Research on PD source successive approximation positioning method based on multi sample information

Qingdong Zhu1, Wenbing Zhu, Zhixin Gao and Mengzhao Zhu
State Grid Shandong Electric Power Research Institute, Jinan, Shandong 250002, China

1 E-mail: yao_yh@whu.edu.cn

Abstract. Ultra High Frequency (UHF) detection technology is widely used in Partial Discharge (PD) detection and positioning of electrical equipment. However, how to achieve accurate and reliable fault localization based on UHF PD is an urgent problem to be solved. In this paper, the multi-samples of PD are calculated by the successive approximation method and the optimization function is established by using the linear spatial relationship between the initial value and the sensors. The particle swarm optimization (PSO) is exploited to search for the minimum value of function, and the optimal result is obtained by cyclic calculation. The optimal PD source position determined by this way has higher accuracy, solving the problem of strong dispersion and large error in PD location by a single sample. The positioning error is reduced from tens of centimetres of the single sample to few centimetres, which is fewer than the results calculated by the average method. In addition, it is found that the positioning precision becomes higher as the number of samples selected for optimize calculation (i.e. \( m \)) decreases.

1. Introduction
Ultra high frequency (UHF) detection technology has the advantages of high sensitivity and strong anti-interference ability. It has been one of the hot issues to apply it to the PD positioning of power transformer [1-3]. For the traditional positioning method, due to the influence of strong electromagnetic interference and complex multi-layer dielectric structure of transformer, it is difficult to accurately obtain the PD signal time difference without delay error no matter what anti-interference technology and time difference extraction algorithm are exploited [4]. At the same time, problems such as local convergence or divergence may occur in the solution process of the positioning algorithm, which makes it difficult to achieve accurate positioning of the transformer with a single positioning solution method, and even leads to positioning failure [5].

In the current practical application, the average value is usually calculated by multiple positioning, so that the calculated PD coordinates are close to the real discharge source position. However, this method is only a simple average calculation of the results, which cannot fundamentally solve the problem of large error [6]. Reference [7] pointed out that the results obtained of the average time difference method could not accurately determine the fault point, and the method of the average positioning result only had a simple operation on the positioning result, which failed to solve the problem of low positioning accuracy. In Reference [8], a new PD location method was proposed by installing a UHF sensor array on both sides of the transformer mailbox. The similarity of the signal waveform was used to determine which side of the PD source was closer to the sensor array, and then
the data measured by the closer sensor was used for calculation. However, for the transformer box, there were few installation positions for the sensors with good receiving effect, and it was unrealistic to arrangement a mass of sensors in a limited position, so the feasibility of this method was low. How to quickly and effectively determine the 3D coordinate position of PD source with high accuracy from complex structure transformer, to grasp the internal insulation condition of equipment and eliminate the hidden trouble in time, is still an urgent problem to be solved in the field of power system fault diagnosis.

In addition, due to the influence of random interference factors, the probability falling at the same position in the transformer box calculated by multiple positioning can be analyzed from the perspective of "crater theory". That is to say, the position values, estimated many times by traditional positioning methods, are randomly distributed in a certain range adjacent to the PD source. We can consider a certain geometric method to make the estimated values focus on a certain coordinate, which is closer to the real PD source position. Therefore, for solving the problem of large positioning error caused by the low time delay acquisition accuracy, this paper researches how to use the geometric relationship between sensor array and PD source to establish a function, and how to use successive approximation positioning method to improve the positioning accuracy. And this paper proposes a PD source successive approximation positioning method based on multi-sample information. It provides theoretical support for the development of targeted and efficient maintenance strategy.

2. Successive approximation positioning method

Due to the diversity and complexity of UHF electromagnetic wave propagation environment in transformer, the acquisition of positioning parameters is easily interfered by many factors. In order to meet the needs of high-precision positioning of PD source in transformer, this paper introduces the concept of "coarse before fine", and proposes a multiple successive approximation positioning method suitable for three-dimensional space, which is used to reduce the dependence on accurate acquisition delay in time difference positioning method and solve the problem of excessive error.

For PD source positioning of transformer, using a group of sample data D_1 collected by four UHF sensors distributed on the box at the same time, the initial position value of a sample can be calculated by the traditional time difference of arrival location method, which is recorded as P_1(x_1, y_1, z_1). Because the location of any PD source is invariant, the initial value of another sample location can also be calculated by the second set of sample data D_2 obtained at another time, which is denoted as P_2(x_2, y_2, z_2). Theoretically, if there is no error in the measured time difference, the values calculated by the positioning algorithm for the sample data D_1 and D_2 are equal. That is to say, the initial values of P_1 and P_2 should be coincident, and their coordinates are the spatial position of the real PD source. However, the signal received by UHF sensor array at different times is the result of PD source propagating and superimposing through different paths in the complex structure of the transformer, which is not a simple straight-line propagation. And due to the influence of random interference factors such as the response characteristics and noise of the detection system, it is bound to cause time error when measuring the time difference of PD UHF signal arriving at each sensor. And the delay of D_1 and D_2 PD signals obtained is not equal, which will lead to the calculated initial positioning values P_1 and P_2 not coincide, and there is a certain error with the real PD source position.

In other words, using the delay information corresponding to N groups of PD signals captured at different times, N samples can be calculated to locate the initial value points P_1, P_2, ..., P_N. Because of the existence of delay error, these points will be randomly scattered around the real PD source. To this end, this paper constructs the objective function through the following methods for point of P_1, P_2, ..., P_N.

According to the space analytic geometry, two points in space can determine a straight line only. The linear equation is established by taking sensor S_0(x_0, y_0, z_0) and initial value of sample P_1(x_1, y_1, z_1) as examples, the linear equation determined by point P_1 and point S_0 can be expressed as:

\[
\frac{x - x_1}{x_1 - x_0} = \frac{y - y_1}{y_1 - y_0} = \frac{z - z_1}{z_1 - z_0}
\]
A sample point and four sensors can determine four linear equations as shown in Formula (1). Figure 1 shows two groups of lines determined by \( P_1 \) and \( P_2 \) points and sensor array respectively.

Theoretically, if the measured delay has no errors, the two groups of lines overlap one by one in space, and the intersection is the real PD source position \( P(x, y, z) \). Nevertheless, the delay measurement error of actual time will cause the two groups of lines not to overlap and become out of plane lines, as well as multiple groups of lines determined by unequal points \( P_N \) and sensor array. Therefore, assuming that the \( N \) initial value points are randomly distributed around the centre of the real PD source, the lines determined by the initial points and sensors can be regarded as the intersection lines with the circle of real PD source centre. According to the spatial relationship between the PD source location and each line, the distance and function of PD source to each line can be constructed as follows:

\[
d = \sum_{k=1}^{N} d_{kl} = d_{11} + \cdots + d_{14} + d_{21} + \cdots + d_{N4}
\]

Figure 1. The diagram of straight lines determined by PD source and sensors.

Figure 2. Diagram of the global search location principle.

where \( k = 1, 2, \ldots, N \) is the number of initial values of samples; \( L = 1, 2, 3, 4 \) is the number of sensors; \( d_{kl} \) is the distance from the PD source to the line determined by the initial value of the \( k^{th} \) sample and the \( l^{th} \) sensor. Obviously, the problem is to optimize the minimum value of Formula (2). Therefore, in the search space, if a point \( P'(x', y', z') \) is found to make the \( d \) value of minimum \( d_{\text{min}} \), the point can be regarded as the PD source location. The schematic diagram of global search and location is shown in Figure 2.

According to the space analytic geometry, \( d_{kl} \) is the distance between the point \( P'(x', y', z') \) and the line \( L \) determined by the initial value \( P_k(x_k, y_k, z_k) \) and the sensor \( S_l(x_l, y_l, z_l) \). The direction vector of \( L \) is \( \mathbf{s} = (x_k - x, y_k - y, z_k - z) \). The area of the parallelogram with \( \overrightarrow{P_kS_l} \) and \( \overrightarrow{P_kS'} \) as adjacent sides is

\[
\left| \overrightarrow{P_kP'S_l} \times \overrightarrow{P_kS_l} \right| = \left| \overrightarrow{P_kP'} \times \mathbf{s} \right|
\]

Furthermore, the parallelogram area can be converted into:

\[
d_{kl} \cdot \left| \overrightarrow{P_kS_l} \right| = d_{kl} \cdot |\mathbf{s}|
\]

Therefore, from Formula (4), it can be obtained:

\[
d_{kl} \cdot |\mathbf{s}| = \left| \overrightarrow{P_kP'} \times \mathbf{s} \right|
\]

\[
d_{kl} = \frac{\left| \overrightarrow{P_kP'} \times \mathbf{s} \right|}{|\mathbf{s}|} = \frac{\left| \overrightarrow{P_kP'} \times \overrightarrow{P_kS_l} \right|}{|\overrightarrow{P_kS_l}|}
\]
where, \( \overrightarrow{PP_k} = (x' - x_k, y' - y_k, z' - z_k) \), \( \overrightarrow{PS_l} = (x_l - x_k, y_l - y_k, z_l - z_k) \). Then, the sum of the distances from the PD source to each straight line can be expressed as:

\[
 d = \sum_{k=1}^{N} d_{kl} = \sum_{k=1}^{N} \frac{\overrightarrow{PP_k} \times \overrightarrow{PS_l}}{|P \overline{S_l}|} 
\]  
(7)

As a result, the minimum \( d_{\text{min}} \) and its corresponding coordinate of Formula (7) need to be optimized and estimated, that is, the geometric space position coordinates of PD source. Considering that PSO algorithm has the advantages of easy implementation, high accuracy, fast convergence and strong global search ability, PSO algorithm was exploited to search Formula (7) \([9, 10]\) In the process of searching, the value of objective function is updated to its optimal position \( P_{\text{best}} \), that is, the value of \( d \) is gradually reduced, and the coordinate value of search point is gradually approaching the optimal position, until the global optimal solution \( G_{\text{best}} \) is found after the termination of PSO algorithm. At this time, the objective function value is the minimum \( d_{\text{min}} \), and the corresponding search point coordinates are in the optimal position, and then the spatial position of PD source can be determined.

3. Experimental analysis of PD signal localization

In order to fully test the effectiveness of the successive approximation positioning method proposed in this paper, PD positioning test and UHF signal measurement were carried out on the simulation Transformer PD experimental platform. The experimental platform of PD measured signal was mainly composed of large transformer box \((240\text{cm} \times 310\text{cm} \times 200\text{cm})\), simulated PD source, high frequency coaxial transmission cable, high-speed oscilloscope and UHF sensor array \((\text{The center frequency is about } 400\text{MHz and the bandwidth is } 350\text{MHz} \sim 525\text{MHz})\). The PD source consisted of a needle plate discharge model placed in a 40 cm diameter and 50 cm high oil filled polymethyl methacrylate tank, which could be placed anywhere in the box. And air was the medium in other parts of the box. In addition, some insulators were placed on the receiving surface of UHF sensor to simulate the influence of obstacles on electromagnetic wave propagation. At the same time, in the process of the experiment, the nearby laboratory was also carrying out other experiments, which had a background noise interference effect on this experiment. The spatial coordinates of PD source and array UHF sensor were shown in Figure 3. In this experiment, the PD source was placed at the position \( P(150,150,140)\text{cm} \), and the four position coordinates of array UHF sensor were \( S_0(0,20,35)\text{cm}, S_1(215,0,20)\text{cm}, S_2(240,295,10)\text{cm}, S_3(20,310,30)\text{cm} \) respectively.

In the experiment, the coordinates of PD source and sensor array remained invariant in the box, and PD signals were detected by sensor array. The data collection interval was 15 minutes, and 20 groups of samples were captured. The measured time delay and initial location values of 20 groups of samples were shown in Table 1.

![Figure 3. Experimental system for PD location.](image)
It could be seen from Table 1 that under the influence of various interference factors, the error of the single sample positioning results and the dispersion of the positioning coordinates was large. If it was regarded as the PD source coordinates directly, it will inevitably lead to the failure of PD positioning. Taking the average value of these 20 samples, the error of positioning results was still up to 11cm, and the accuracy needed to be improved.

Table 1. The measured time-difference and positioning results at different moments.

| Number | Time difference (ns) | Initial positioning value (cm) | Error (cm) |
|--------|----------------------|--------------------------------|------------|
| 1      | -1.01, -1.89, 0.41   | (137, 176, 143)                | 29.22      |
| 2      | -0.61, -2.12, 0.24   | (154, 139, 137)                | 12.08      |
| 3      | -0.60, -2.09, 0.25   | (144, 138, 152)                | 18.00      |
| 4      | -1.05, -1.85, 0.33   | (164, 177, 145)                | 30.82      |
| 5      | -0.71, -2.50, 0.17   | (153, 171, 126)                | 25.42      |
| 6      | -0.90, -2.01, 0.44   | (142, 149, 156)                | 17.92      |
| 7      | -0.59, -1.75, 0.61   | (164, 145, 161)                | 25.73      |
| 8      | -0.58, -2.21, 0.19   | (161, 169, 130)                | 24.12      |
| 9      | -0.43, -1.81, 0.31   | (177, 164, 142)                | 30.49      |
| 10     | -0.49, -1.88, 0.27   | (166, 139, 148)                | 21.00      |
| 11     | -0.56, -2.07, 0.52   | (164, 148, 151)                | 17.92      |
| 12     | -0.70, -1.89, 0.49   | (139, 166, 153)                | 23.37      |
| 13     | -0.83, -2.10, 0.28   | (161, 142, 139)                | 13.64      |
| 14     | -0.48, -1.77, 0.35   | (136, 169, 137)                | 23.79      |
| 15     | -0.42, -2.02, 0.38   | (165, 155, 148)                | 17.72      |
| 16     | -1.13, -2.18, 0.55   | (184, 154, 149)                | 35.40      |
| 17     | -0.62, -2.32, 0.27   | (161, 142, 139)                | 13.64      |
| 18     | -0.81, -1.52, 0.56   | (140, 166, 157)                | 25.40      |
| 19     | -0.65, -1.60, 0.47   | (169, 161, 146)                | 22.76      |
| 20     | -0.75, -1.71, 0.54   | (144, 146, 154)                | 15.75      |
| Average |                      | (156, 157, 146)                | 11.00      |

In order to verify the effect of the successive approximation localization method on improving the accuracy of PD source localization, we discussed the influence of the number of samples selected each time \(20 \geq m \geq 2\) on the final result in four cases.

1. When \(m=20\), that was to say, all the samples in Table 1 were selected as a group for optimization, and the optimization objective function in Formula (6) was constructed. Then the particle swarm optimization algorithm was used to globally search for the minimum \(d_{\text{min}}\). The search boundary was the spatial range of the transformer. The result of global search optimization was \((154, 155, 146)\), and the error was 8.77cm.

Table 2. The results of optimization objective function \((m=10)\).

| Number | First optimization /cm | Second optimization /cm | Error /cm |
|--------|------------------------|-------------------------|-----------|
| 1-10   | (154, 151, 141)        | (153, 153, 142)         | 4.69      |
| 11-20  | (153, 152, 143)        |                         |           |

Table 3. The results of optimization objective function \((m=4)\).

| Number | First optimization /cm | Second optimization /cm | Third optimization /cm | Error /cm |
|--------|------------------------|-------------------------|------------------------|-----------|
| 1-4    | (149, 151, 142)        | (152, 152, 142)         | (153, 151, 143)        | 4.27      |
| 5-8    | (156, 151, 140)        |                         |                        |           |
| 9-12   | (157, 152, 145)        |                         |                        |           |
| 13-16  | (149, 154, 140)        |                         |                        |           |
| 17-20  | (153, 150, 144)        |                         |                        |           |
Table 4. The results of optimization objective function \((m=2)\).

| Number | First optimization /cm | Second optimization /cm | Third optimization /cm | Forth optimization /cm | Fifth optimization /cm | Error /cm |
|--------|-------------------------|--------------------------|------------------------|------------------------|------------------------|-----------|
| 1–2    | (154, 140, 137)         | (156, 154, 141)          |                        |                        |                        |           |
| 2–4    | (157, 146, 145)         | (156, 154, 141)          |                        |                        |                        |           |
| 5–6    | (148, 161, 138)         | (160, 149, 146)          | (156, 153, 142)        |                        |                        |           |
| 7–8    | (164, 145, 149)         | (157, 149, 140)          |                        | (154, 150, 140)        |                        |           |
| 9–10   | (161, 155, 142)         | (159, 156, 141)          |                        | (158, 148, 140)        |                        |           |
| 11–12  | (139, 166, 133)         | (158, 143, 139)          |                        |                        |                        |           |
| 13–14  | (160, 142, 139)         | (154, 142, 139)          |                        |                        |                        |           |
| 15–16  | (134, 154, 140)         | (154, 142, 139)          |                        |                        |                        |           |
| 17–18  | (161, 142, 139)         | (154, 142, 139)          |                        |                        |                        |           |
| 19–20  | (145, 138, 144)         | (154, 152, 139)          |                        |                        |                        |           |

② When \(m=10\), every 10 samples in Table 1 would be optimized for the first time, and then the two values obtained from the first optimization continued to be optimized again (here, when \(m\) was less than 10 in the second optimization, it would be regarded as one group for calculation). The results of two optimization calculations were shown in Table 2.

③ When \(m=4\), every 4 samples in Table 1 were divided into a group according to the sequence. According to the step of successive approximation positioning method, after three times of optimization, the results of successive calculation were shown in Table 3.

④ When \(m=2\), every two samples in Table 1 were divided into a group. According to the step of successive approximation positioning method, after five times of optimization, the results of successive calculation were shown in Table 4.

Comparing Tables 2, 3 and 4, it was found that the smaller the \(m\) value was, the higher the accuracy became. The disadvantage was that the number of optimization was increased, that is, the amount of calculation also increased. Therefore, the appropriate \(m\) could be selected to reduce the cost of calculation according to the number of samples. Figure 4 showed the selected \(m\) and positioning error curve.

Figure 4. Relation between sample number in every step and error.

Figure 4 indicated that the error of the average method for 20 samples was 11cm. When introducing successive approximation positioning method, with the decrease of the number of samples selected each time, the positioning error showed a downward trend. The positioning result of measured PD signal grew more and more close to the real discharge position. The positioning error was 8.77cm as the number of samples is 20. When \(m=2\), the error reduced to 4cm, which was less than 11cm of the average method, and the positioning accuracy was significantly improved.
4. Conclusions

① A successive approximation method for PD source localization of transformer based on multi sample was proposed in this paper. Firstly, TDOA method was used to positioning the initial PD source of a single sample. And the optimal function was established based on the linear spatial relationship between the PD source and the sensors. The minimum value of function was searched by particle swarm optimization. Finally, the optimal PD location was obtained by dynamic adjustment according to the previous positioning results.

② The results of simulation test showed that the positioning accuracy of the optimized processing was improved greatly compared with the initial value of single sample with large error. The error reduced from tens of centimetres to a few centimetres, which was lower than 11cm of the average method. The positioning result got closer to the real PD source location.

③ It was found that the positioning accuracy would become higher with the decrease of the number of samples (i.e. \( m \)) selected each time. Nevertheless, the disadvantage of PSO algorithm was that the amount of calculation increased.

References

[1] Gao S W, Ding D W, Liu W D and Feng R 2009 Location of PD by searching in space using UHF method High Voltage 35 2680-84

[2] Mirzaei H R, Akbari A, Gockenbach E, Zanjani M and Miralikhani K 2013 A novel method for Ultra-High-Frequency partial discharge localization in power transformers using the particle swarm optimization algorithm IEEE Electr. Insul. Mag. 29 26-39

[3] Karami H, Azadifar M, Mostajabi A, Rubinstein M, Karami H, Gharehpetian G B, et al. 2020 Partial discharge localization using time reversal: application to power transformers Sensors 20 1419

[4] Chai H, Lu S, Phung B T and Mitchell S 2019 Comparative study of partial discharge localization based on UHF detection methods CIRED 2019(Madrid) pp 1076

[5] Zhao A Y 1996 Geometrical diffraction for antenna measure Mod. Electr. Technol. 1 26-9

[6] Huang L 2014 Research on positioning method of successive approximation for partial discharge source based on semidefinite relaxation Chongqing Univ

[7] El Mountassir O, Stewart B G, Memekein S G and Ahmadinia A 2012 Effect of noise on the location accuracy of partial discharges using radiated rf detection techniques 47th Int. Univ Power Engineering Conf. (London) pp 1039-44

[8] Zheng S S, Li C R and He M 2013 A novel method of newton iteration in complex field and lattice search for locating partial discharges in transformers Proceedings of the CSEE 33 155-61

[9] Shao M R, Wang B B and Dou Z F 2009 Application of gradient shrink method in location of transformer partial discharge Comput. Appl. Eng. Educ. 45 209-10

[10] Nesterov Y and Nemirovskii A 1994 Interior-point polynomial algorithms in convex programming Stud. Appl. Numer. Math