The Location of Partial Discharge Sources inside Power Transformers Based on TDOA Database with UHF Sensors

Naifan Xue¹, Junjie Yang²,³, Member, IEEE, Daoyi Shen², Peng Xu⁴, Kaixu Yang¹, Zhuhang Zhuo¹, Linnan Zhang¹, Jinshui Zhang¹

¹The College of Electronics and Information Engineering, Shanghai University of Electric Power, Shanghai, 200082, China
²Shanghai DianJi University, Shanghai, 201306, China
³Shanghai Global Technology Co., Ltd, Shanghai, 201210, China
⁴State Grid Power Research Institute of Shanghai Electric Power Corporation, Shanghai, 200437, China

Corresponding author: Junjie Yang (e-mail: yangjunjie@shiep.edu.cn).

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ABSTRACT This paper proposes a new method to locate the partial discharge (PD) sources inside the high-voltage power transformers with ultra-high frequency (UHF) sensors, based on the time difference of arrival (TDOA) database. A TDOA database includes the TDOA information of possible PD sources inside a power transformer, which is established under the construction of the system of the tested power transformer and the high accuracy of the minimum distance between a possible PD source and a UHF sensor. We employ the tangent transmission model of PD signals and the shortest path algorithm to solve the distance problem in case of an obstacle obstructing the transmission of PD signals. In order to verify the feasibility and accuracy of this new TDOA database method, we carry out two experiments. One experiment was conducted with a 110kV power transformer and the other was carried out with a platform for PD of electric power equipment. The experimental research results which are composed of location coordinates, transmission path and TDOA information indicate that the TDOA database method can locate single PD source as well as multiple PD sources simultaneously with the location error less than 0.3m.

INDEX TERMS PD source location, UHF method, TDOA database, The tangent transmission model, The shortest path algorithm.

I. INTRODUCTION Power transformers are of considerable significance in the power grid, of which the operating statement directly affects the stability and safety of the entire grid. In recent years, the inaccurate statistics and analysis results demonstrate that the partial discharges (PD) which are basically caused by improper manufacture-installation, winding deformation or core vibration during the operational process threaten the reliability of power transformers gravely [1-3]. Hence the location of partial discharge source in the power transformer has an indicative value for measuring the degree of insulation damage and drawing up corresponding maintenance strategies.

Currently, there are three dominating approaches to locating PD sources: electrical, acoustic and ultra-high frequency (UHF) methods. The electrical method is not available for locations in power transformers which are far more complicated than other electrical equipment such as GIS on account of its poor positioning accuracy. Though the ultrasonic signals are not affected by electromagnetic interference, the ultrasonic method can hardly distinguish the multi-source discharge fault, and the ultrasonic signal will severely attenuate when passing through the intricate structure of transformers such as windings and boards. However, UHF location method is strongly sensitive to PDs inside the transformers and multi-PD sources can be located simultaneously [4-6].

The UHF method uses UHF sensors installed on the transformer tank to detect the PD signal, and obtains the data including time difference of arrival (TDOA) between sensors...
which is confirmed as the most accurate parameter to solve the PD location problem, angles of arrival (AOA) at the sensors and the received signal strength indication (RSSI) of the UHF sensors. To solve the TDOA equations, researches concentrated on different optimal algorithms such as Newton iteration method, particle swarm optimization (PSO) and back propagation (BP) neural network [7-9]. Though the errors in [7-9] satisfy the experimental requirement, the divergence problem caused by the optimal problem has not been considered. What’s more, most of these researches are based on the simulation without practical experiments and the problem of multi-PD sources location has not been solved. Even further, the transmission deviations in the simulation caused by obstacles inside the power transformers during the calculation of TDOA have not been considered [10-15].

As an improvement, a new method based on the TDOA database [16] is proposed in this paper. The simulated system for power transformers with the tangent transmission model and the TDOA database is established after the process of TDOA error correction. Meanwhile two experiments are carried out to verify the feasibility and the accuracy of TDOA database method to solve the single and multiple PD sources location problem.

II. THE ESTABLISHMENT OF TDOA DATABASE

A. THE MODEL OF POWER TRANSFORMERS

The partial discharge localization system is composed of UHF sensors, a signal amplifier, a high-speed analog-to-digital converter, a microprocessor and personal computer (or server), as shown in Fig. 1.

![Power Transformer](image)

**FIGURE 1.** The PD localization system.

The system first analyzes the structure of the tested transformer and establishes a TDOA database according to different sensors which collect UHF signals from the PD sources inside the transformers. When partial discharges occur in the transformer, the sensor array detects the UHF signals emitted by the discharge source and attains the time difference of signals received by each sensor through conversion, processing and analysis, and obtains the location of PD source by searching the TDOA database.

The metal parts such as windings and iron cores inside the transformer block the propagation of UHF electromagnetic waves and cause changes such as reflection, refraction and diffraction in the transmission path, thus the transformer structure must be modelled for the TDOA database as shown in Fig. 2. We use .NET Windows Presentation Foundation (.NET WPF) and Helix 3D to model the transformer structure. The needed parameters for the three-dimensional transformer model includes: the length, width and height of the transformer tank; the spatial resolution of the model, which determines the computational complexity and the accuracy of the location; the velocity of ultra-high frequency electromagnetic wave inside the insulating medium of the transformer; the origin of coordinates and the exact installation position coordinates of each UHF sensor; the position coordinates of each cylinder and cube abstracted by the internal components of the transformer; the color and transparency used for modelling. The model of the transformer structure should be established on the basis of the actual transformer structure. If there are other components in the transformer, such as on-load tap changers and the taps coming from the windings to the on-load tap changers, they should also be added into the transformer model accordingly. It should be pointed out that the windings are modelled as a forbidden region in our transformer model, which means the PDs occurring inside the windings cannot be located with the TDOA database system introduced in the following section. In other words, if the PD is inside a winding, then the winding should not be a forbidden region and it should be assumed that the signal can travel out through a nearby oil duct at the speed of light in oil, which will be completely a different model and system [17-18].

![Transformer Structure](image)

**FIGURE 2.** The simplified model of the transformer structure.

B. THE CALCULATION OF TDOA

For all the internal points of the transformer model based on the transformer modelling data, the distance between the point and the installed sensor is calculated respectively in order to attain the arrival time. Then, the TDOA between two sensors can be calculated, which is the foundation of the UHF electromagnetic wave transmission database. Fig.3 is the schematic diagram of TDOA calculation with four UHF sensors.
means that our model is composed of a number of vertices of tangency and normal vectors of the polygon patches. That is to say, in a network graph model composed of many vertices of tangency, the minimum distance problem on a curved surface is equivalent to the problem of finding the shortest path between the initial point and the ending point.

**FIGURE 3.** The schematic diagram of TDOA calculation.

It is assumed that 4 sensors \( S_1, S_2, S_3, S_4 \) are installed on the surface of the transformer, of which the coordinates are \( S_1(X_1, Y_1, Z_1), S_2(X_2, Y_2, Z_2), S_3(X_3, Y_3, Z_3) \) and \( S_4(X_4, Y_4, Z_4) \). The distances between any point \( V_k(X_{V_k}, Y_{V_k}, Z_{V_k}) \) inside in tank and the sensors are \( d_{V_k-1}, d_{V_k-2}, d_{V_k-3}, d_{V_k-4} \). If there is no component obstructing the transmission path between the point \( V_k \) and the sensor \( S_p \), the distance \( d_{V_k-p} \) can be calculated as follows (\( p = 1,2,3,4 \)):

\[
\begin{align*}
    d_{V_k-1} &= \sqrt{(X_{V_k} - X_1)^2 + (Y_{V_k} - Y_1)^2 + (Z_{V_k} - Z_1)^2} \\
    d_{V_k-2} &= \sqrt{(X_{V_k} - X_2)^2 + (Y_{V_k} - Y_2)^2 + (Z_{V_k} - Z_2)^2} \\
    d_{V_k-3} &= \sqrt{(X_{V_k} - X_3)^2 + (Y_{V_k} - Y_3)^2 + (Z_{V_k} - Z_3)^2} \\
    d_{V_k-4} &= \sqrt{(X_{V_k} - X_4)^2 + (Y_{V_k} - Y_4)^2 + (Z_{V_k} - Z_4)^2}
\end{align*}
\]

If there is an obstacle in the straight-line transmission path, \( d_{V_k-p} \) is defined as the distance of the shortest path after the UHF electromagnetic wave’s reflection and the diffraction according to the Fermat’s principle [19]. The tangent transmission model of PD signals is introduced to solve the obstacle problem. Fig. 4 is a two-dimension schematic diagram of transmission path with an obstacle. The transmission path deviates twice on the surface of the obstacle.

**FIGURE 4.** The two-dimension schematic diagram of transmission path with an obstacle.

Compared to the condition without the obstacles, the problem of the minimum distance between two points on the curved surface has to be solved. In our power transformer model, different windings and cores with curved surfaces are composed of quantities of polygon patches, which indirectly

**FIGURE 5.** The three-dimension schematic diagram of transmission path on a cylinder obstacle.

The schematic tangent transmission paths of PD signals when obstructed by a simulated core is shown in Fig. 5. It can be seen that the black transmission path deviates twice via the tangent vertices on the surface of the core.

With the optimal substructure character [20], the shortest path algorithm based on Dijkstra’s algorithm [21] is employed to solve the minimum distance problem in our TDOA model. Several definitions on the point sets and the parameters are determined as follows:

1) The universe set \( U \) is defined as a collection of all points (possible PD sources) in the power transformers, of which the number \( N \) is determined by the spatial resolution.

2) The set \( S \) is defined as a collection of the points that has found the shortest path. On the original condition, only the initial point belongs to the set \( S \).

3) The set \( Q \) is defined as a collection of the points that has not found the shortest path. Obviously, \( Q = U - S \).

4) The distance between the initial point and other points is defined as \( d_{V_k} \), where \( k (k = 1,2,3, ..., N) \) refers to the sequence number of the points inside the power transformer and the vertex \( V_1 \) is the starting point. Usually, the starting point is the position of the UHF sensors.

5) The distance between two neighbor points connected by a single path is defined as \( arc_{e,f} \), where \( e \) and \( f \) refer to the sequence number of the two connected points.

The major steps of the algorithm are examined in detail as follows:

step 1) Initialize the data structure.

On the original condition, only the initial point \( V_1 \) belongs to the set \( S \). The initial assignment is:

\[
d_{V_1} = 0, d_{V_k} = +\infty \quad (k = 2,3, ..., N)
\]

Then, find one neighbor point \( V_m \) of the starting point and update the value \( d_{V_m} \) by:

\[
d_{V_m} = \min\{d_{V_k} + arc_{e,f}\} \quad (k = 2,3, ..., N)
\]
\[ d_{v_m} = \min \{d_{v_m}, d_{v_1} + \text{arc}_{1-m}\} \]  
\( (3) \)

Finish updating all the neighbors of the initial point by means of (3).

step 2) Find the vertex \( V_i \in Q \), of which the distance valve \( d_{v_i} \) is the lowest. 

After the first update, all the neighbors of the initial point have a new value of \( d_{v} \). Find the lowest value \( d_{v_j} \) among the points in the set \( Q \), and put the related point \( V_i \) to the set \( S \).

step 3) Judge whether the vertex \( V_i \) has a neighbor and whether \( d_{v_i} \) needs to be updated. 

If the point \( V_i \) has a neighbor \( V_x \), update \( d_{v_x} \) by:
\[ d_{v_x} = \min \{d_{v_x}, d_{v_j} + \text{arc}_{i-x}\} \]  
\( (4) \)

Then, finish updating all the neighbors of the point \( V_i \) by means of (4).

If the point \( V_i \) doesn’t have a neighbor, the process of \( V_i \) is terminated and no value needs to be updated.

step 4) Repeat step 2), 3) until \( S = U \) or \( Q = \emptyset \), and the final updated \( d_{v_k} \) will be the valve of the shortest path between the initial point and any other point inside the power transformer.

After the calculation of the distance, the arrival time from any point \( V_k \) to sensor \( p \) can be attained by:
\[ t_p = \frac{d_{v_k-p}}{v_m}, p = 1,2,3,4 \]  
\( (5) \)

where \( v_m \) is the propagation speed of electromagnetic waves in the internal medium of the transformer. In our experiments with the real power transformer, \( v_m = 2.018 \times 10^8 \text{m/s} \). Though there is empty space inside the tank of the transformer model shown in Fig.2 or 5, the addition of other components will not affect the feasibility of the shortest path algorithm based on Dijkstra’s algorithm. The time difference of arrival between two sensors can be easily calculated as follows:
\[ t_{ij} = t_i - t_j \]  
\( (6) \)

To establish a mapping relation between the TDOA and the coordinates of the points, all points inside power transformer are processed in way of (5) and (6). Then, each point is related to a corresponding group of TDOA shown as follows:
\[ (t_{21}, t_{31}, t_{41}, t_{32}, t_{42}, t_{43}) \rightarrow (X_{v_k}, Y_{v_k}, Z_{v_k}), \]  
\( k = 1,2,3,\ldots,N \)  
\( (7) \)

We are using correlation to determine the time delay between pulses. To calculate the time difference of two waveforms (each waveform’s amplitude having been sampled as a sequence of number), we fix one waveform and shift the other waveform (in axis of time) in a reasonable range. For each shift, we calculate the correlation of two waveforms. The shift corresponding to the maximum result of the correlation will be the time difference between these two waveforms [12, 22].

III. THE ERROR CORRECTION AND THE OPTIMIZATION OF THE TDOA DATABASE METHOD

Since the time difference of arrival between different sensors measured by the UHF method is usually on the order of nanoseconds or even picoseconds, the accuracy of the time delay is very high. However, the actual transformer winding structure is complex, which may cause the amplitude of the UHF electromagnetic wave passing through it to be attenuated and the propagation path to change, thereby affecting the location of PD sources [23]. As TDOA database is established by theoretical time, it is necessary to implement the error correction. The major steps are as follows:

1) When calculating the time difference, the theoretical time of the PD source reaching the sensors can be calculated using the method introduced in Section II. The theoretical TDOA \( t_{ij} \) between sensor \( i \) and \( j \) can be obtained according to (1). The time difference in measurement \( t_{ij} \) can be attained from the start time of the waveform obtained by the oscilloscope. The time difference error can be calculated as:
\[ \Delta t_{ij} = t_{ij} - t_{ij} \]  
\( (8) \)

where \( i \) and \( j \) are the sequence numbers of the sensors.

Then, the time difference error is added to the actual result \( t_{r-ij} \) of the PD location experiment, which is described as:
\[ t_{ij} = t_{r-ij} + \Delta t_{ij} \]  
\( (9) \)

\[ (t_{21}, t_{31}, t_{41}, t_{32}, t_{42}, t_{43}) \rightarrow (X_{v_k}, Y_{v_k}, Z_{v_k}), \]  
\( k = 1,2,3,\ldots,N \)  
\( (10) \)

2) Because of the space resolution of the TDOA database model, in the actual experiment, it is often measured that several possible PD sources may be located in one region. The estimation point far away from the center is discarded, and the remaining estimation points are superimposed and averaged, the result of which is the final estimated PD source location.

The time complexity of the Dijkstra’s algorithm for PD location is \( O(n^2) \), of which \( n \) refers to the scale of the problem. The proof is as follows:

1) When finding the distance \( d_{v_j} \) from the set \( Q \), the times needed under the worst circumstance are \((k-1), (k-2), \ldots, (2), (1)\). The total number of times is:
\[ (k-1)+(k-2)+\cdots+2+1 = \frac{k^2-k}{2} = \frac{k^2}{2} \]  
\( (11) \)

2) When updating the distance \( d_{v_i} \), all the neighbors need to be found, so the total number of times is the number of connection line, which is expressed as \( E \).

The time complexity is:
\[ O\left(\frac{k^2}{2}+E\right) \sim O(n^2) \]  
\( (12) \)

In the above-mentioned time complexity analysis of Dijkstra’s algorithm for PD location, it can be seen that the
process of finding the distance $d_{V_i}$ from the $Q$ set greatly affects the performance of the algorithm. Hence heap optimization is introduced to reduce the complexity to $O(n \log n)$.

IV. THE EXPERIMENTAL VERIFICATION FOR TDOA DATABASE MODEL

Two experiments are carried out to verify the feasibility and accuracy of the TDOA database model for PD location.

A. THE EXPERIMENT CARRIED OUT WITH THE 110KV POWER TRANSFORMER

1) EXPERIMENTAL SET UP

The first experiment is conducted with an 110kV transformer, of which the basic parameters are shown in Table I. The appearance of the tested transformer is shown in Fig. 6. The length, width and height of the transformer are 2.83m, 1.828m and 1.88m, respectively. One vertex of the tank shown in Fig. 6 is chosen for the origin of coordinates. Four UHF sensors are installed on the tank of the tested transformer shown in Fig. 7 and 8. The sensors should be installed as far as possible in three dimensions, for example, not on the same side of the tested transformer. And the sensors should not be close to the metal parts inside the transformer [6, 12, 24]. The coordinates of the sensors in the first experiment are Sensor1 (0.2m, 0, 1.53m), Sensor2 (2.63m, 0, 1.53m), Sensor3 (2.53m, 1.82m, 1.58m), Sensor4 (0.2m, 1.82m, 0.3m). The bandwidth of the installed sensors is 300MHz to 1500MHz. The sampling rate of the high-speed analog-to-digital converter is 1.5GSA/s.

<table>
<thead>
<tr>
<th>Transformer Parameters</th>
<th>Numerical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>YD-25/110</td>
</tr>
<tr>
<td>Rated Capacity</td>
<td>25kVA</td>
</tr>
<tr>
<td>Nominal Voltage</td>
<td>0.38/110kV</td>
</tr>
<tr>
<td>Rated Current</td>
<td>65.7/0.23A</td>
</tr>
<tr>
<td>No-load Current</td>
<td>&lt;10%</td>
</tr>
<tr>
<td>Connection Symbol</td>
<td>1/1–0</td>
</tr>
<tr>
<td>Rated Frequency</td>
<td>50Hz</td>
</tr>
</tbody>
</table>

To generate a partial discharge source, a needle type electrode and a ring type electrode are installed inside the power transformer shown in the Fig. 7. The coordinates of the set PD source are (1.2m, 0.8m, 1.6m), which is near the center of the tank.

2) THE ESTABLISHMENT OF TDOA DATABASE

The front, left and vertical views of the three-dimensional transformer model are shown in Fig. 8.

In Fig. 8, the cylinder simulates the winding and the core of the tested 110kV transformer. Four sensors are labelled in different colors for ease of reference. It can be seen that Sensor1 and Sensor2 are installed on the same face of the tank and Sensor3 and Sensor4 are on the opposite face. The height of Sensor4 is lower than the other three sensors.

After coping with all the points inside the tank, the TDOA database is established based on Dijkstra’s algorithm. In the first experiment, the spatial resolution is 0.02m. Taking the point (1.1m, 1.5m, 1.1m) near the winding for example, the transmission paths between the possible PD source to different sensors are shown in Fig. 9.
FIGURE 9. The transmission paths of the point (1.1m, 1.5m, 1.1m).

From Fig. 9, it can be found that there is no obstacle between the point (1.1m, 1.5m, 1.1m) and Sensor 1, 3, and 4, so the corresponding path is a straight line. However, the core obstructs the transmission between the sample point and Sensor 2. The transmission path is shown from another angle in Fig. 10.

FIGURE 10. Two clear deviations of the transmission paths from another angle.

It can be seen that two deviations have been made to minimize the transmission distance between the sample point and Sensor 2 from Fig. 10. By searching the established TDOA database, the time difference of arriving at different sensors from the sample point (1.1m, 1.5m, 1.1m) can be attained as follows:

\[
\begin{align*}
    t_{14} &= t_1 - t_4 = 2.67\,\text{ns} \\
    t_{24} &= t_2 - t_4 = 5.33\,\text{ns} \\
    t_{34} &= t_3 - t_4 = 1.33\,\text{ns}
\end{align*}
\]  

(13)

3) PD SOURCE LOCATION RESULT AND ANALYSIS

After establishing the transformer model and the TDOA database, the tested transformer is connected to all sensors, the voltage-applied system and the detecting instruments. After the transformer is in normal working condition, TDOA data collection is conducted for 80 times and the location of the PD source is shown in Fig. 11. Fig. 12 shows the UHF signal waveforms detected by 4 sensors. The waveforms have different shapes and amplitudes.

FIGURE 11. The three views of the location result in the experiment with the 110kV transformer.

The marked area in Fig. 11 is composed of seven cubes and a sphere. The cubes represent the location results, among which the red cube represents the most frequent result in the 80 times detections. The red sphere is the average of all the possible location results. The marked area is shown in details in Fig. 13.
From the front, left and vertical views of the detailed location result area, it can be found that the red sphere and the red cube nearly coincide. The average location of the PD source in the first experiment is (1.3m, 0.7m, 1.3m). The transmission paths between the result point to different sensors are shown in Fig. 14.

From searching the established TDOA database, the time difference of arriving at different sensors from the result location point (1.3m, 0.7m, 1.3m) can be attained as follows:

\[
\begin{align*}
\tau_{14} &= t_1 - t_4 = -2.67\text{ns} \\
\tau_{24} &= t_2 - t_4 = -4.00\text{ns} \\
\tau_{34} &= t_3 - t_4 = -3.33\text{ns}
\end{align*}
\]  (14)

The comparison and error calculation between the actual position and the experimental result are made in Table II.

From Table II, it can be calculated that the coordinates error is (0.1m, 0.1m, 0.1m). The errors of the three different dimensions are the same mainly because the installation of the four sensors is uniformly distributed on the tank of the tested transformer. The absolute error of distance is 0.17m which is lower than 0.3m satisfying the need of the experimental location.

B. THE EXPERIMENT CARRIED OUT WITH THE PLATFORM FOR PARTIAL DISCHARGE OF ELECTRIC POWER EQUIPMENT

1) EXPERIMENTAL SET UP

The second experiment is conducted with a platform for PD of electric power equipment. The appearance of the platform is shown in Fig. 15. The length, width and height of the tank are 4m, 1.9m and 2.5m, respectively. Four UHF sensors are installed on the tank of the platform shown in Fig. 15. The coordinates of sensors are Sensor1 (2.15m, 0m, 2.35m), Sensor2 (3.9m, 0m, 1.3m), Sensor3 (2.11m, 1.9m, 0.21m) and Sensor4 (0.2m, 1.9m, 1.16m). The bandwidth of the installed sensors is 300MHz to 1500MHz. The sampling rate of the high-speed analog-to-digital converter is 1.5GSA/s.

Two groups of sub-experiments are conducted in the platform shown in Fig. 15. One is the location of a single PD source in different areas inside the platform. The coordinates of the set PD sources are (2.2m, 1.7m, 0.1m) and (3.9m, 1.7m, 1.0m), respectively. The other is to locate two PD sources simultaneously. The coordinates of the set PD sources are (2.2m, 1.1m, 1.3m) and (3.9m, 1.6m, 1.2m). It should be
pointed out that as the experimental methods and experimental procedure are basically the same, so there is no need to give elaborate descriptions in every sub-experiment.

2) THE ESTABLISHMENT OF TDOA DATABASE

The front, left and vertical views of the three-dimensional platform model are shown in Fig. 16.

![Fig. 16. The three views of the established platform model.](image)

In Fig. 16, the cylinders simulate the windings and the cores inside the platform. Four sensors are labelled in different colors for ease of reference. It can be seen that Sensor 1 and Sensor 2 are installed on the same face of the tank and Sensor 3 and Sensor 4 are on the opposite face. The height of Sensor 3 is the lowest, and the height of Sensor 1 is the highest. The locations of Sensor 1 and 3 are nearly on the median of the face. In the second experiment, the spatial resolution is 0.02m. The $v_x$ in equation (5) is $3 \times 10^8 m/s$. Taking the point (2.7m, 0.4m, 1.3m) as an example, the transmission paths between the possible PD source to four sensors are shown in Fig. 17.

![Fig. 17. The transmission paths of the point (2.7m, 0.4m, 1.3m).](image)

3) PD SOURCE LOCATION RESULTS AND ANALYSIS

In the first sub-experiment, the set PD source is located at the coordinates of (2.2m, 1.7m, 0.1m), which is at the center of the platform near Sensor 3.

After the platform is in normal working condition, TDOA data collection is conducted for 40 times and the location results of the PD source is shown in Fig. 18. Since the front, left and vertical views cannot show the location results clearly, a partially enlarged PD location image is shown as follows:

![Fig. 18. The partially enlarged views of the location results in the first sub-experiment.](image)

The average location of the PD source is (2.2m, 1.8m, 0.2m). The transmission paths between the result point to different sensors are shown in Fig. 19. Fig. 20 shows the UHF signal waveforms detected by 4 sensors.

![Fig. 19. The three views of the transmission paths from the result point (2.2m, 1.8m, 0.2m) to different sensors.](image)
The UHF signal waveforms detected by 4 sensors in the first sub-experiment.

The time difference of arriving at different sensors from the result location \((2.2, 1.8, 0.2)\) can be attained as follows:

\[
\begin{align*}
    t_{21} &= t_2 - t_1 = 0\text{ ns} \\
    t_{31} &= t_3 - t_1 = -8.67\text{ ns} \\
    t_{41} &= t_4 - t_1 = -2.00\text{ ns}
\end{align*}
\]  

The comparison and error calculation between the actual position and the experimental result are made in Table III.

<table>
<thead>
<tr>
<th>Actual PD Position (m)</th>
<th>Experimental Result (m)</th>
<th>The Absolute Error of Distance (m)</th>
<th>The Relative Error of Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>((2.2, 1.7, 0.1))</td>
<td>((2.2, 1.8, 0.2))</td>
<td>0.14</td>
<td>2.43%</td>
</tr>
</tbody>
</table>

From Table III, it can be calculated that the coordinates error is \((0, 0.1, 0.1)\). The error of X-axis is 0 mainly because the distribution distance of the four sensors in the X-axis direction is larger than the distribution distance in the Y-axis direction and the Z-axis direction, which means the location accuracy is much higher. The absolute error of distance is 0.14m which is lower than 0.3m satisfying the need of the experimental location.

In the second sub-experiment, the set PD source is located at the coordinates \((3.9, 1.7, 1.0)\), which is at the corner of the platform. TDOA data collection is conducted for 40 times and the location results of the PD source is shown in Fig. 21. Fig. 22 shows the UHF signal waveforms detected by 4 sensors.

FIGURE 20. The UHF signal waveforms detected by 4 sensors in the first sub-experiment.

FIGURE 21. The location results in the second sub-experiment.

FIGURE 22. The UHF signal waveforms detected by 4 sensors in the second sub-experiment.
The time difference of arriving at different sensors from the result location point (1.3m, 0.7m, 1.3m) can be attained as follows:

\[
\begin{align*}
    t_{21} &= t_2 - t_1 = -3.33\text{ns} \\
    t_{31} &= t_3 - t_1 = -2.67\text{ns} \\
    t_{41} &= t_4 - t_1 = 3.33\text{ns}
\end{align*}
\]

(17)

The error analysis between the actual position and the experimental result is made in Table IV.

<table>
<thead>
<tr>
<th>Actual PD Position (m)</th>
<th>Experimental Result (m)</th>
<th>The Absolute Error of Distance (m)</th>
<th>The Relative Error of Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>(3.9, 1.7, 1.0)</td>
<td>(3.9, 1.5, 1.1)</td>
<td>0.22</td>
<td>1.13%</td>
</tr>
</tbody>
</table>

From Table IV, it can be calculated that the coordinates error is (0m, 0.2m, 0.1m). The distance error is 0.22m which is lower than 0.3m satisfying the need of the experimental location.

In the third sub-experiment, two PD sources are placed at the coordinates of (2.2m, 1.1m, 1.3m) and (3.9m, 1.6m, 1.2m). One of the PD sources is at the center and the other is at the corner of the tank. This sub-experiment is carried out to locate two PD sources simultaneously. Since the discharge time of PD sources is short, the insulation needs restoration time to perform the next discharge. Therefore, the duty ratio of the discharge pulse is small which means the probability of simultaneous discharge of multiple discharge sources is rare. That is to say, the sensors will only receive the PD signal from only one PD source at one time. In the localization results, different PD sources are separately located in different areas.

TDOA data collection is conducted for 40 times and the location results of the PD source is shown in Fig. 24. Fig 25 shows the UHF signal waveforms detected by 4 sensors. The amplitude of the detected waveforms retains the same level compared to the first and second sub-experiments because the duty ratio of discharge is low.
The two main areas where the results locate.

As the location results are divided into two parts, the average of all the results represented by the red sphere is meaningless. Two average results should be calculated according to the data collected in the corresponding area, respectively. The location result in the gap area between two cores is shown in Fig. 27.

The location result near the corner of the platform is shown in Fig. 29.

The comparison and error calculation between the actual position and the experimental result are made in Table V.

The time difference of arriving at different sensors from the result location point (2.2m, 1.3m, 1.5m) can be attained as follows:

\[
\begin{align*}
t_{21} &= t_{2} - t_{1} = 2.00 \text{ ns} \\
t_{31} &= t_{3} - t_{1} = -0.67 \text{ ns} \\
t_{41} &= t_{4} - t_{1} = 2.00 \text{ ns}
\end{align*}
\] (18)

The time difference of arriving at different sensors from the result location point (3.9m, 1.6m, 1.1m) can be attained as follows:

\[
\begin{align*}
t_{21} &= t_{2} - t_{1} = 2.00 \text{ ns} \\
t_{31} &= t_{3} - t_{1} = -1.00 \text{ ns} \\
t_{41} &= t_{4} - t_{1} = 2.33 \text{ ns}
\end{align*}
\] (19)
From Table V, it can be calculated that the coordinates errors are (0m, 0.2m, 0.2m) and (0m, 0m, 0.1m). The distance errors are 0.28m and 0.1m, which are both lower than 0.3m satisfying the need of the experimental location. Table VI shows a comparison between TDOA database method with other localization methods [14, 25-26].

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REFERENCES

V. CONCLUSION AND PROSPECT
This paper proposes a new method that is based on the TDOA database to solve the problem of PD source location, which can solve the location of multiple PD sources and does not have the non-convergence problem. The location error in the tested 110kV power transformer is less than 0.2m. The location error in the PD simulated platform is less than 0.3m. In addition, to achieve even better location accuracy, the tested UHF sensors should be installed as far as possible in the direction of three axes. Since the windings are modelled as a forbidden region, the PDs occurring inside the windings cannot be located with the tangent transmission model. On that occasion, the windings should not be a forbidden region and it should be assumed that the signal can travel out through oil duct at the speed of light in oil with a new transformer model, which will be our future work.


Naifan Xue received the B.S. degree in electrical engineering from North China Electric Power University, Beijing, China, in 2016. He is currently pursuing the M.S. degree in electrical engineering at Shanghai University of Electric Power, Shanghai, China. His research interest includes the condition monitoring, the detection and location of PD sources in high voltage equipment.

Junjie Yang received his B.S. and M.S. degrees both from Changchun University of Science and Technology, in 1998 and 2001, respectively, and the Ph.D. degree from Shanghai Jiao Tong University in 2005. He is a full professor of Shanghai Dianji University. His research interest includes smart grid, wireless sensor networks, diagnosis of power equipment and optical networks.

Daoyi Shen received his B.S. and Ph.D. degree in signal and information processing from University of Science and Technology of China, in 2003 and 2008, respectively. From 2008 to 2013, he was an engineer in the State Grid Shanghai Municipal Electric Power Company. Since 2013, he has been the vice president in Shanghai Global Technology Co., Ltd. His research interest includes PD signal processing in high voltage equipment and the detection and location of PD sources.

Kaixu Yang received the B.S. degree in electrical engineering from Changzhou University, Changzhou, China, in 2017. He is currently pursuing the M.S. degree in electrical engineering at Shanghai University of Electric Power, Shanghai, China. His research interest includes the condition monitoring and the optimization scheduling in microgrid.

Zhuhang Zhuo received the B.S. degree in electrical engineering from Wenzhou University, Wenzhou, China, in 2017. He is currently pursuing the M.S. degree in electrical engineering at Shanghai University of Electric Power, Shanghai, China. His research interest includes the condition monitoring and the optimization scheduling in microgrid.

Linnan Zhang received the B.S. degree in electrical engineering from North China Electric Power University, Baoding, China, in 2017. He is currently pursuing the M.S. degree in electrical engineering at Shanghai University of Electric Power, Shanghai, China. His research interest includes the condition monitoring, the detection and location of PD sources in high voltage equipment.

Jinshui Zhang received the B.S. degree in electronic and information Engineering from Minnan Normal University, Fujian, China, in 2018. He is currently pursuing the M.S. degree in electrical engineering at Shanghai University of Electric Power, Shanghai, China. His research interest includes the condition monitoring, the detection and location of PD sources in high voltage equipment.