Improvements in AEPD location identification by removing outliers and post processing

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***Abstract*—The mathematical model of an Acoustic Emission Partial Discharge (AEPD) system is solved in the literature using Newton's method with redundant number of sensors (more than 4; eight in this case). The system for numerical experiments consists of eight sensors. The algorithm is implemented using three different initial guesses. For the calculated PD source coordinates, histograms are plotted. After finding the mean and standard deviation, coordinate values which are lying outside different fractions of sigma are removed. The average of remaining set is calculated and it is found that, the accuracy of location identification can be greatly improved.**

***Keywords*—acoutic emision; location identification; Newton's method; outlier; partial discharge; standard deviation**

I. Introduction

Partial discharge (PD) is a localized electric discharge that partially bridges the insulation between conductors. Local electrical stress concentration in the insulation causes PD. It has high significance on the life of insulation [1]. Even though the magnitude of partial discharges is small, they can cause progressive deterioration which leads to ultimate failure. There are electrical and acoustic methods for PD measurement [2]. Acoustic Emission (AE) methods have many advantages compared to electrical PD detection methods [3]. In large electrical apparatus like power transformers, locating the PD source is as important as detecting it. AE methods provide an indication of PD source location within an electrical apparatus. They are noninvasive and immune to electromagnetic noise. The sensitivity of this method does not vary with the test object capacitance.

To locate the PD source, mathematical model of an AEPD system is developed [4]. One of the methods to solve this mathematical model is iterative method (Newton's method) [5]. The major disadvantage of an iterative method is the need to have an initial guess. The convergence of solution is mainly dependent on the quality of the initial estimate [6]. Some of the other methods for solving the mathematical model of an AEPD system are genetic algorithm, semi definite relaxation etc. Genetic Algorithm (GA) cannot guarantee the convergence to exact root, but it will locate regions where the roots are likely to exist [7]. Semi definite relaxation seems to have advantage in locating AEPD even with the error in time delay measurement [8].

A minimum of four sensors are required to locate the PD source. Eight sensors are considered in the present work. This leads redundancy in number of sensors used, which can be used advantageously as all combinations may lead to convergence and successful location identification of AEPD. Therefore from the eight sensors, four sensors are considered at a time to form 70 ($^8C_4$) combination of sensors. The PD source is located using each combination separately. The average of the coordinate values of AEPD location found using this 70 combination of sensors is considered as the AEPD source location.

Statistical tools can be used for analyzing the results. Histogram is one such statistical tool. The purpose of a histogram is to graphically summarize the distribution of a data set. The most common form of the histogram is obtained by splitting the range of the data into bins (called classes) of equal size. From the histogram, outliers can be easily identified. An outlier is the one that does not belong to the same distribution as the bulk of the data. The solution can be improved by removing the outliers. In the present study the efficacy of this process is demonstrated.

II. Acoustic technique for PD source location

Acoustic emission techniques are passive, based on detecting the signals emitted from the discharge using suitable sensors. The output of these sensors is analyzed using a conventional data acquisition system. Multiple acoustic emission sensors are located on the transformer tank wall. By measuring the relative time of arrival of the acoustic wave at these sensors, the location of the PD within the transformer can be located [2].

A. Physical model

The physical model of an AEPD location system consists of multiple acoustic emission sensors located on the transformer tank wall. These sensors are named S_1, S_2 … S_n, where n is the total number of sensors used. The sensor nearest to the source of partial discharge receives the signal first [9]. This sensor is named S_1.Time delay of other sensors with respect to the sensor S_1 is calculated. These sensors are named S_2, S_3, S_4 etc., in the increasing order of their time delays. The physical model of an AEPD system is shown in Fig. 1.

B. Mathematical model

To solve for the PD coordinates, the AEPD physical system is modeled mathematically. Nonlinear sphere equations are formed by considering each sensor as the center

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of the sphere and the distance between the sensor and the PD source as radius. In this model, the spheres intersect each other at the PD location [9]. A minimum of four equations are needed to solve the complete problem. The four unknowns are the coordinates of PD source (x, y and z) and the acoustic wave propagation time from source to the nearest sensor (T_1). The radius of the sphere is given by the product of velocity of sound in oil (v) and the acoustic arrival time (T). (x_{s1}, y_{s1}, z_{s1}), (x_{s2}, y_{s2}, z_{s2}), …….(x_{sn}, y_{sn}, z_{sn}) are the coordinates of the sensors S_1, S_2 …S_n respectively. Difference in time τ_{12} is the time delay of the second sensor to the nearest sensor. Difference in time τ_{13} is the time delay of the third sensor to the nearest sensor and so on. The 'n' nonlinear sphere equations are given in (1).

$$(x-x_{s1})^2 + (y-y_{s1})^2 + (z-z_{s1})^2 = (vT_1)^2$$
$$(x-x_{s2})^2 + (y-y_{s2})^2 + (z-z_{s2})^2 = \{v(T_1+\tau_{12})\}^2$$
$$(x-x_{s3})^2 + (y-y_{s3})^2 + (z-z_{s3})^2 = \{v(T_1+\tau_{13})\}^2$$
$$\vdots$$
$$(x-x_{sn})^2 + (y-y_{sn})^2 + (z-z_{sn})^2 = \{v(T_1+\tau_{1n})\}^2 \qquad (1)$$

These nonlinear equations can be solved using direct methods or by iterative methods [5]. Newton's method, which is an iterative method, can solve these nonlinear equations with greater accuracy, if we are able to provide proper initial guess [5].

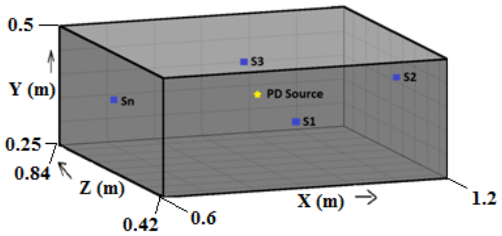

Fig. 1. Physical model of an AEPD system

C. Newton's method

Newton's method is one of the oldest and most widely used techniques for solving system of nonlinear equation. If proper initial guesses are provided, it will locate the roots accurately whereas other random search techniques can only locate the regions where the roots are likely to exist. Newton's method is an iterative, multidimensional root finding method. This method gives a very efficient means of converging to a root, if we have a sufficiently good initial guess. Consider N nonlinear equations involving variables x_i as shown in (2). Let x denote the entire vector of values x_i and F denote the entire vector of functions F_i. In the neighborhood of x_i, each of the functions F_i can be expanded in Taylor series as shown in (3). The Jacobian matrix is the matrix of partial derivatives given in (4). Equation (3) can be written using matrix notations as shown in (5). The second and higher order terms are neglected. By setting $F_i(x+\delta x) = 0$, we obtain a set of linear equations for the corrections that move each function closer to zero simultaneously. This is shown by (6). The correction factor δx can be found by using (7). The corrections are then added to the solution vector as in (8), and the process is iterated to convergence. The process is stopped when the difference between two solutions in successive iteration is smaller than a predefined value.

$$F_i(x_1, x_2, x_N) = 0 \qquad (2)$$

where i = 1, 2 …. N.

$$F_i(x+\delta x) = F_i(x) + \sum_{j=1}^{N} \frac{\partial F_i}{\partial x_j}\delta x_j + 0(\delta x^2) \qquad (3)$$

$$J_{ij} = \partial F_i / \partial x_j \qquad (4)$$

$$F(x+\delta x) = F(x) + J\delta x + 0(\delta x^2) \qquad (5)$$

$$J\delta x = -F \qquad (6)$$

$$\delta x = J^{1}F \qquad (7)$$

$$x_{new} = x_{old} + \delta x \qquad (8)$$

III. Details of Available Data

The physical dimensions and sensor position related data for the numerical experimentation is used from [10]. AE sensors integrated with preamplifier (model number: R15I) are used. Eight AE sensors are mounted on the container surface, sensors 1 to 4 on the surface ABCD and sensors 5 to 8 on the surface EFGH, as shown in Fig. 2. Identical stainless steel needles of tip radius 150 μm are used as PD sources. The transformer tank dimensions are given as (0.6000 m X 0.2500 m X 0.4200 m).

The sensor coordinates are given in table 1.The threshold for AE system is given as 30 dB and the AE wave velocity is 1250 m/s. The actual coordinates of PD source location is (0.3500, 0.1100, 0.1500). Depending on the distance of AEPD source with respect to the AE sensors, the order in which the sensors receive the AEPD signals is (2, 4, 1, 3, 6, 8, 7, 5). The origin is shifted from the original position (one tank dimension away) so as to have all non-zero sensor coordinates for the convenient implementation of simulation. The orientation of tank with origin shifted is shown in Fig. 2. After shifting the origin, the AEPD location will be (0.9500, 0.3600, 0.5700).

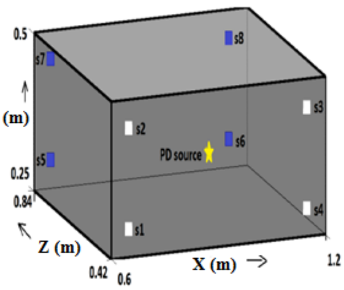

Fig. 2. Schematic of tank orientation, arrangement of sensors and simulated PD source.

TABLE I. COORDINATES OF THE SENSOR LOCATIONS [10].

Sensor Sl. No.	X (m)	Y (m)	Z (m)
S_1	0.6475	0.2950	0.4200
S_2	1.1475	0.2950	0.4200
S_3	0.6475	0.4550	0.4200
S_4	1.1475	0.4550	0.4200
S_5	0.6475	0.2950	0.8400
S_6	1.1475	0.2950	0.8400
S_7	0.6475	0.4550	0.8400
S_8	1.1475	0.4550	0.8400

IV. IMPLEMENTATION OF ALGORITHM

Newton's method implemented is used to conduct numerical experiments using three different initial guesses. The three initial guesses are chosen randomly. The initial guesses for x, y, and z coordinates of PD sources are chosen within the transformer tank dimension and initial guess for arrival time of signal to nearest sensor is chosen between the minimum and maximum time for a signal to travel within the tank. These three initial chosen guesses are given in table 2. Histograms are plotted for the estimated coordinates of PD source. The histogram of estimated X coordinates for 70 ($^8C_4$) combination of sensors is given in Fig. 3.

TABLE II. INITIAL GUESSES USED FOR NEWTON'S METHOD

Initial Guess	X^0 (m)	Y^0 (m)	Z^0 (m)	T_1^0 (ms)
IG-1	0.7800	0.3250	0.5460	0.0002
IG-2	0.7200	0.3000	0.5040	0.0001
IG-3	0.6600	0.2750	0.4620	0.0001

V. APPLICATION OF STATISTICAL TOOL

Experimental data are often affected by errors which are difficult to recognize. Statistics provides systematic and powerful tools to extract meaningful information from masses of raw data. Here an attempt is made using 'standard deviation' for analyzing the superfluous data.

The spread of values around the mean is called variability or dispersion of the data. The most commonly used measure of variability is the standard deviation which is given by (9). Here x_i are the data points, where i=1, 2, …n. Here n is the total number of data points. The variance is given by (10).

$$\text{Standard deviation } (\sigma) = \sqrt{variance} \quad (9)$$

$$\text{Variance } (\sigma^2) = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{(n-1)} \quad (10)$$

A. Algorithm for error minimization

- **Step 1**: Choose different fractions of standard deviation.
- **Step 2**: From the calculated coordinates of PD source, values outside the selected fraction of standard deviation are eliminated.
- **Step 3**: The average of the remaining coordinate values are calculated.
- **Step 4**: Percentage deviation error in calculated PD location with respect to the actual PD location is determined. Percentage deviation error is found using (11). The maximum tank dimension stated in (11) for the present simulation work is given in (12).

$$Percentage\ deviation\ error = \frac{Distance\ between\ actual\ and\ located\ PD\ source}{Maximum\ tank\ dimension} \quad (11)$$

$$Maximum\ tank\ dimension = \sqrt{0.600^2 + 0.250^2 + 0.420^2} \quad (12)$$

- **Step 5**: The fraction of standard deviation which results in minimum error is selected and used for post processing.

MATLAB codes are developed for the above algorithm and the results are analyzed.

VI. RESULTS AND ANALYSIS

Location detection of AEPD source is implemented in MATLAB using Newton's method. The PD source coordinates are located using all the 70 possible combinations using 8 sensors. The average of the coordinate values found is considered as the location of the PD source. The percentage deviation error in the result obtained can be determined, as the actual coordinates of the PD source is known a prior in the present study. Percentage deviation error calculated after removing values outside different fractions of sigma are given in table 3. From table 3, it is seen that the error goes on decreasing as we decrease the fraction of sigma. An optimum value of fraction of sigma should be selected because, if the selected value is very small, it may so happen that there will not be any calculated PD coordinates within that fraction of sigma. As there is not much difference in error for the fractions 0.5 and 1.5, for all the three different initial guesses, 1.5 is chosen as the optimum fraction of sigma. And the values outside 1.5 sigma are removed for re-estimating while calculating the improved PD location. The histogram of X coordinates after removing the outliers (values outside 1.5 sigma) is shown in Fig. 4.

Comparison of percentage deviation error (designated as "error"), before and after removing the outlier is given in table 4. "Deviation error" is the distance error between the actual location and estimated location.

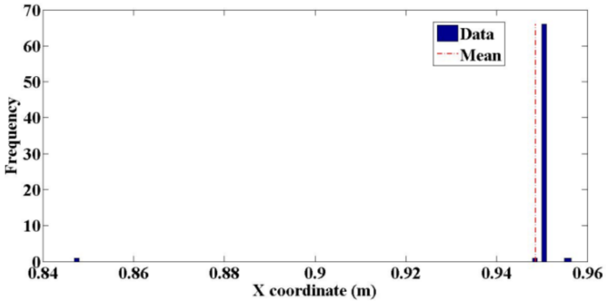

Fig. 3. Histogram plot of estimated X coordinates with all 70 combinations considered.

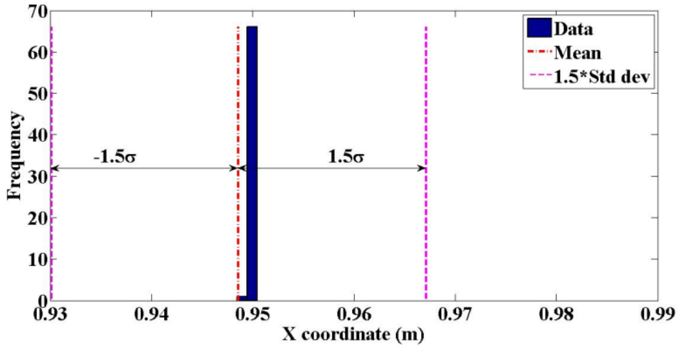

Fig. 4. Histogram plot of estimated X coordinates after removing the outlierswith all 70 combinations considered.

TABLE III. PERCENTAGE DEVIATION ERROR CALCULATED TAKING VALUES WITHIN DIFFERENT FRACTIONS OF SIGMA FOR THE THREE INITIAL GUESSES

FRACTION OF SIGMA	PERCENTAGE DEVIATION ERROR		
	ig1	*ig2*	*ig3*
0.5	1.0282E-04	1.0282E-04	1.0438E-04
1	1.4286E-04	1.0282E-04	1.0438E-04
1.5	1.4286E-04	1.0282E-04	1.0438E-04
2	6.1439E-04	1.2000E-04	1.2240E-04
2.5	6.1439E-04	1.2000E-04	1.2240E-04
3	6.1439E-04	5.9103E-04	1.2240E-04

VII. CONCLUSIONS

More than four (minimum required number) numbers of AEPD sensor based can be used advantageously in fine-tuning the location identification process. Error incurred in AEPD location detection can be minimized by using statistical means if more than four sensors data is available. As we decrease the fraction of sigma, the percentage error goes on decreasing. An optimum value of fraction of sigma should be selected. After the removal of outliers, the percentage deviation error (distance error between the actual location with respected to estimated location) will be of the order of 10^{-4}.

TABLE IV. EFFECT OF REMOVING OUTLIERSONERRORS IN COORDINATES OF PD LOCATED, AND ERROR IN DISTANCE (FOR 3 INITIAL GUESSES).

		BEFORE ELIMINATION	AFTER ELIMINATION
IG-1	*X*	0.9486	0.9500
	Y	0.3598	0.3600
	Z	0.5722	0.5701
	Error	2.6482E-03	1.4286E-04
IG-2	*X*	0.9490	0.9500
	Y	0.3598	0.3600
	Z	0.5733	0.5701
	Error	3.4693E-03	1.0282E-04
IG-3	*X*	0.9485	0.9500
	Y	0.3597	0.3600
	Z	0.5719	0.5701
	Error	2.4626E-03	1.0438E-04

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