Partial Discharge Angle of Arrival Estimation Using UHF Wireless Sensor Array

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Abstract. The detection and localization of partial discharge (PD) in air-insulated substations by ultra-high frequency (UHF) technology is widely studied. Existing UHF PD localization system mainly focus on time-difference of UHF signal, which requires very high synchronized sampling rate. This paper proposes a received signal strength (RSS) based angle of arrival (AoA) method by a circle UHF wireless sensor array. An AoA estimation scheme is derived through the radiation pattern of designed UHF antenna. Interpolation and neural network are applied to improve the AOA resolution. A field test is performed to verify the effectiveness of the proposed PD localization system. The results show that the estimated error on average is below 7°. Compared to the time-difference-based method, the accuracy of our designed system is more feasible for practical application considering its significant low-cost feature.

1. Introduction
Partial discharge (PD) is one of the main causes of power equipment insulation failure in substation. Localization of PD can provide information for condition monitoring and diagnosis of power equipment [1-2]. Ultra-high frequency (UHF) detection technology has been applied in practice because of high sensitivity and strong anti-interference [3-5]. Different from the method of installing UHF sensors on specific equipment, researchers in University of Strathclyde propose a method of monitoring and localization PD in open substation using the UHF sensor array [6-7], which reduce the installation cost and maintenance work UHF sensors.

The UHF monitoring technology of PD in open substation often adopt Time of Arrival (TOA) or Time Difference of Arrival (TDOA). These methods require sensors to have a high time synchronization of nanosecond and a sample rate of several gigahertz. And it leads to a high hardware cost and a poor portability [8]. Recently, the UHF monitoring technology of PD based on Received Signal Strength (RSS) has received great interest in the world because its lower equipment costs and better environmental adaptability [9-10].

The paper combines the localization of PD based on UHF RSS with the technology of wireless sensor array and proposes an Angle of Arrival (AOA) estimation in open substation with low costs. In this paper, we design a circle UHF wireless sensor array in terms of the radiation pattern of each sensor. The radiation shape of the monopole antenna we used is not isotropic and has a maximum value and a minimum value at the specific angle. The minimal RSS is searched for to calculate the
angle of PD. Interpolation methods are applied to improve the AOA resolution. To verify the proposed algorithm, a field test is carried out in the high voltage test laboratory. The results show the mean of estimation error is less than 8°.

The rest of the paper is organized as follows. In section II, we introduce the basic principle of the AOA estimation based on RSS. Section III presents the algorithm of the RSS-based AOA estimation using UHF wireless sensor array. Section IV shows a field test and corresponding results. Section V compare the proposed method with time-difference-based PD source localization method. And section VI concludes the paper.

2. Basic Principle of AOA Estimation Based on RSS

The paper uses the PCB elliptical monopole UHF antenna whose radiation patterns at 1100 MHz of the sensor are shown in Fig. 1. It can be observed that the maximum value towards Z axis positive direction and decrease to XOY plane to achieve the minimum value. And there is an enhancement in the negative half axis of X axis. Usually the antenna is installed in a mental container and encapsulated with transparent electromagnetic material in the positive direction of the Z axis. Due to electromagnetic shielding effect, the enhancement in the negative half axis of X axis disappears and the minimum value is in the negative half axis of X axis.

![Figure 1. Radiation Patterns at 1100 MHz of the UHF Sensor.](image)

The main parameters of PD UHF wireless sensor we use are: the input UHF signal bandwidth is from 300MHz to 1500MHz with a 2.7MHz A/D sampling rate to obtain the RSS value of PD UHF signal.

To put it simply, the AoA of PD source is decided by the sensor position of the array that receives the maximum or minimum UHF RSS value. Fig. 2 shows the preliminary test of a sensor array where four sensors are set towards 0°, 90°, 180° and 270° respectively. The picture conveys that when the electromagnetic signal produced by PD is positive to each of four sensors, its RSS value is largest, while the RSS value is smallest when PD is back to the sensor.

![Figure 2. Preliminary Test of Original Sensor Array.](image)
3. RSS-Based AOA Estimation Method Using UHF Wireless Sensor Array

Based on the preliminary test, an AOA estimation system by UHF wireless sensor array is proposed and depicted in Fig. 3. Twelve sensors, written as S1, S2, ..., S12, are placed evenly in a circle frame. When the PD happens somewhere, the sensors in the array receive RSS data and differences between data are using to find the angle of PD source. Considering that the gradient near the maximum value of the signal is small, the gradient near the signal minimum is large. We search for the minimum’s angle and the angle of PD source is got by adding or subtracting 180° to the minimum’s angle.

![Figure 3. Scheme of AoA Measuring System with Round UHF Wireless Sensor Array.](image)

After PD happens, twelve received RSS data are screened and calibrated to calculate the AOA. Interpolation and neural network algorithm are used to improve the resolution. The flow chart of AOA estimation algorithm is shown in Fig. 4.

![Figure 4. Algorithm for AoA Estimation.](image)
3.1. Data Preprocessing

Since there are subtle differences in the manufacture of 12 sensors, it is necessary to perform consistency calibration on the 12 sensors. PD test is performed under the same environment, and the average value of each sensor which receive the same PD signal is recorded as \([F_1, F_2, \ldots, F_{12}]\). The calibration coefficient \(f_i\) is obtained by:

\[
f_i = \frac{F_i}{F_i} \quad i = 1, 2, \ldots, 12
\]  

(1)

The received data is a \(m \times n\) matrix, written as \(\psi'\):

\[
\psi' = \begin{bmatrix}
  s'_{1,1} & s'_{1,2} & \cdots & s'_{1,n} \\
  s'_{2,1} & s'_{2,2} & \cdots & s'_{2,n} \\
  \vdots & \vdots & \ddots & \vdots \\
  s'_{m,1} & s'_{m,2} & \cdots & s'_{m,n}
\end{bmatrix} = [S'_1, S'_2, \ldots, S'_n]
\]  

(2)

where \(m\) is the number of data samples and \(n\) is the number of sensors. The matrix \(\Psi\) is achieved by dividing \(\psi'\) by \(f_i\) to reduce consistency differences:

\[
\psi = \begin{bmatrix}
  s_{1,1} & s_{1,2} & \cdots & s_{1,n} \\
  s_{2,1} & s_{2,2} & \cdots & s_{2,n} \\
  \vdots & \vdots & \ddots & \vdots \\
  s_{m,1} & s_{m,2} & \cdots & s_{m,n}
\end{bmatrix} = \begin{bmatrix}
  S'_1 \\
  S'_2 \\
  \vdots \\
  S'_n
\end{bmatrix} \cdot \begin{bmatrix}
  f_1 \\
  f_2 \\
  \vdots \\
  f_n
\end{bmatrix}
\]  

(3)

The voltage of PD between each sample has a little fluctuation although the voltage value is set the same on the equipment. Normalization is applied in each sample of 12 sensor data:

\[
s_{i,j} = \frac{s_{i,j}}{\sum_{j=1}^{12} s_{i,j}} / 12 \quad i = 1, 2, \ldots, m
\]  

(4)

Normalization not only preserves the relative relationship between the same set of 12 data, but also reduces the impact of fluctuation of voltage of PD on each sample data.

3.2. Neural Network Training

After calibration and normalization of collected data, the data should be selected for interpolation. Neural network is a powerful tool for learning nonlinear complex system. This paper introduces back propagation neural network (BPNN) [11]. The typical architecture of BPNN is shown in Fig. 5.

![Figure 5. Architecture of BPNN.](image-url)
BPNN usually has three layers: input layer, hidden layer and output layer. The number of neurons in input vector $X$ is equal to the number of inputs. The output vector $Y$ is one-dimensional. The result is 1 or 0. When the variable of inputs has a big difference between the column vectors of the matrix, the result of output layer is 0. Otherwise, the result is 1. If the variable fluctuates a lot compared to the mean value of the column vector, the AOA estimation is inaccurate.

3.3. Curve Fitting and Interpolation
When the data is preprocessed, the row vector are applied to find the smallest value by curve fitting and interpolation. Cubic spline interpolation algorithm is used in this paper. Since the sensors are evenly placed in a circle, the interval of angle for each sensor is 30°. When the data is curve fitted, the sequence $[0^\circ, 30^\circ, \ldots, 330^\circ]$ is regard as abscissa data, and twelve RSS data are regard as ordinate data. To reduce the error of AOA estimation, the 1st column vector’ data are copied to the right of the 12th column vector’s data as the 13th column vector’s data. That is in line with reality that the sensor S1 is adjacent to sensors S2 and S12 at the same time.

Cubic spline interpolation uses the 3rd-degree polynomials at each of the intervals:

$$s(x) = a_j x^3 + b_j x^2 + c_j x + d_j$$

where $x \in (x_j, x_{j+1})$, $j = 1, 2, \ldots, n$ and $s(x_j) = s_{i,j}$, $s(x_{j+1}) = s_{i,j+1}$. The coefficients $a_j, b_j, c_j, d_j$ are to be resolved.

Considering the smoothness conditions at each connection node, the equation set can be achieved:

$$\begin{align*}
    s(x_j - 0) &= s(x_j + 0) \\
    s'(x_j - 0) &= s'(x_j + 0) \quad j = 2, 3, \ldots, n \\
    s''(x_j - 0) &= s''(x_j + 0)
\end{align*}$$

(6)

There are $4n-2$ equations, plus each node has an equation. While there are $4n$ unknown numbers, two equations need to be added. We choose default boundary conditions. That is:

$$s''(x_1) = s''(x_n) = 0$$

(7)

After curve fitting and interpolation, the minimum value and its represented angle on the curve are searched for. The result of AOA estimation is addition or subtraction of the angle. The final AOA estimation is the average of all samples’ results.

4. Experimental Verification of the Proposed Method
A field test is performed as shown in Fig. 6. Twelve UHF wireless sensors are placed in a circle mental frame with a diameter of 50 cm. And the frame is on a tripod which is about one-meter height. The PD source is EM TEST DITO, which meets EN/IEC 61000-4-2 standard that set to generate PD signal per second and is 5 m far away from the sensor array.

Figure 6. The Test Environment.
The angle of PD source is set $240^\circ$ and the mobile phone receive 3000 RSS data. Fig. 7(a) shows the cubic spline interpolation of RSS data and Fig. 7(b) shows AoA results of cubic spline interpolation. Most of points are between $240^\circ$ and $300^\circ$, but there are several points out of this range and the results are dispersive. The results of AoA after BPNN is shown in Fig. 8. The points in Fig. 8 are denser and between $240^\circ$ and $270^\circ$. The average value of the points in Fig. 8 is $245.9^\circ$. We can see that BPNN can reduce the noise points and improve the accuracy of AoA.

![Figure 7. Cubic Spline Interpolation.](image1)

![Figure 8. AoA Results of Cubic Spline Interpolation after BPNN Training.](image2)

The statistical details are also reported in Table 1. The average error of AoA is $6.9^\circ$.

| Parameters               | Results |
|--------------------------|---------|
| Result of AOA estimation/°| 245.9   |
| Average error/°          | 6.9     |
| Maximum deviation/°      | 13      |
| Standard deviation/°     | 3.7     |
5. Conclusion
An RSS-based AOA estimation method by UHF wireless sensor array to locate PD source in air-insulated substation is proposed in this paper. The method is based on the sensor’s radiation pattern that the sensor has its maximum value and minimum value at specific angle. BP neural network and interpolation algorithm are used and significantly improved the AoA accuracy. The final average error of PD AoA by our proposed method is less than $7^\circ$.

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