulse signal is a partial discharge signal by analyzing, comparing the graphics and necessary processing: for the pulse interference with fixed phase, the distribution of the pulse amplitude of the signal on each sinusoidal cycle is analyzed, and the distribution of the pulse amplitude on the n-phase is analyzed $\Phi$. For the interference pulse which has time correlation with the positive wave voltage phase, the relationship between phase and time is analyzed $Q-\Phi-T$. The three-dimensional atlas showed regular figures such as ellipse, circle, S-shape and oblique line; Due to the uncertainty of the phase, amplitude and times of the random interference pulse, the phase of the image is often disordered $Q-\Phi$. Three dimensional atlas was used to distinguish.
3.2 Determination of steering gear rotation angle

With steering gear rotation angle $\Delta \beta$ as an example, the calculation of the stepper motor rotation angle $\Delta \alpha$. The calculation is the same. In the longitudinal projection diagram as shown in Fig. 6, the solid line represents the projection position relationship at the current time, B is the projection distance between the partial discharge source s and the side ab of the antenna array, and a is the projection distance between the partial discharge source s and the side CD of the antenna array; The dotted line shows the longitudinal rotation of the antenna array $\theta$. The projection of the partial discharge source at the center after the angle. At this time, the line between the partial discharge source and the center of the antenna array should be perpendicular to the array projection, and the projection distance m between the partial discharge source and the AB side and CD side of the antenna array should be equal. Note that the side length of the antenna array is L, and the specific calculation is as follows:

According to the geometric relationship, b and a are the heights of $\triangle SAB$ and $\triangle SCD$. The $S_{\triangle SAB}$ and $S_{\triangle SCD}$ can be obtained from Helen's formula.

\[
\begin{align*}
P &= \frac{(L + ct_1 + ct_2)}{2} \\
S_{\triangle SAB} &= \sqrt{P(P-L)(P-ct_1)(P-ct_2)} \\
P &= \frac{(L + ct_1 + ct_2)}{2} \\
S_{\triangle SCD} &= \sqrt{P(P-L)(P-ct_1)(P-ct_2)}
\end{align*}
\]

$c$ is the propagation velocity of electromagnetic wave and $c$ is equal to $3 \times 10^8$ m/s. Then a and b can be expressed by formula (3):
Since the change rates of a and b are the same, and \( a + b = 2m \), the projection distance \( h \) from the PD source to the center of the array can be expressed by equation (4):

\[
h = \sqrt{\left(\frac{L}{2}\right)^2 + m^2} = \sqrt{\left(\frac{L}{2}\right)^2 + \left(\frac{a + b}{2}\right)^2}
\]

According to the cosine theorem, formula (5) can be obtained:

\[
\begin{cases}
  a^2 = h^2 + \left(\frac{L}{2}\right)^2 - 2 \cdot h \cdot \frac{L}{2} \cdot \cos(\theta + 90^\circ) \\
  b^2 = h^2 + \left(\frac{L}{2}\right)^2 - 2 \cdot h \cdot \frac{L}{2} \cdot \cos(90^\circ - \theta)
\end{cases}
\]

The expression of rotation angle \( \theta \) can be obtained by subtracting the two expressions:

\[
\theta = \arcsin\left(\frac{a^2 - b^2}{2hl}\right)
\]

Angle \( \theta \) is the required rotation angle of the steering gear in the clockwise direction, and \( \Delta \beta = \beta - \beta_0 = \theta \), where \( \beta_0 \) represents the current rotation angle of the steering gear, \( \beta \) represents the desired angle after the steering gear rotates.

From this, we can get the required rotation angle of the steering gear. Similarly, we can get the required rotation angle of the stepper motor \( \Delta \alpha \), so the signal acquisition controller can output the control signal to control the movement of the steering gear and the stepper motor, and the steering gear and the stepper motor cooperate to adjust the direction of the antenna array to complete an automatic positioning operation.

### 3.3 Four antenna array positioning method

Take the square antenna array plane as the XOY plane of the coordinate system, assume that the side length of the square is \( l \), and take the center point of the square as the coordinate origin, as shown in the figure 7 below.
At this time, the spatial coordinates of four square antenna arrays 1, 2, 3 and 4 are respectively: (L/2, L/2, 0), (-L/2, L/2, 0), (-L/2, -L/2, 0), (L/2, -L/2, 0). Let the coordinates of the PD source be (x, y, z), then the time from the PD source to antenna 1, 2, 3 and 4 can be T1, T2, T3 and T4 respectively. By comparing the coordinate position and signal arrival time of the four antennas, the following equations can be listed:

\[
\begin{align*}
T1 &= \sqrt{\left(\frac{x-L}{2}\right)^2 + \left(\frac{y-L}{2}\right)^2 + \frac{z^2}{c^2}} \\
T2 &= \sqrt{\left(\frac{x-L}{2}\right)^2 + \left(\frac{y+L}{2}\right)^2 + \frac{z^2}{c^2}} \\
T3 &= \sqrt{\left(\frac{x+L}{2}\right)^2 + \left(\frac{y+L}{2}\right)^2 + \frac{z^2}{c^2}} \\
T4 &= \sqrt{\left(\frac{x+L}{2}\right)^2 + \left(\frac{y-L}{2}\right)^2 + \frac{z^2}{c^2}}
\end{align*}
\]

In this formula, c is the speed of light, and the value is 3*10^8 m/s. By solving this multiple equation, the coordinates of PD source can be accurately calculated.

At the same time, we don't solve equation (2) directly, because it's difficult to get exact solutions for nonlinear equations, Newton method needs to update Jacobian matrix, the calculation is complex, and the convergence condition is more strict, it takes a long time, but the accuracy is higher. Therefore, the fixed point iterative method is proposed, which has the advantages of simple solution, faster calculation time and better convergence, and the coordinate accuracy of positioning calculation is only 0.01m, so this method has greater advantages. Structure \( x_{i+1} = \phi(x_i) \) and the exact solution of the equation can be obtained.

4. Simulation experiment of local discharge monitoring

4.1 Automatic orientation test

In order to verify the feasibility of the PD monitoring device and method, an experimental platform for PD monitoring and positioning device in substation is built, including PD simulator, self direction setting device composed of motor and antenna array, high-speed oscilloscope, etc. The antenna array is arranged in a square way, and the contour side length L=2m, as shown in Figure 8.
Fig. 8. Diagram of Simulation Experiment Device for Local Discharge Monitoring

A partial discharge simulator is placed around the antenna array randomly, and the UHF signal received by the antenna is collected by the oscilloscope. The sampling rate is set to 5GHz, and the following waveforms can be obtained: Fig. 8 shows the signal sent by the partial discharge simulator, that is, the UHF signal received by two omnidirectional antenna lines when the antenna array is not adjusted and the partial discharge is generated. It is obvious from the waveform that there is a large time difference between the two signals, so the antenna array direction needs to be adjusted; After the signal acquisition controller controls the self direction setting device to complete the adjustment of the antenna array direction, that is, the time difference of the control signal is within the preset threshold T, the signal waveforms received by the two omni-directional antennas are shown in Figure 9. Through the comparison of the two pictures, it can be seen that the time difference of 493.6ns is reduced to 8.0 ns, which significantly shortens the time difference of the signal, and the time difference of the signal is controlled within the time threshold T, so that the partial discharge source is facing the antenna array, the indication of the laser light is reliable, and the real-time accurate positioning is realized. The analysis of the experimental results shows that the positioning error is less than 2° Within.

Fig. 9. Signal Waveforms Received by the First Two Omni-directional Antennas for Pointing Adjustment
4.2 Experiment on precise location of partial discharge source

Build the simulation test platform as shown in the figure below, which includes four UHF monitoring sensor antennas, one simulated partial discharge instrument and subsequent signal acquisition and processing module.

Fig.11. Simulation Experiment Diagram of Four Antenna Array
In this square array, keep the distance between the four sensor arrays at 2m, set the coordinates of sensor 1 as (0m, 0m, 2m), sensor 2 as (0m, 0m, 0m), sensor 3 as (2m, 0m, 0m), and sensor 4 as (2m, 0m, 2m). The test was carried out in the three-dimensional plane determined by the square array, and the coordinates of the simulated PD instrument were kept at (0.5m, 5m, 0.5m). Turn on the analog partial discharge instrument, simulate the partial discharge signal, and collect the time data reaching the four antennas. At this time, through the position determination algorithm proposed in this paper, combined with the automatic orientation device proposed in test 3.1, the accurate position of the partial discharge instrument can be obtained. In order to avoid the possibility of contingency and large error in a single test, 10 partial discharge location tests were conducted in this test, and the location distribution diagram was drawn as shown in the figure below. The black square is the sensor antenna, the red circle is the test location, and the blue diamond is the actual location of the partial discharge instrument.

![Fig.12. 3D Map of Location Distribution](image)

It can be seen from the figure that the position of the localized discharge source deviates from the actual position, but the deviation is small. The position distribution obtained from many tests is around the actual discharge source. And through the analysis of experimental data, it can be seen that the positioning error of PD is about 0.19m, which improves the positioning accuracy compared with other positioning methods. At the same time, it also verifies that the positioning method based on positioning algorithm and supplemented by automatic orientation device is feasible and practical.

5. Conclusion

Aiming at the problem that it is difficult to locate the partial discharge accurately in all directions at present, this paper proposes a partial discharge positioning method based on four antenna array positioning and supplemented by automatic orientation:

(1) In view of the deficiency that the PD monitoring and positioning device of substation can only realize PD monitoring in one space plane, this paper proposes an automatic directional device which can realize PD monitoring and positioning in three-dimensional space. The device adjusts the direction of antenna array through stepping motor and steering gear, so that the array can point to any direction in three-dimensional space. After adjustment, the laser light is used to indicate the position of PD source, so as to realize the automatic positioning of PD source direction.

(2) This paper also proposes an algorithm to determine the direction of PD source, which is suitable for the device N-Q-Φ. Then, according to the spatial geometric relationship, the rotation angles of the servo and the stepper motor are determined respectively to output the corresponding control signals, and the control accuracy is improved by closed-loop multiple feedback adjustment.

(3) On the basis of this method, combined with the automatic orientation device, a positioning method is proposed, which is mainly based on the positioning method and supplemented by the self orientation method. Through the field simulation test, the practicability of this method is verified. The
analysis of experimental data shows that the orientation error of this method is within 2 °. The positioning error is about 0.19M and the positioning accuracy is good.

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