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Antenna Array Layout for the Localization of Partial Discharges in Open-Air Substations

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Abstract: Partial discharges are ionization processes inside or on the surface of dielectrics that can unveil insulation problems in electrical equipment. The charge accumulated is released under certain environmental and voltage conditions attacking the insulation both physically and chemically. The final consequence of a continuous occurrence of these events is the breakdown of the dielectric. The electron avalanche provokes a derivative of the electric field creating an electromagnetic impulse that can be detected with antennas. The localization of the source helps in the identification of the piece of equipment that has to be decommissioned. This can be done by deploying antennas and calculating the time difference of arrival (TDOA) of the electromagnetic pulses. However, small errors in this parameter can lead to great displacements of the calculated position of the source. Usually, four antennas are used to find the source but the array has to be correctly deployed to have minimal errors in the localization. This paper demonstrates by simulation and experimentally that the most common layouts are not the best options and proposes a simple antenna layout to reduce the systematic error in the TDOA calculation due to the positions of the antennas.

Keywords: Antennas; Radio-Frequency Localization; Partial Discharges; Particle Swarm Optimization

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1. Introduction

Measuring partial discharges (PD) helps in early warning systems to detect which piece of high voltage equipment is prone to failure. This type of events emit energy in radio-frequency bands so they can be detected with antennas. Moreover, if an array of antennas is strategically placed nearby the asset, the PD source can be located accurately. There are many references devoted to the localization of partial discharges inside transformers and GIS substations. In most cases, the source is surrounded by the antennas, so the location is straightforward and the accuracy is excellent. The difficulties appear when the source is outside the polygon created by the four antennas, then, the uncertainty in the possible solutions is notably higher. There is an interesting paper by Moore et al. that studies the location performance of two configurations forming a square and a star determining that the first one is the best option, [1]. There is also a mathematical study in [2] that concludes with some evident hints about how to place the antennas and test them in a square layout. Again, the square configuration is used in [3] and [4]. The authors in [4] further included a trapezoidal layout and tested the arrays in a 400 kV substation obtaining an experimental measure of the statistical error. However, the sources were included inside the polygon of the antenna layout so their analysis is different from what it is proposed in this paper. In our study we propose a trapezoidal layout forcing the PD source to be outside the polygon defined by the array. We show both, through a realistic modelling of different antenna deployments that takes into account errors in the measurement of the TDOA and by experimental measurements, that a trapezoidal array improves the performance of a squared deployment, having better accuracy and less dispersion than other configurations.

2. Finding the Radio-Frequency Source

The speed of propagation, c, the distance, D_i and the time t_i that takes a pulse in $\mathbf{P_s} = (x_s, y_s, z_s)$ to propagate in free space to the antenna i in $\mathbf{P_i} = (x_i, y_i, z_i)$ is given by:

$$D_i = c \cdot t_i = \sqrt{(x_i - x_s)^2 + (y_i - y_s)^2 + (z_i - z_s)^2} = \|\mathbf{P_i} - \mathbf{P_s}\| \tag{1}$$

Unfortunately, the absolute time of arrival is not known and it is necessary to measure the time difference of arrival to every pair of antennas to find the source position. The equation is then changed to:

$$D_{ij} = c(t_i - t_j) = \|\mathbf{P_i} - \mathbf{P_s}\| - \|\mathbf{P_j} - \mathbf{P_s}\| \tag{2}$$

The exact determination of the TDOA, $t_i - t_j$, is key to have an accurate position of the source and small variations in this parameter can induce a large uncertainty, [1].

There are multiple factors that can lead both to uncertainties or even errors in the TDOA. These factors have different origins that we have classified into three categories: due to the nature of the signal, due to the position of the antennas and due to the measuring procedure. This paper takes into account two of these three factors, the first one is how the antenna geometry affects the location performance and the second accounts for measurement errors that are generated under different circumstances such as the antennas position and their electrical response.

Our work assumes that there is a strong line-of-sight and that reflections are attenuated and delayed in such a way that they do not interfere in the free-space assumption and all other error sources will be encompassed in a single error given by the sampling time of the PD signal. Then, we will show that choosing an appropriate layout can reduce the uncertainty in the location of the source.

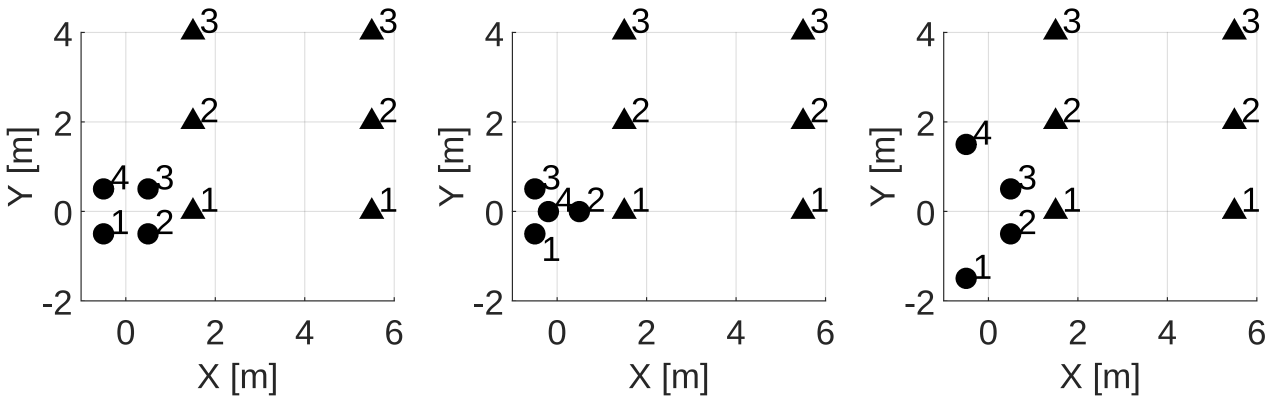
3. Antenna Deployment and Sensitivity to Measurement Errors

Finding the sensitivity to the different measurement error sources in the TDOA analytically in Equation (2) to obtain all possible solutions to the source position is a difficult task. The proposed approach assumes an error of one time sample, $|\epsilon_{ij}| = T_s$, sequentially in all six TDOA giving a total of $3^6 = 729$ possible solutions. Larger errors are not considered because the cluster of positions would be too vast and set far from the actual location.

Therefore, Equation (2) would be changed to $D'_{ij} - \|\mathbf{P_i} - \mathbf{P'_s}\| + \|\mathbf{P_j} - \mathbf{P'_s}\| = 0$ where D'_{ij} is the distance including the error $\pm\epsilon_{ij}$ and $\mathbf{P'_s}$ is the position of the source with the error in the TDOA. Let $\hat{\mathbf{P}}_\mathbf{s} = (\hat{x}_s, \hat{y}_s, \hat{z}_s)$ be the estimation of its position, setting the same equation for all pairs of antennas and summing all equations together gives:

$$f(\hat{x}_s, \hat{y}_s, \hat{z}_s) = \sum_{i=1}^{L-1} \sum_{j=i+1}^{L} \left(D'_{ij} - \|\mathbf{P_i} - \hat{\mathbf{P}}_\mathbf{s}\| + \|\mathbf{P_j} - \hat{\mathbf{P}}_\mathbf{s}\| \right)^2 \quad (3)$$

where L is the number of antennas and the distance differences have been squared to consider only positive values in the objective function. Equation (3) would be 0 for the correct estimation of $\hat{\mathbf{P}}_\mathbf{s}$, so any method that minimizes $f(\hat{x}_s, \hat{y}_s, \hat{z}_s)$ would give the position of the source. Particle swarm optimization (PSO) is a feasible option as shown in [5].



(a) Square array **(b)** Star array **(c)** Trapezoidal array

Figure 1. Three scenarios to test the performance of the antenna arrays.

The behavior of three different antenna arrays were tested for three positions of the source at two distances with the x component at $x = 1.5$ m and $x = 5.5$ m, Figure 1. In every scenario the PSO algorithm is run to obtain all possible solutions when there is an error of $\pm\epsilon_{ij}$ in the TDOA. Then, the solutions are analyzed statistically calculating the distance of the mean value in X and Y axis to the actual position of the source as a measure of the error in the localization; and the standard deviation of the distance of all possible values to the actual position, as a measure of the dispersion of the data. All antennas are in the same plane so the component z is not relevant in this study and the paper focuses the results in the plane XY. To have an adequate resolution in the Z axis, at least one of the antennas should be placed in a different plane.

Figure 2 shows simulation results with the source in $x = 1.5$ m. The triangle ($\triangle$) is the position of the source and the inverted triangle ($\bigtriangledown$) is the position of the mean of all data. The first row corresponds to the source in the position 1 of Figure 1 and the second row to the position 2. The position 3 was also simulated but it is not shown.

Table 1 contains the statistical measurements for all possible positions on Figure 1. The table on the left corresponds to $x = 1.5$ m and the table on the right to $x = 5.5$ m. Every row corresponds to positions 1, 2 and 3, respectively. Notice that the closest distances of the mean values in components x and y to the source corresponds to the proposed trapezoidal configuration. This configuration also shows the lowest dispersion in the data.

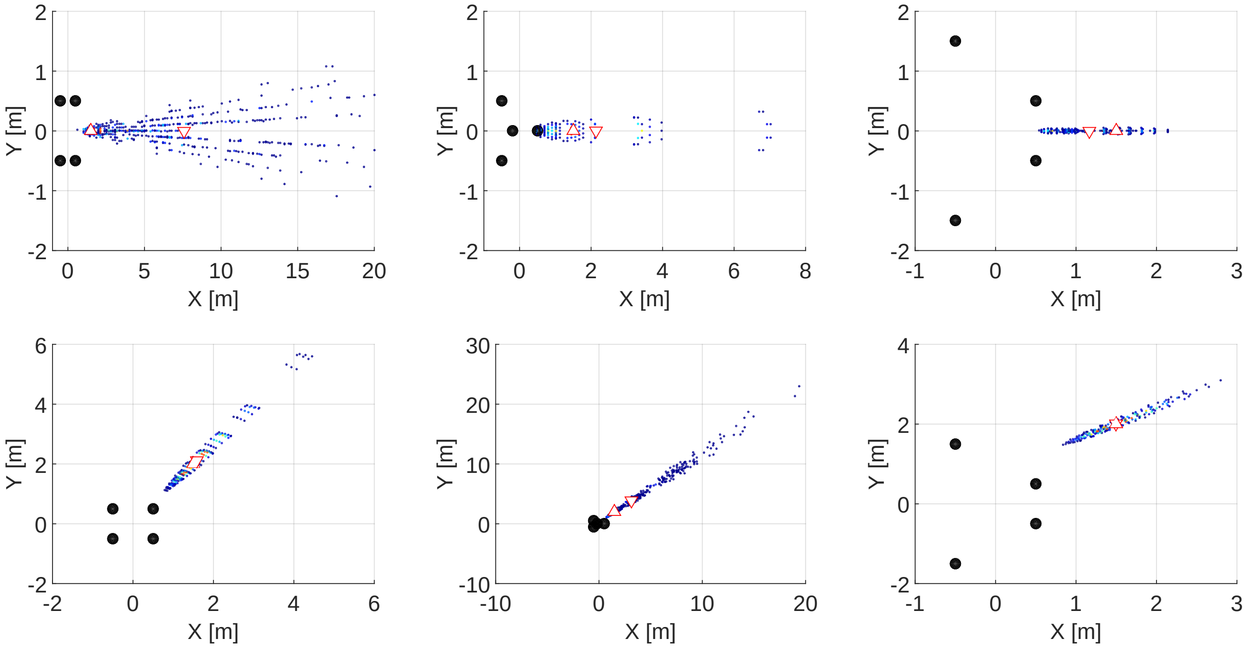


Figure 2. Simulation results for three antenna layouts and positions 1 and 2.

Table 1. Measurements of the error in the location and dispersion of data for the three antenna configurations. Left table $x = 1.5$ m and right table $x = 5.5$ m.

		Square	Star	Trapz
Pos 1	Mean	6.09	0.64	**0.34**
	Std	10.54	6.25	**0.28**
Pos 2	Mean	0.15	2.49	**0.01**
	Std	0.66	3.94	**0.25**
Pos 3	Mean	3.27	6.61	**1.53**
	Std	7.90	10.98	**3.10**

		Square	Star	Trapz
Pos 1	Mean	33.93	10.72	**1.57**
	Std	40.30	27.87	**1.67**
Pos 2	Mean	5.39	6.04	**0.71**
	Std	11.04	13.06	**1.00**
Pos 3	Mean	3.45	7.16	**0.23**
	Std	7.93	10.16	**1.61**

4. Experimental Study

The three antenna array layouts were tested in a laboratory. The antennas are monopoles 10 cm long which are omnidirectional and have good response in the range of frequencies where partial discharges emit [6]. All coaxial cables have the same length and are connected to an oscilloscope with four channels.

The partial discharge source is created using a 25 kV high-voltage cable connected to a voltage controlled transformer. A copper wire is bent to form a ring around the high-voltage cable and then, connected to ground. The resulting test object will have a high electric field divergence in that loop that will be able to create surface partial discharges.

The sampling frequency used in this paper is 5 GS/s, which corresponds to a sampling time $T_s = |\epsilon_{ij}| = 200$ ps. Differences in the TDOA below this time resolution will not be detected. Considering that the speed of propagation is the speed of light, c, the resolution in distance is 6 cm. Interpolation can help to artificially increase the resolution and improve the results [1,5], so the sampling time is increased tenfold using cubic splines. All measurements consist of a set of 500 partial discharges. The time differences of arrival are calculated using a cumulative energy method with negative slope, [5], and then, all TDOA greater $\pm\epsilon_{ij}$, one sample, are discarded to have the same conditions as in the previous section. The remaining TDOA are used to locate the source using PSO.

Experimental measurements were taken for positions 1 and 2 with $x = 1.5$ m, Figure 3, giving the error and dispersion results of Table 2. The best results are again obtained with the trapezoidal configuration which permits a more accurate positioning of the source with less dispersion. Only in position 1 has the star layout a slightly better dispersion. These results are better than those shown in Table 1 because in the simulations all possible deviations in the TDOA are analyzed while in the experimental results there is a limited number of cases; then, the dispersion in the simulations is higher than in the experimental results.

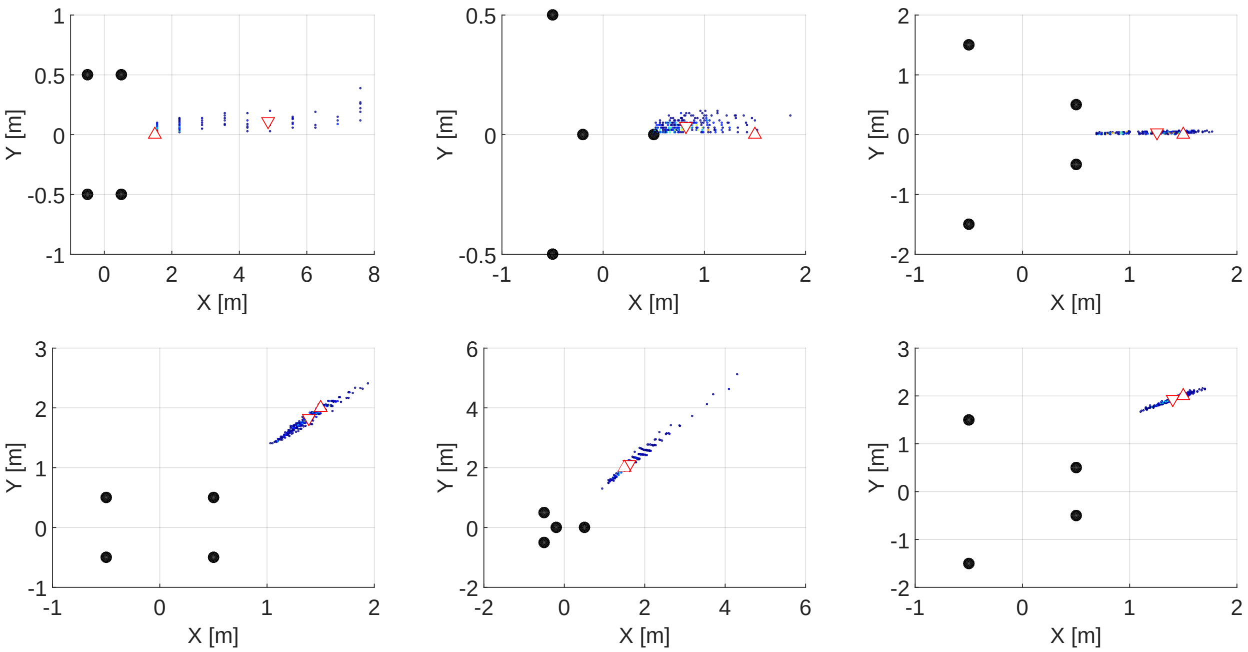


Figure 3. Experimental results for three layouts and position 1 and 2.

Table 2. Error in location and dispersion in experimental data. Left, position 1 and right, position 2.

	Square	Star	Trapz
Mean	3,35	0,69	**0,27**
Std	8,54	**0,21**	0,23

	Square	Star	Trapz
Mean	0,25	0,35	**0,14**
Std	0,17	0,48	**0,10**

5. Conclusions

Choosing an adequate layout of antennas can help in the localization of PD sources. This paper shows that the trapezoidal configuration can reduce the dispersion of the possible solutions of the source better than other configurations such as a square or a star. Additionally, the average value of all data in the components x and y is also closer to the actual position of the source. If the partial discharge source is far from the antenna array, the performance of the trapezoidal configuration is even better which is very appropriate when measuring this type of events in open air substations. The study in the axis Z has been omitted because all antennas are in the same plane; at least one of the antennas have to be placed outside the horizontal plane to have sufficient resolution in height if localization is space is intended.

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Conflicts of Interest

The authors declare no conflict of interest.

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