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Error Analysis and Antenna Array Placement Optimization of Localization System for Partial Discharge in Substation

Abstract: *The measurement and diagnosis of partial discharge (PD) is accepted as one of the most valuable means for assessing the quality of high voltage (HV) power apparatus and its running status. However, the current partial discharge monitoring mainly based on equipment, which needs multi-process test equipment, high cost, and large maintenance engineering. This paper introduced the use of four antennas array to receive ultra-high frequency (UHF) signal, and define 3-D coordinate system, then located PD source in the field of the substation. Furthermore, this paper discussed the principles of the location algorithm based on time difference, analyzed the origin of its location error, then the connection of location error and the placement of antenna array and the error of time difference has been discussed theoretically. Finally, this paper provided the optimal placement of the radio frequency antenna array.*

Streszczenie. W artykule opisano czteroantenowy odbiornik sygnału UHF w zastosowaniu do analizy źródła wyładowania niezupełnego. Analizowano błąd określenia pozycji źródła w zależności od rozłożenia systemu anten. ***Analiza możliwości lokalizowania źródła wyładowania niezupełnego z wykorzystaniem czterech anten UHV***

Keywords: partial discharge; antenna array; localization algorithm; error analysis; optimal arrangement
Słowa kluczowe: wyładowanie niezupełne, anteny UHV, lokalizacja wyładowania

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Introduction

Partial Discharge (PD) is not only the indication of insulation degradation but also the cause of further insulation degradation [1]. Therefore, PD detection is the most effective method for insulation detection and diagnosis. The current PD detection and localization for substation equipment is mainly performed on single equipment. However, partial discharge fault may occur to any high-voltage power equipment in the substation. So PD monitoring device needs to be installed on every substation, which leads to the problems of high cost, low efficiency and large maintenance workload.

The PD detection system proposed in this paper is nothing like the conventional one which needs to be installed on single equipment for on-line monitoring. Instead, a group of ultra-high frequency (UHF) sensors array is installed within the space of entire substation to receive UHF electromagnetic waves produced by PD. Thus, only a single set of detection devices is needed for PD monitoring and pre-warning of all the substation equipment as well as PD analysis [2-7]. In this group of UHF sensors, the equipment or equipment parts are first screened preliminarily for any defects, after the defective equipment or equipment parts are located, detailed analysis and location will start [8-18]. The use of this group of sensor arrays has the advantages of low cost and high efficiency. The proposed system has been installed and put into operation in a 220kV substation.

University of Strathclyde in UK has conducted preliminary study and verification over the feasibility of partial discharge localization within the entire substation [2-7, 19-20]. In this paper the location algorithm based on time difference method is proposed after the system principle and realization methods are introduced. Then the main error sources are analyzed, and the relationship of localization error with the error of time delay sequence of the four channels of signals and that related to antenna array arrangement are derived theoretically. Finally, optimal arrangement of antenna array in the system has been proved and provided by quantitative analysis.

Principle of PD detection and localization system based on UHF antenna array

This system utilizes omnidirectional antenna array to receive UHF electromagnetic waves produced from PD to locate PD source in the entire substation. Four antennas are installed in the substation, and they are connected to the signal acquisition system to acquire and store UHF electromagnetic waves signals produced by the same PD source synchronously. Then the time delay sequence can be estimated by signal processing. Finally, the localization of PD sources in the entire substation is realized based on time delay sequence. The schematic diagram is shown in Fig.1.

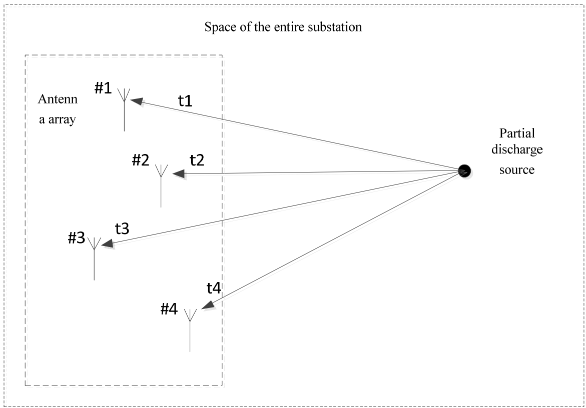

Fig.1. Schematic diagram for partial discharge detection and location system using antenna array

Fig.2. TVA early warning system installation

The Tennessee Valley Authority (TVA) installed an early warning system in a *69 kV* substation adjacent to a coal-fired power station. This site was chosen due to insulator pollution problems related to the particulates from the power station's combustion stacks. This trial began in December 2005 and is continuing to date (July 2008). Installation:

The system was installed in a relocatable trailer, the system is shown in Fig.2 [2].

The time for PD signal to propagate from certain point within the substation to the ith antenna of the UHF antenna array is denoted as *i*, the 3D coordinates of the i^{th} antenna is (x_i, y_i, z_i); and the coordinates of the PD source is (x, y, z). Then, the localization equation set obtained through spatial and geometric analysis is:

$$(1)\qquad \begin{cases} c\Delta t_{12} = d_1 - d_2 \\ c\Delta t_{13} = d_1 - d_3 \\ c\Delta t_{14} = d_1 - d_4 \end{cases}$$

where Δt_{1i} is the time difference between PD signal received by the i^{th} antenna and PD signal received by the 1^{st} antenna. $\Delta t = \left(\Delta t_{12}, \Delta t_{13}, \Delta t_{14}\right)^T$, *c* is the propagation speed of electromagnetic wave, and d_i is the distance from the PD source to the i^{th} antenna, *i.e.*

$$(2)\qquad \begin{cases} \Delta t_{1i} = t_1 - t_i \\ c = 3.0\times 10^8 m/s \\ d_i = \sqrt{\left(x-x_i\right)^2 + \left(y-y_i\right)^2 + \left(z-z_i\right)^2} \end{cases}$$

The Newton iterative method is used to solve the nonlinear equation set (1), which obtains the position coordinates PD source. The block diagram of system realization is shown in Fig.3.

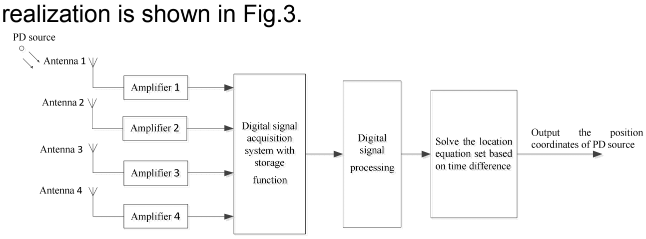

Fig.3. System implementation diagram

According to equation set (1), the location error of the detection system is mainly derived from error of wavefront arrival time for the signals received by the four antennas, and it is associated with the antenna array arrangement.

Error analysis of 3D localization algorithm based on time difference

Now, the relationship between localization error and antenna array arrangement and the error of time delay sequence of the received signal is analyzed.

Substituting equation (2) to equation set (1), and differentiating the two sides of equation set (1), it can be observed that

$$(3)\qquad c\cdot dt = J\cdot dX$$

where $dt = \left(d\Delta t_{12}, d\Delta t_{13}, d\Delta t_{14}\right)^T$ is the error of the time delay sequence of the received signals, $dX = \left(dx, dy, dz\right)^T$ is localization error of the system, and **J** is Jacobian matrix.

$$(4)\qquad J = \begin{pmatrix} \frac{x-x_1}{d_1}-\frac{x-x_2}{d_2} & \frac{y-y_1}{d_1}-\frac{y-y_2}{d_2} & \frac{z-z_1}{d_1}-\frac{z-z_2}{d_2} \\ \frac{x-x_1}{d_1}-\frac{x-x_3}{d_3} & \frac{y-y_1}{d_1}-\frac{y-y_3}{d_3} & \frac{z-z_1}{d_1}-\frac{z-z_3}{d_3} \\ \frac{x-x_1}{d_1}-\frac{x-x_4}{d_4} & \frac{y-y_1}{d_1}-\frac{y-y_4}{d_4} & \frac{z-z_1}{d_1}-\frac{z-z_4}{d_4} \end{pmatrix}$$

From equation (3), it can be observed that

$$(5)\qquad dX = J^{-1}\cdot c\cdot dt$$

$$(6)\qquad \left(dX\right)\left(dX\right)^T = c^2 J^{-1}\left(dt\right)\left(dt\right)^T\left(J^{-1}\right)^T$$

Denoting $P_{dX} = \left(dX\right)\left(dX\right)^T$, the localization error is evaluated by Euclidian 2-norm.

$$(7)\qquad \left\|dX\right\|_2 = \sqrt{dx^2+dy^2+dz^2} = \sqrt{tr\left(P_{dX}\right)}$$

where $tr\left(\cdot\right)$ denotes the matrix trace. From equations (4-7), it is observed that the localization error is associated to the error of time delay sequence and the relative position of PD source to each antenna. Now we study the relationship between the localization error and the arrangement of antennas array, when the time delay sequence is fixed. Assuming that $\left\|dt\right\|_2 = \sigma_t^2$, it is known from equations (6) and (7)

$$(8)\qquad \left\|dX\right\|_2 = \sqrt{tr\left(P_{dX}\right)} = c\sigma_t^2\sqrt{tr\left(J^{-1}J^{-T}\right)}$$

The inversion formula of matrix

$$(9)\qquad J^{-1} = \frac{1}{\det(J)}J^*$$

where $\det(J)$ is the determinant of J, and J^* is the adjoint matrix of J. Substitute equation (9) to (8)

$$(10)\qquad \left\|dX\right\|_2 = \frac{c\sigma_t^2}{\left|\det(J)\right|}\sqrt{tr\left[J^*\cdot\left(J^*\right)^T\right]}$$

Due to the properties of the adjoint matrix

$$(11)\qquad \left\|dX\right\|_2 = \frac{c\sigma_t^2}{\left|\det(J)\right|}\sqrt{tr\left[\left(J^TJ\right)^*\right]}$$

It can be proved that the matrix $\left(J^TJ\right)$ is positive definite. Denoting its eigenvalues $\lambda_1 \ge \lambda_2 \ge \lambda_3 > 0$, the eigenvalues of $\left(J^TJ\right)^*$ are $\lambda_2\lambda_3$ 、 $\lambda_1\lambda_3$ and $\lambda_1\lambda_2$, so

$$(12)\qquad tr\left[\left(J^TJ\right)^*\right] = \lambda_2\lambda_3+\lambda_1\lambda_3+\lambda_1\lambda_2$$

$$(13)\qquad \det(J^TJ) = \left(\det(J)\right)^2 = \lambda_1\lambda_2\lambda_3$$

Substitute equations (12) and (13) to equation (10)

$$(14)\qquad \left\|dX\right\|_2 = c\sigma_t^2\sqrt{\frac{\lambda_2\lambda_3+\lambda_1\lambda_3+\lambda_1\lambda_2}{\lambda_1\lambda_2\lambda_3}} = c\sigma_t^2\sqrt{\frac{1}{\lambda_1}+\frac{1}{\lambda_2}+\frac{1}{\lambda_3}}$$

According to arithmetic mean-geometric mean inequality

$$(15)\qquad \left\|dX\right\|_2 \ge 3c\sigma_t^2\sqrt{\frac{1}{\lambda_1+\lambda_2+\lambda_3}}$$

and

$$(16)\qquad \lambda_1+\lambda_2+\lambda_3 = tr\left(J^TJ\right) = \sum_{i,j=1}^{3}J_{ij}^2$$

where J_{ij} is element of the i^{th} row and j^{th} column of J. Substituting J, it is observed

$$tr\left(J^TJ\right) = \sum_{i=2}^{4}\left[\left(\frac{x-x_1}{d_1}-\frac{x-x_i}{d_i}\right)^2+\left(\frac{y-y_1}{d_1}-\frac{y-y_i}{d_i}\right)^2+\left(\frac{z-z_1}{d_1}-\frac{z-z_i}{d_i}\right)^2\right]$$

(17)

Since distance between the PD source and the antenna array is much farther than that between two array elements

$$(18)\qquad tr\left(J^TJ\right) \approx \sum_{i=2}^{4}\left[\left(\frac{x_1-x_i}{\bar{d}}\right)^2+\left(\frac{y_1-y_i}{\bar{d}}\right)^2+\left(\frac{z_1-z_i}{\bar{d}}\right)^2\right] = \frac{\sum_{i=2}^{4}d_{1i}^2}{\bar{d}^2}$$

then

$$\|dX\|_2 \geq 3c\sigma_t^2 \frac{\overline{d}}{\sqrt{\sum_{i=2}^{4} d_{1i}^2}} \tag{19}$$

where $\overline{d} = (d_1 + d_2 + d_3 + d_4)/4$ is average distance between the PD source and the antenna array, d_{1i} is the distance between the 1^{st} antenna and the i^{th} antenna.

According to equation (19), the localization algorithm will be with greater accuracy, when time delay estimation sequence of the received signal is more accurate, the PD source is closer to the antenna array, and the arrangement of the antenna array is more disperse. In the case that the arrangement of the antenna array plane area is limited, the sum of distance between the 1^{st} and other three antennas should be larger.

Quantitative analysis of the influence of antenna array arrangement on PD source localization

The antenna array composed of 4 antennas is arranged in the *30 x 50* (unit: *m*) area of the substation to receive UHF signals radiated from PD source. The above analysis indicates that the position coordinates of PD source can be obtained by solving equation set (1) based on the time difference between PD signals received by four antennas. Thus, PD source within the entire substance can be located. The following gives a discussion on the influence of antenna array arrangement on PD source localization.

Influence of the shape of antenna array arrangement on PD source localization

Firstly, the arrangement methods of antenna array within the small area of *10 x 6* (unit: *m*) in substation are considered.

Assuming that the position coordinates of the 4 antennas are respectively A_1 *(0, 0, 0)*, A_2 *(10, 0, 0)*, A_3 *(10, 6, 0)*, and A_4 *(4, 2, 5)*, the arrangement diagram is shown in Fig.4.

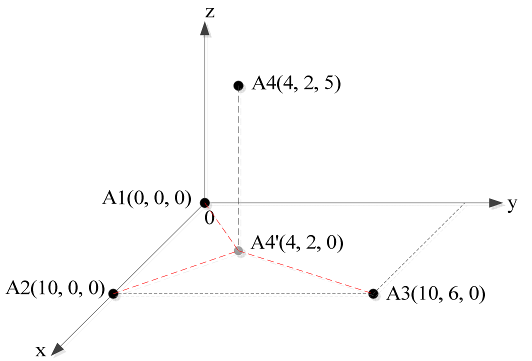

Fig.4. Antenna arrangement diagram of Y-shape (Unit: *m*)

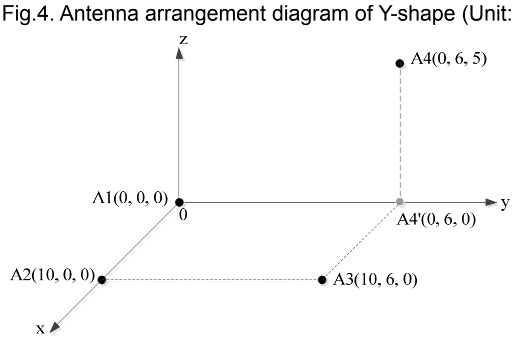

Fig.5. Antenna arrangement diagram of rectangle (Unit: m)

As shown in Fig.4, projection of the antenna array in *xoy* plane is Y-shape, and A_4' is the projection of A_4. Assuming that PD source is at the (20, 10, 3), the time delay sequence can be calculated to be $(27.01, 37.94, 15.20)^T$ (unit: ns), substitute the time delay sequence to the localization equations, the assumed location can be accurately solved. Assuming that the position coordinates of the 4 antennas are respectively A_1 (0, 0, 0), A_2 (10, 0, 0), A_3 (10, 6, 0), and A_4 (0, 6, 5), the arrangement diagram is shown in Fig.5.

As shown in Fig.5, projection of the antenna array in *xoy* plane is rectangle. Assuming that PD source is at *(20, 10, 3)*, the time delay sequence can be calculated to be *(27.01, 37.94, 15.20)* (unit: *ns*), substitute the time delay sequence to the localization equations, the assumed location also can be accurately solved.

Next, we consider the wave head time error PD of UHF signals received by the 1^{st} antenna. From equation (2) it can be known that this error will cause error of the time delay sequence. If the sampling rate of the acquisition system is *25 GHz*, the localization results for the two arrangements (see Fig.3. and 4.) are compared under the same time delay sequence error, as shown in Table 1.

Table.1 Location results of Y-shape and rectangle antenna array arrangement

Error Points	Rectangular Projection	Y-shaped Projection
0	(20, 10, 3)	(20, 10, 3)
1	(20.25, 10.8, 3.09)	(20.15, 11.72, 2.98)
2	(20.44, 10.95, 3.08)	(20.42, 12.1, 2.99)
3	(20.98, 10.68, 2.91)	(20.65, 12.44, 3)
4	(21.4, 11.43, 2.95)	(20.9, 12.88, 3)
5	(21.67, 11.69, 2.93)	(22.99, 11.99, 3.01)

According to arrangement of the antenna array and results comparison in Table.1, PD source localization is more precise for rectangular projection than for Y-shaped projection, when antenna array is arranged in similar area in a smaller scope in the entire substation. According to the result of equation (19), the perimeter of rectangular is longer than Y-shaped.

Influence of dispersity antenna array arrangement on PD source localization

Assuming that the position coordinates of the 4 antennas are respectively A_1 (0, 0, 0), A_2 (50, 0, 0), A_3 (50, 30, 0), and A_4 (0, 30, z_4), the antennas array diagram is shown in Fig.6.

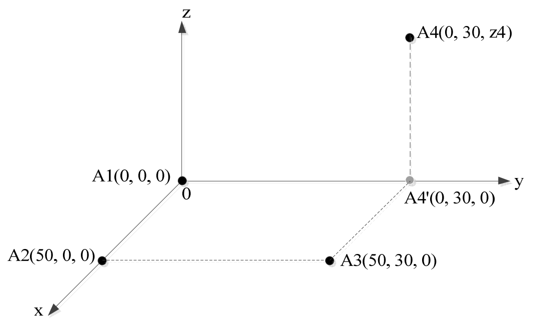

Fig.6. Antennas array diagram arranged on four corners of the substation (Unit: *m*)

By means of analyzing and calculating theoretically, the localization error is much small as this arrangement method of antenna array than the arrangement in a small scope in *3.1*, when the sampling rate of the system is *25 GHz*. Now we compare the localization error caused by error of wave head time of the UHF signal received by 1^{st} antenna at different height of the 4^{th} antenna, when the sampling rate is *1.5 GHz*. Assuming that PD source is at *(20, 10, 3)*, the localization results are shown in Table.2.

According to Table.2, the localization accuracy can be improved by increasing the height of 4^{th} antenna appropriately. From the geometric analysis, when all the antennas are arranged in *xoy* plane, *i.e.* $z_4=0$, the points which are symmetrical with respect to *xoy* have the same distance to each antenna. Thus, the localization result might be the symmetrical point even there is no errors. According to equation (19), the localization results can be more accurate, if the antenna array is arranged at 4corners of the substation than at a small scope, irrespective of the factor of attenuation of electromagnetic wave, when the sampling rate is not high enough.

By analyzing the localization results, when the antennas are arranged at the corners of the substation, the localization error in *xoy* plane is smaller than *50 cm*, when the antenna array is plane-arranged. The localization error at *z*-coordinate will be also smaller than 1m, when the 4^{th} antenna is raised *10 m*.

Table.2 Location results of antenna array arranged on 4 corners of substation

Height of A_4 / Error Points	$z_4 = 0$	$z_4 = 5$	$z_4 = 10$	$z_4 = 15$
0	(20, 10, -3)	(20, 10, 3)	(20, 10, 3)	(20, 10, 3)
1	(20.25, 10, 5.1)	(20.15, 10.2, 3.05)	(20.4, 9.7, 4)	(20.6, 9.6, 3)
2	(20.35, 10, 7)	(20.65, 9.6, 6)	(20.3, 9.9, 4)	(20.3, 9.8, 3.9)
3	(20.3, 10.2, 9.05)	(20.55, 9.8, 6.8)	(20.3, 10.5, 2)	(20.3, 10.5, 2)
4	(20.35, 10.6, 9.05)	(20.65, 9.4, 7.8)	(20.4, 10.6, 2)	(20.4, 10.6, 1.95)
5	(20.35, 10.6, 8.4)	(20.8, 9.6, 8.6)	(20.35, 10.7, 3)	(20.65, 10.6, 3)

Conclusions

This paper first presents the principle and realization methods of PD source localization system based on antenna array. The localization algorithm based on the time difference has been proposed in depth. Then the main error sources are analyzed and the relationship of the localization error with antenna array arrangement and with the error of time delay sequence is inferred. Finally, the optimal arrangement for UHF antenna array is given, with the following conclusions.

1) The localization algorithm will be with greater accuracy, when time delay estimation sequence of the received signal is more accurate, and the PD source is closer to the antenna array.
2) In order to obtain the accurate location of the PD source by the localization algorithm based on time delay sequence, the antenna array should be arranged as dispersedly as possible.
3) The accuracy of localization can be improved by increasing the height of one of the antennas appropriately.
4) When the antenna array must be arranged in a smaller area in substation, the localization accuracy will be greater as the perimeter is longer, for example the arrangement with rectangular projection on *xoy* plane corresponds to higher precision of PD source location than Y-shaped projection.

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