Noniterative Method for Combined Acoustic-Electrical Partial Discharge Source Localization

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***Abstract*—The combined acoustic-electrical system is used in the factory or plant environment for the partial discharge (PD) source localization in power transformers. A noniterative method for this combined acoustic-electrical PD-locator-system is devised and presented in this paper for the first time. It employs three acoustic emission (AE) sensors. The proposed method is compared with the existing noniterative method used in the all-acoustic system, which employs four AE sensors. The comparative study shows that the proposed method can locate the PD source irrespective of its position within the tank, whereas the prevailing noniterative method for the all-acoustic system fails to locate the PD source at certain positions within the tank. The effect of the sensor positioning on the performance of the method is studied, and some guidelines for the sensor placement on the transformers tank wall in a factory or plant environment are suggested. The proposed method is also applied to the data taken from the published literature. The localization results are compared with those of an existing iterative method (Newton's method) to prove its superiority in terms of computational time.**

***Index Terms*—Acoustic sensors, fault location, partial discharges, power transformers, time of arrival estimation.**

I. Introduction

THE partial discharge (PD) measurement is a nondestructive tool commonly used in the high voltage (HV) laboratories to verify the integrity of the insulation system of HV components [1]. In power transformers, when the oil insulation ages with time, its physical properties change. This may influence the shape of the PD signal. Thus, the PD signals can also be used for identifying the aging of the transformer oil insulation [2].

The PD measurement methods can be classified into electrical and nonelectrical types. The electrical method includes the pulse current method, and the nonelectrical method includes the acoustic method [3]. Detecting the presence of the PD alone is not useful in the case of a large test object, such as a power transformer or a distribution class switchgear cubicle, unless the location of the PD source is indicated [4]. There will be significant reduction in the time consumption for the repair of the transformer, if the source of the discharge is located accurately. The localization of the PD source using the electrical method requires the knowledge of the design data of the transformers. This is because the response of the transformer RLC network to the PD current impulse is strongly dependent upon the design of the transformer. This makes the localization of the PD source using the electrical method a difficult task [1], [5]. The acoustic PD detection technique has some advantages compared to the other PD detection techniques. This technique is noninvasive and immune to electromagnetic interference. The sensitivity of this method does not vary with the test object capacitance as in the case of the electrical PD detection. The acoustic PD detection method can be extended to facilitate the PD source localization using multiple (minimum of four) acoustic emission (AE) sensors [4]. The AE technique is a good real-time solution for both PD detection and PD source localization [6]. The acoustic PD source localization method is successful only for those PD sources that emit their acoustical waves directly into the oil. This is due to the factors such as absorption, dispersion, reflection, and attenuation in the composite insulating system [1]. It is also important to estimate the signal arrival time of waves that take direct acoustic path from the source to sensors [6]. When the PD is detected electrically, the specific PD source can be recognized as the PD pattern depends on the type of the PD source and its location [1]. However, the acoustic method does not have the capability to recognize the type of source generating PD.

The acoustic waves from a PD source can be detected by suitable sensors located on the transformers tank wall and its output can be analyzed using a conventional data acquisition system [7]. The detection of the acoustic signal from the PDs using the noncontact type of sensors is also reported in the literature [8]. The acoustic detection of the PD signals using a fiber-optic sensor immersed in oil is reported in [9]. Though this method results in enhanced sensitivity, it is invasive.

The two general categories of the acoustic location system are the all-acoustic system and the combined acoustic-electrical system [6]. In the all-acoustic system, an array of acoustic sensors is used for PD detection and localization. The signal arrival time at each sensor is the propagation time of the acoustic signal from the PD source to the sensor location. The difference in the signal arrival time (time-delay) at the various sensors is used for the PD source localization in the all-acoustic system. The combined

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acoustic-electrical system pairs a current or voltage measurement device that can detect the PD electrically, with the array of acoustic sensors. The simplest approach for the PD source localization is by measuring the electrical signal simultaneously with the acoustic signal. Here, the electrical signal is considered to be detected instantaneously. Thus, the absolute signal arrival time at each sensor is measured as the time-difference between the electrical PD detection, and the acoustic signal detection by the acoustic sensor. In the combined acoustic-electrical system, instead of the time-delay, the absolute time is used for the PD source localization [6]. The combined acousto-optical system [10] and the system with a simultaneous measurement of optical and ultra high frequency (UHF) signal [11] also use absolute time for PD source localization.

The major advantage of the combined acoustic-electrical PD-locator-system is that it avoids false PD alarms, caused by using either the electrical or acoustic method independently. The false alarm from the electrical signals can be due to the corona in the air [7]. The noises of the oil pumps and the magnetostriction in the core can generate emissions with a frequency range like that of the acoustic PD itself [12], [13]. The false alarms from the acoustic signals can also be caused by rain [7]. The major disadvantage of using an acoustic system along with an electric PD measurement in the field is that it may be difficult to obtain a clean electric PD measurement due to the electrical noise [14], [15]. In the off-line test or in the laboratory environment, these noises can be eliminated by shielding or by properly bonding the metal components. Therefore, the combined acoustic-electrical PD-locator-system is more suitable in the factory or plant environment than in the field [6].

The algorithms used for PD source localization play a key role in the accuracy of the location detection. The commonly used methods for solving the mathematical model of an acoustic emission partial discharge (AEPD) system are Newton's method and the least square iterative algorithm [16], [17]. The convergence of these algorithms is highly dependent on the quality of the initial guess. Moreover, the computational time required for the iterative algorithms is relatively high compared to noniterative algorithm. The genetic algorithm is yet another method used for PD source localization [18], [19]. The genetic algorithm can rapidly locate regions where the solutions are likely to exist but cannot guarantee the convergence to an exact solution [20]. The pattern recognition method can also be used for PD source localization [21], [22]. This method is carried out by dividing the transformer tank into several submodules. A greater number of submodules means the accuracy will be greater, but the amount of data that is to be handled will be enormous. Difficulty also arises when the internal dimensions of the transformer tank are not fully known [19], [23]. The global positioning system (GPS) algorithm [24], and noniterative method for all-acoustic system [23] are other methods used for PD source localization. These methods give multiple solutions. The solution in which the PD source coordinates are within the tank dimension and the acoustic signal arrival time from source to sensor is positive is considered as the actual PD location. When more than one solution possess these characteristics then selection of actual PD location from these multiple solutions become difficult [19].

In this paper, a noniterative algorithm is devised for PD source localization using the combined acoustic-electrical system, which can overcome some lacunae identified in the existing algorithms. The guidelines for the sensor placement for the reliable implementation of the proposed method are also suggested. In addition, the effect of the PD source position on the performance of the proposed method is analyzed. The proposed method is also applied to the experimental data published in the literature [25]. The performance of the proposed method is compared with that of Newton's method (iterative method) and with the noniterative method (used in the all-acoustic system).

The aim and scope of the present work is the development of a noniterative (direct) method to locate the PD source. This method does not require an initial guess and also does not have any convergence problem. Since the method is noniterative, the computational time required is less compared to other iterative, guided and random search methods. The proposed method can locate the PD source irrespective of the relative distances between the sensors and the PD source. There will be no inherent error in PD localization due to the proposed noniterative algorithm. If there is any error in the data such as acoustic signal arrival time from PD source to various sensors and the velocity of the acoustic wave in transformer oil, it will be reflected in the localization result. However, how to choose the velocity of acoustic wave for PD localization and how to identify any significant error in measurement of acoustic signal arrival time from PD source to various sensors are also discussed in this paper.

II. Proposed Noniterative PD Source Localization Method

In the combined acoustic-electrical system, the electrical signal triggers the PD signal measurement. Multiple AE sensors are placed on the transformers tank wall. The absolute time of propagation of the acoustic signal from the PD source to the multiple sensors is given by the time-delay between the electrical PD detection and acoustic signal reception by each sensor. The PD source can be located by knowing the absolute time and velocity of the acoustic signal in the propagation medium [26]. Therefore, for the localization of the PD source in the transformer, the three major requirements are: (i) a robust algorithm to solve the mathematical model of the combined acoustic-electrical system, (ii) the acoustic wave velocity, and (iii) precise measurements of acoustic arrival times. These are discussed in the following subsections.

A. *Proposed Noniterative Algorithm*

The PD source coordinates are located by solving the mathematical model of the combined acoustic-electrical system. The nonlinear sphere equations can be formed by considering each sensor to be the center of the sphere and considering the distance between the sensor and the PD source to be the radius [27], [28]. In the system of nonlinear equations (1) to (3), the unknown quantities are the coordinates of the PD source (x, y, z). Since there are three unknowns, a minimum of three sensors are required to locate the PD source, unlike the four sensors needed for the all-acoustic system (time-difference approach).

$$(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 = (vT_1)^2, \quad (1)$$

$$(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2 = (vT_2)^2, \quad (2)$$

$$(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2 = (vT_3)^2, \quad (3)$$

where (x_n, y_n, z_n), $n = 1$ to 3, are the coordinates of the three sensors, T_n, $n = 1$ to 3, is the absolute time of propagation of the acoustic signal from the source to the three sensors, and v is the velocity of acoustic signal in transformer oil [6].

All the spheres intersect with each other at the PD source location. The points of intersection of two spheres lie on a plane in which the PD source can be located. The equations of the two intersecting planes that are formed by the intersection of the spheres (1) and (2), and (1) and (3) are given in (4) and (5), respectively:

$$k_1 x + k_2 y + k_3 z = k_4, \quad (4)$$

$$k_5 x + k_6 y + k_7 z = k_8, \quad (5)$$

where the constants in these equations are given in (6) to (13):

$$k_1 = 2(x_2 - x_1), \quad (6)$$

$$k_2 = 2(y_2 - y_1), \quad (7)$$

$$k_3 = 2(z_2 - z_1), \quad (8)$$

$$k_4 = (x_2^2 - x_1^2) + (y_2^2 - y_1^2) + (z_2^2 - z_1^2) + v^2(T_1^2 - T_2^2), \quad (9)$$

$$k_5 = 2(x_3 - x_1), \quad (10)$$

$$k_6 = 2(y_3 - y_1), \quad (11)$$

$$k_7 = 2(z_3 - z_1), \quad (12)$$

$$k_8 = (x_3^2 - x_1^2) + (y_3^2 - y_1^2) + (z_3^2 - z_1^2) + v^2(T_1^2 - T_3^2). \quad (13)$$

The points of intersection of the two planes lie on a line on which the PD source can be located. The line formed by the intersecting planes (4) and (5) is given in (14):

$$\frac{x - k_9}{k_{10}} = \frac{y - k_{11}}{k_{12}} = \frac{z}{k_{13}} = A, \quad (14)$$

where the constants in this equation are given in (15) to (19):

$$k_9 = \frac{k_1 k_4 k_6 - k_2 k_4 k_5 - k_1 k_2 k_8 + k_2 k_4 k_5}{k_1(k_1 k_6 - k_2 k_5)}, \quad (15)$$

$$k_{10} = k_2 k_7 - k_3 k_6, \quad (16)$$

$$k_{11} = \frac{k_1 k_8 - k_4 k_5}{k_1 k_6 - k_2 k_5}, \quad (17)$$

$$k_{12} = k_3 k_5 - k_1 k_7, \quad (18)$$

$$k_{13} = k_1 k_6 - k_2 k_5. \quad (19)$$

The variable A in (14) needs to be determined. The coordinates of any point on the line (x, y, z) are obtained from (14) and are given in (20) to (22):

$$x = k_9 + k_{10} A, \quad (20)$$

$$y = k_{11} + k_{12} A, \quad (21)$$

$$z = k_{13} A. \quad (22)$$

The PD source can be located on the line (14) as well as on the spheres (1) to (3). The line intersects any one of the spheres in two points, resulting in a quadratic equation. The quadratic equation (23) is formed by substituting the coordinates (20) to (22) in the sphere (1):

$$k_{14} A^2 + k_{15} A + k_{16} = 0, \quad (23)$$

where the constants in this equation are given in (24) to (26):

$$k_{14} = k_{10}^2 + k_{12}^2 + k_{13}^2, \quad (24)$$

$$k_{15} = 2k_9 k_{10} + 2k_{11} k_{12} - 2k_{10} x_1 - 2k_{12} y_1 - 2k_{13} z_1, \quad (25)$$

$$k_{16} = x_1^2 + y_1^2 + z_1^2 - 2k_9 x_1 - 2k_{11} y_1 - v^2 T_1^2 + k_9^2 + k_{11}^2. \quad (26)$$

The solutions of the quadratic equation (23) give the values of the variable A. By substituting the values of variable A in (20) to (22), two sets of solution can be obtained for the coordinates of the PD source (x, y, z). Among these solutions one is the actual location that is accepted, and the other is rejected. The rejection of a solution can be due to any of the PD source coordinates being negative or outside the transformer tank dimensions. The detailed flowchart for the PD source localization in transformers using the newly devised noniterative method in a combined acoustic-electrical system is given in Fig. 1. This method is applicable to any mixed acoustic system where the time of origin of the PD is known (absolute time approaches).

The efficacy of the proposed method is studied using the numerical experiments and the application of the proposed method to the published data from the literature [25]. The guidelines for a suitable sensor positioning is also suggested, which will result in the reliable implementation of the proposed method. It will also help in overcoming the ambiguity in choosing the actual solution among the two available solutions.

B. Acoustic Wave Velocity

In transformers, the oil occupies most of the insulating space. Therefore, the velocity of waves propagating in transformers could be considered as its velocity in the oil [29]. According to IEEE Std C57.127-2007, the acoustic wave velocity typically used for the PD source localization in transformers is 1413 m/s at 20° [6]. Temperature has a significant effect on the propagating velocity of the acoustic signal [30]. In [30], the sonic velocity in oil is measured over the temperature range of −30° to 130°. Estimating the mean oil temperature and then using the corresponding sound velocity for PD localization is a good guess [27]. Most of the studies have treated transformer as a homogeneous medium and substituted the velocity of sound in oil as the velocity of acoustic wave propagation from the source to sensor [21], [27], [31]–[33].

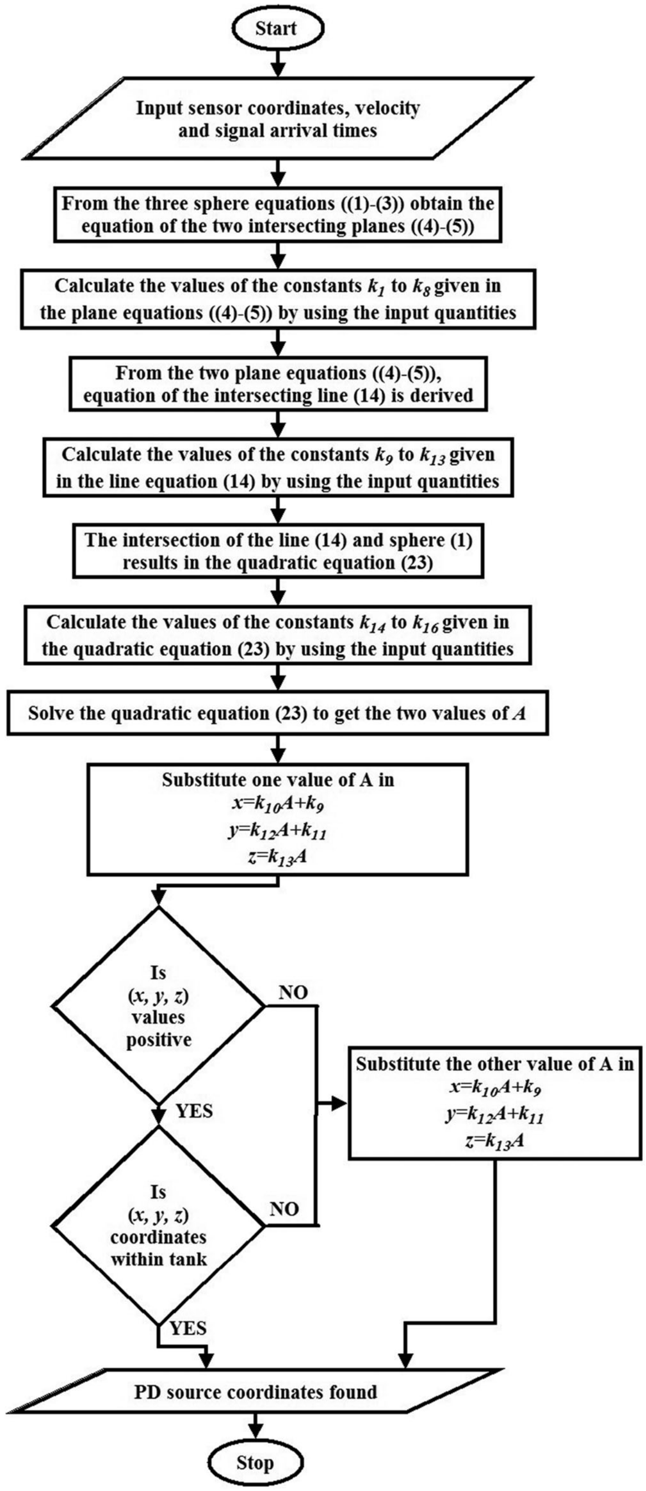

Fig. 1. Detailed flowchart for PD source localization in power transformers using the newly devised noniterative method for the combined acoustic-electrical system.

C. Acoustic Signal Arrival Time From PD Source to AE Sensor

The acoustic signal from the PD source can reach the AE sensor either through direct-path or structure-borne-path. The acoustic waves propagating from the source directly to the sensor in a straight line through the oil are the direct-path waves. The structure-borne-path waves are the acoustic waves that hit the nearby transformer tank wall and reach the sensor propagating through the tank wall [6].

The non-linear sphere equations given in (1) to (3) are formed by assuming that the acoustic sensors detect the direct-path waves. The radius of the sphere is the product of time (absolute time of propagation of the acoustic signal from the source to the sensor) and velocity (velocity of acoustic signal in transformer oil). If all the sensors detect the direct-path wave, then the spheres intersect with each other at the PD location. Hence the system of sphere equations will have a real solution. Therefore, it is very important that direct acoustic path based PD localization should be conducted.

The acoustic wave velocity in metal is greater than in oil. Therefore, the time taken by the structure-borne-path wave to reach the sensor will be lesser compared to the direct-path wave. If any sensor first detects the structure-borne-path wave, then the radius of the sphere formed with the corresponding sensor as center will have a smaller radius and it will not pass through the PD location. Hence, the system of sphere equations will not have a real solution. Therefore, in such cases the PD source will be located in the complex-number-field.

In the proposed noniterative algorithm, the intersection of two spheres form a plane. The PD source can be located on this intersecting plane. Two such planes intersect in a line. The PD source can be located on this line. The line intersects any one of the spheres in two points. This results in a quadratic equation given in (23). One of the solutions of this quadratic equation is the PD source location. If the quadratic equation does not have a real root, it implies either the sensor detected the structure-borne-path wave or there is a significant error in the time measurement. The nature of the roots of the quadratic equation can be identified from the discriminant value. The discriminant of the quadratic equation given in (23) is given in (27).

$$\text{Discriminant} = k_{15}^2 - 4k_{14}k_{15}, \tag{27}$$

A negative value for the discriminant implies the quadratic equation have complex roots. Thus, by checking the sign of the discriminant value it is possible to identify whether the sensor detects the direct-path wave or the structure-borne-path wave. The negative value of the discriminant also indicates a significant error in the signal arrival time measurement. Therefore, such time measurements should be considered invalid and cannot be used for combined acoustic-electrical PD localization. Similarly, in an all-acoustic system, the invalid time-delay measurement (significant error in time measurement) can be identified using discriminant value [28].

The efficacy of the proposed method to identify the structure-borne-path waves using discriminant value is verified by applying it to the experimental data published in [34]. The three locations of the sensor, the location of the source of the PD, and the absolute signal arrival times (from the source to the sensors) that are reported in [34] have been used to verify the proposed method. The related data that are reported in [34] are as follows. A transformer tank of size 0.9 m × 1.1 m × 0.6 m ((z-axis) x (x-axis) x (y-axis)) is used. The AE sensor used for the experiment

TABLE I
ABSOLUTE SIGNAL ARRIVAL TIME GIVEN IN [34] AND THE CORRESPONDING DISCRIMINANT VALUE COMPUTED AND PD SOURCE COORDINATES ESTIMATED FOR EACH ABSOLUTE-TIME GROUP

Estimation method	Absolute signal arrival time (μs)			Discriminant value	PD source coordinates (m)		
	T_A	T_B	T_C	(m^2)	x	y	z
Predicted	214.29	416.50	250.00	2.03×10^{-6}	0.75	0.30	0.35
Measured	216	300	250	−0.26	0.58	0.11	0.35 + 0.43i
Correction-1	216	380	250	−0.07	0.69	0.22	0.35 + 0.22i
Correction-2	216	450	250	0.04	0.80	0.36	0.53

is the PAC (type R15I) resonant sensor. It has a built-in 40 dB pre-amplifier. The typical operation range of the sensor is from 100 kHz to 450 kHz and the resonant frequency is ∼160 kHz. The coordinates of the PD source used for the experiment is (0.75, 0.30, 0.35) m. To detect the acoustic signals from the PD source, the sensor is placed at three different locations (point A, point B, and point C) on the transformer tank wall. The coordinates of the sensor when placed at point A, point B, and point C are S_A(0.75 0.60 0.35), S_B(0.25 0.60 0.35), and S_C(1.10 0.30 0.35), respectively. The velocity of the acoustic signal in oil is taken as 1400 m/s.

When the sensor is placed at point A and point C, the sensor is placed normal to the PD source and the direct-path-wave is the quickest. At point A and point C the sensor first detects the direct-path wave. As stated in [34], point B is outside the critical incidence angle. Therefore, for the sensor placed at point B, the structure-borne-path wave is the quickest. At point B, the sensor first detects the structure-borne-path wave. The attenuation of the AE signals in the metal is larger than in transformer oil [35]. Therefore, the higher magnitude oscillations in the received signal correspond to the signal arrival time of direct-path wave. The signals detected by sensor at point A and point C have a sharp wavefront with the magnitude reaching its maximum almost at the beginning. On the contrary, the signal detected by sensor at point B is relatively small in the beginning (for some time) and then the magnitude increases suddenly.

In [34], the arrival time of the direct-path-wave is identified from the signal received by the sensor at point B by applying two corrections. Correction-1: the time measurement based on ignoring the smaller oscillation (that are present before the sudden change in amplitude of the oscillation) in the wavefront, and Correction-2: the time measurement based on the oscillation with largest amplitude.

The signal arrival time from PD source to AE sensor, with sensor placed at the three locations (point A, point B, and point C) are estimated in four different ways in [34]: (i) calculated theoretically (predicted), (ii) measured based on first detected signal (measured), (iii) identified by applying Correction-1, and (iv) identified by applying Correction-2. T_A, T_B, and T_C are the absolute signal arrival time from PD source to AE sensor placed at point A, point B, and point C, respectively. The four groups of absolute signal arrival time from source to sensor reported in [34], the corresponding discriminant value computed, and the PD source coordinates estimated for each absolute-time group are given in Table I.

From Table I, when using the predicted (with no error) value of signal arrival time, the discriminant value is positive and the noniterative algorithm located the PD source accurately. When the measured (structure-borne-path wave) signal arrival time is used, the discriminant value is negative and the noniterative algorithm located the PD source in the complex-number-field. When the signal arrival time after applying Correction-1 is used, the discriminant value is still negative and the PD source is located in the complex-number-field. When the signal arrival time after applying Correction-2 is used, the discriminant value became positive and the PD source is located in the vicinity of the actual PD location.

Even though, to some extent, it is possible to identify the signal arrival time of direct-path wave by examining the amplitude of the measured signal, it is not a foolproof method. The attenuation of AE signals can also happen because of barriers or other physical obstacles present in the path of acoustic wave propagation. It is possible to identify whether the sensor detected the direct-path-wave or the structure-borne-path wave by checking the discriminant value in the proposed noniterative algorithm. The discriminant value also tells whether there is a significant error in time measurement. The structure-borne-path waves results in incorrect localization of the PD source. Therefore, IEEE Std C57.127-2007 suggests that the estimated PD source location should be confirmed by using a variety of sensor locations [6].

The real-number-field is the only search space for iterative (Newtons method) and search (Genetic Algorithm) algorithms. Therefore, any significant error in time measurement may lead to false localization of the PD source. The possibility of identifying the structure-borne-path wave or significant error in time measurement by checking the discriminant value is an added advantage of proposed noniterative method.

III. Performance Verification of the Proposed Method

The two important facets to be examined for any PD source localization method are the effect of the sensor positioning and the effect of the PD source position on its performance. The occurrence of the PD at a location is random. Hence, a good PD source localization method should locate the PD source irrespective of its position within the tank. For this, two analyses are carried out.

The first numerical experiment based analysis is made to examine the effect of the sensor positioning on the performance of the proposed method.

TABLE II
COORDINATES OF THE SENSOR CONFERRING TO THE LAYOUT GIVEN IN [6] ON THE $z = 0$ PLANE

Sensor number (Sn)	x_n (m)	y_n (m)	z_n (m)
S1	0.75	0.75	0.00
S2	0.75	1.50	0.00
S3	0.75	2.25	0.00
S4	1.50	0.75	0.00
S5	1.50	1.50	0.00
S6	1.50	2.25	0.00
S7	2.25	0.75	0.00
S8	2.25	1.50	0.00
S9	2.25	2.25	0.00

The second numerical experiment based analysis is carried out to find the effect of the PD source position (the relative distances between the PD source and the sensors) on the performance of the method. In the process, the proposed method is also compared with a noniterative method used for PD source localization in the all-acoustic system.

For the verification of the proposed method, relevant computer codes are developed.

A. *Effect of the Sensor Positioning*

An effective localization of the PD source is highly dependent on the initial placement of the AE sensors on the transformers tank wall. For a three-phase transformer, when the phase in which the PD source present is unknown, a layout of an initial placement of the sensors for PD source localization is suggested in [6]. This is also stated to be the ideal initial placement [6]. These sensors are placed on one plane of the transformers tank wall. This arrangement is given for a factory or plant environment [6]. To study the effect of sensor positioning on the proposed method, numerical experiments are carried out considering a similar sensor arrangement as suggested in [6].

The numerical experiment reveals that such a sensor arrangement can cause the failure of the proposed algorithm in certain conditions. Hence, some guidelines are required for the reliable implementation of the proposed algorithm. These guidelines are evolved by analyzing the results obtained from the numerical experiments.

1) Details of Numerical Experiments: A transformer tank of size 3 m × 3 m × 3 m is considered for the numerical experiment. Nine AE sensors are placed on the transformers tank wall conforming to the layout suggested in [6] on the $z = 0$ plane. The sensor coordinates considered for the numerical experiment are given in Table II. The layout of the sensor arrangement with nine sensors for the numerical experiment is given in Fig. 2.

A minimum of three sensors are required for PD source localization. Since there are nine sensors, 84 $({}^9C_3)$ combinations of the sensors are possible. Three randomly chosen PD sources are located by considering these combinations of sensors separately. The coordinates of the three chosen PD source positions are (2.8, 0.9, 1.7) m, (1.3, 1.4, 0.7) m and (0.5, 2.6, 2.8) m. The devised method is applied to locate these PD sources. Among the 84 combinations of the sensors, 35 combinations of the sensors failed to locate the PD source. The same combination of sensors failed to locate the PD sources in all three cases for this arrangement of sensors. The reason for failure of the method in these cases is analyzed. From (15) and (17) we can see that the denominators of these equations become zero whenever $k_1 = 0$ or $(k_1k_6 - k_2k_5) = 0$. In such cases the constants k_9 and k_{11} cannot be determined and the algorithm fails to locate the PD source. The conditions for which the algorithm fails to locate the PD source and the corresponding number of combinations failed are given in Table III.

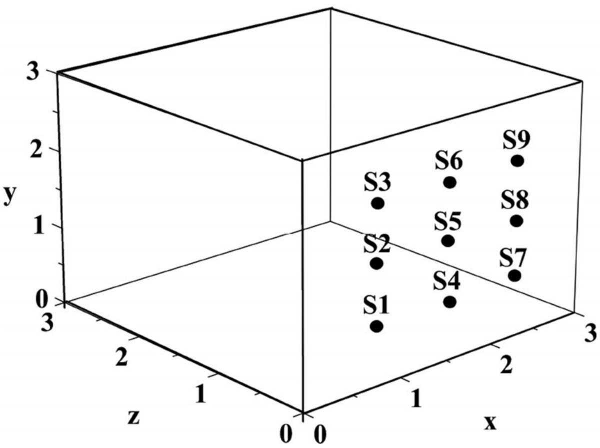

Fig. 2. The sensor layout (similar to layout suggested in [6]) used for the numerical experiment.

From the numerical experiment (with the devised method), when all the sensors are placed in the $z = 0$ plane, among the two sets of solutions, only one set of solutions will have positive values for the *x*, *y*, and *z* coordinates of the PD source and that will be the actual PD source location. The other solution will have a negative value for the z-coordinate of the PD source and that solution can be rejected. Thus, the problem of selecting the actual PD source location from the two available solutions can be solved by placing all the sensors in the $z = 0$ plane. Conversely, the plane on which the sensors are placed is to be considered a $z = 0$ plane.

From the analysis of the devised method, two more conditions can cause the failure of the method, which do not occur in the numerical experiments with the present layout (see Fig. 2). These conditions are (i) $x_1 = x_2$ & $y_1 = y_2$ and (ii) $x_1 = x_3$ & $y_1 = y_3$. These conditions occur only when all the sensors are not placed on the same plane and hence do not show up in the present numerical experiments.

Considering all six conditions for which the devised method fails to locate the PD source, the new guidelines for the sensor placement are that (I) all three sensors in a combination should have distinct x-coordinate values and distinct y-coordinate values, (II) all the sensors should be kept on one plane and that plane should be considered a $z = 0$ plane, and (III) the sensors should not be kept in a straight line. Such sensor arrangement helps in the reliable implementation of the devised algorithm, and it will never fail to locate a PD source.

The sensor coordinates for the nine sensors conforming to these evolved guidelines are given in Table IV. When the sensors are placed according to the new proposed guidelines, all 84 combinations of the sensors accurately locate all three PD sources (that are chosen randomly for the numerical experiment).

TABLE III
THE CONDITIONS FOR WHICH THE PROPOSED METHOD FAILS TO LOCATE THE PD SOURCE FOR THE LAYOUT GIVEN IN FIG. 2

Condition number	Sensor positioning	Number of combinations failed	Suggested remedy via sensor repositioning
1	$x_1 = x_2 = x_3$	3	The x-coordinates of all the three sensors should not be same
2	$y_1 = y_2 = y_3$	3	The y-coordinates of all the three sensors should not be same
3	$x_1 = x_2$	27	This condition can be avoided by proper sensor numbering. The sensors should be numbered in such a way that the first two sensors (out of three) should not have the same x-coordinate value
4	$(x_2 - x_1)(y_3 - y_1) = (x_3 - x_1)(y_2 - y_1)$	2	The sensors should not be placed in a straight line

TABLE IV
COORDINATES OF THE SENSORS USED FOR NUMERICAL EXPERIMENT CONFORMING TO PROPOSED GUIDELINES

Sensor number (Sn)	x_n (m)	y_n (m)	z_n (m)
S1	0.40	0.24	0.00
S2	0.60	1.76	0.00
S3	0.50	2.75	0.00
S4	1.24	0.25	0.00
S5	1.25	1.74	0.00
S6	1.26	2.76	0.00
S7	2.40	0.26	0.00
S8	2.50	1.75	0.00
S9	2.60	2.74	0.00

TABLE V
FIVE SAMPLE PD SOURCE POSITIONS (PD-1 TO PD-5) THAT CANNOT BE LOCATED USING NONITERATIVE METHOD FOR THE ALL-ACOUSTIC SYSTEM BUT CAN BE LOCATED USING THE PROPOSED METHOD

PD sample		PD-1	PD-2	PD-3	PD-4	PD-5
PD location (m)	x	0.5	0.5	0.5	0.5	0.5
	y	1	1	1	1	1
	z	0.3	0.7	1.4	1.6	2.5
Absolute signal arrival time (μs)	T_1	582.6	734.7	1130	1256	1851
	T_2	582.6	734.7	1130	1256	1851
	T_3	1257	1334	1586	1678	2160
Time-delay (μs)	t_{12}	0	0	0	0	0
	t_{13}	192.7	160.6	110.4	100.2	69.40
	t_{14}	674.0	599.2	456.5	422.5	309.1

B. Effect of the PD Source Position

The occurrence of the PD at a location is random; an effective method should accomplish the PD source localization irrespective of its position. The second numerical experiment based analysis is conducted to determine the effect of the PD source position on the performance of the devised method. The numerical experiment shows that the noniterative method available for the all-acoustic system fails to locate certain PD source positions, whereas the proposed method is reliable and can locate any PD source irrespective of its positions with the sensor arrangement guidelines suggested in subsection A.

1) Details of Numerical Experiments: The transformer tank of size 3 m $\times$ 3 m $\times$ 3 m is divided into submodules of size 0.1 m $\times$ 0.1 m $\times$ 0.1 m. Each vertex of the submodule is considered a PD source position. In this way, 24,389 PD source positions are considered within the tank. These PD source positions are located using the noniterative method available for the all-acoustic system [23] and the noniterative method proposed for the combined acoustic-electrical system. The nine sensors conforming to the proposed guidelines are given in Table IV. This sensor arrangement is used for the numerical experiments.

The proposed method for the combined acoustic-electrical system requires only three sensors to locate the PD source. Since there are nine sensors, 84 ($^9C_3$) combinations of the sensors are possible. The 24,389 PD source positions are located separately using all 84 combinations of the sensors. As the location of the PD source and the sensors are known, by taking the velocity of acoustic signal in oil as 1,413 m/s (typical value of acoustic wave velocity at 20°, this can change according to temperature, moisture content and properties of the oil) [6], the absolute signal arrival time from source to sensor is calculated theoretically. The noniterative method proposed for the combined acoustic-electrical system located all 24,389 PD source positions successfully.

The noniterative method available for the all-acoustic system requires four sensors to locate the PD source. For PD source localization, this method uses the time delays in acoustic signal reception of the other sensors with respect to the sensor that is nearest to the PD source [23]. These time-delays are designated as t_{1j}, where j (2 to 4) is the sensor number, when the sensors are arranged in the increasing order of their time-delays in signal reception with respect to Sensor-1 (nearest sensor). These time-delays are calculated theoretically. The 24,389 PD source positions are located separately using all 126 ($^9C_4$) combinations of the sensors. The method fails to locate many of these PD source positions. The analysis of the failed cases shows that the method fails to locate the PD source whenever there is more than one sensor nearest to the PD source. This implies that these sensors are equidistant from the PD source. In such cases, the absolute signal arrival time from the PD source to these sensors becomes equal. Thus, the time-delay in signal reception between these sensors will be zero.

Table V shows five sample PD source positions that could not be located using the noniterative method available for the all-acoustic system. The combination of the sensors that is used in this case is the first four sensors given in Table IV. These PD sources are successfully located using the noniterative method proposed for the combined acoustic-electrical system. The combination of the sensors that is used in this case is the first three sensors given in Table IV. The absolute times and the time-delays calculated for implementing the PD source localization in the combined acoustic-electrical system and the all-acoustic system, respectively, are also given in Table V. From Table V, time-delay t_{12} is zero, and the absolute times T_1 and T_2 are equal for these PD source positions. This shows that the noniterative method used in the combined acoustic-electrical system can locate the PD source even when there is more than one sensor nearest to the PD source.

A detailed analysis is carried out for confirming the dependency of the noniterative method available for the all-acoustic system on the PD source position. In this numerical experiment, from each combination of the sensors (four sensors), two sensors are considered at a time to form six $(^4C_2)$ pairs of sensors. For each pair of sensors, an equation of the plane is found such that every point on the plane is equidistant from the two sensors. To find the points on that plane, the y and z coordinates are varied from 0.1 to 2.9 (because the tank dimension is 3 m) in steps of 0.1. For each y and z coordinate, the corresponding x-coordinate is calculated. If this point (*x, y, z*) lies within the transformer tank, then it is considered a PD source position. These PD sources are located independently using all 126 $(^9C_4)$ combinations of the sensors. This method failed to locate the PD source whenever the sensors that are equidistant from the PD source become the nearest sensors to the PD source because, in such cases, the time-delay will become zero. These time-delays appear in the denominator of some of the constants given in [23]. Therefore, all the constants cannot be determined (become Not a Number (NaN)); hence, the method fails to locate the PD source.

From the above discussion, the performance of the noniterative method available for the all-acoustic system is dependent on the PD source position (the relative distances between the sensors and PD source), whereas the performance of the noniterative method proposed for the combined acoustic-electrical system is independent of the PD source position inside the transformer tank.

IV. Application of Proposed Method to the Published Data [25]

The efficacy of the proposed method is verified by applying it to the experimental data published in [25]. From the published literature, the locations of the sensors, the location of the source of the PD, and the absolute signal arrival times (from the source to the sensors) that are reported have been used to verify the proposed method. The related data that are reported in [25] are as follows. In the experiment, a transformer tank of size 1 m × 1 m × 0.5 m (l × b × h) is used. The AE sensors used for the experiments have a bandwidth of 20–85 kHz with a resonance frequency at 45 kHz. The experimental data is reported only for the xy plane (plane where $z =$ constant). Four acoustic sensors are used with the sensor coordinates S1(0.5, 0.0) m, S2(0.0, 0.5) m, S3(0.5, 1.0) m, and S4(1.0, 0.5) m. Five groups of absolute signal arrival times (AT-1 to AT-5) from a PD source position of (0.50, 0.25) m to the three sensors (S1, S2, and S3) are reported in [25]. These data taken from [25] are given in Table VI. In these arrival time measurements reported, the worst case error (from the set of 5 measurements) in absolute signal arrival time $(T_1, T_2,$ and $T_3)$ for the sensors S1, S2, and S3 are –0.04%, +9.20%, and +6.07% respectively. For more details related to the PD measurement system and the overall system set-up [25] can be referred.

TABLE VI
Absolute Arrival Time Reported ([25]), and Calculated for a Known PD Location ([25]) With the Velocity of Acoustic Signal Taken From [6]

	Group Name	T_1 (μs)	T_2 (μs)	T_3 (μs)
Experimental absolute time data reported in [25]	AT-1	177	432	557
	AT-2	177	431	555
	AT-3	177	428	557
	AT-4	177	430	563
	AT-5	177	428	559
Theoretically calculated absolute time	AT-6	176.93	395.62	530.79

TABLE VII
The PD Source Localization Results of Proposed Method and Newton's Method

Method	Group name	PD source coordinates (m)		Computational time (s)
		x	y	
Proposed noniterative method	AT-1	0.5316	0.2216	2.23×10^{-4}
	AT-2	0.5321	0.2238	2.14×10^{-4}
	AT-3	0.5247	0.2216	2.14×10^{-4}
	AT-4	0.5215	0.2149	4.05×10^{-4}
	AT-5	0.5225	0.2193	3.71×10^{-4}
	AT-6	0.5000	0.2500	4.00×10^{-4}
Newton's method	AT-1	0.5316	0.2216	1.93
	AT-2	0.5321	0.2238	1.83
	AT-3	0.5247	0.2216	1.39
	AT-4	0.5215	0.2149	1.19
	AT-5	0.5225	0.2193	1.06
	AT-6	0.5000	0.2500	4.12

As the location of the PD source is known, by taking the velocity of acoustic signal in oil as 1,413 m/s (typical value of acoustic wave velocity at 20°, this can change according to temperature, moisture content and properties of the oil) [6], the theoretical value of the acoustic signal propagation time from the PD source to each sensor can be calculated. This is given as group AT-6 in Table VI. Due to noise, initial oscillation of the AE burst signals and the sensor bias errors; the experimentally measured arrival times in [25] (AT-1 to AT-5) deviate from the theoretical value (AT-6).

The PD source localization is conducted using the proposed method (noniterative method) and Newton's method (iterative method). A zero vector is used as the initial guess for Newton's method. A constant z-plane is considered for the numerical experiment. Any constant z-plane, other than $z = 0$ can be considered. If the $z = 0$ plane is considered, while implementing Newton's method, the Jacobian determinant will become zero, and the method will fail to locate the PD source. However, there is no such problem with the proposed method. The results are compared in Table VII.

The PD source located using each group of absolute signal arrival times (AT-1 to AT-6) are given in Table VII. From Table VII, it can be seen that AT-1 to AT-5 (experimental data from [25]) show errors in PD localization, whereas AT-6 has zero distance percentage error. There is no error in PD localization inherently due to the proposed method, but errors can crop up due to the error in signal arrival time estimation. The proposed noniterative method works satisfactorily. From Table VII, the time taken by Newton's method for estimating the PD source location is on the order of seconds, whereas, for the proposed method, the time taken is on the order of 10^{-4} seconds. Therefore, the time taken by the proposed method to locate the PD source is substantially less compared to Newton's method without compromising the accuracy of PD source localization. For the theoretically calculated signal arrival time (AT-6), with no error in time measurement, the PD source localization is accurate with both the proposed method and Newton's method.

Since there are five groups of signal arrival time measurements available, the PD source is located using each group separately. The mean value of these estimated locations is considered the statistical PD source location. The statistical location of the PD source using the proposed method is (0.5265, 0.2202). In [25], it is stated that the sensor S_2 has a bias error; therefore, the time measurement is erroneous. Even in such a case, the proposed method has estimated the statistical PD source location with a distance percentage error of 2.83%,
where

$$\text{Distance percentage error} = \frac{\text{Distance between actual and located PD source}}{\text{Maximum tank dimension}} \times 100, \tag{28}$$

and where

$$\text{Maximum tank dimension} = \sqrt{l^2 + b^2}. \tag{29}$$

In the present analysis, Newton's method converged for all groups of absolute times (AT-1 to AT-6). However, with the iterative method, it may converge or diverge depending on the quality of the initial guess. With the proposed noniterative method, it will never have a convergence problem and does not require an initial guess.

V. Conclusion

A noniterative method for the PD source localization in a power transformer using a combined acoustic-electrical system is devised and tested.

For the reliable implementation of the proposed noniterative method, the following guidelines are suggested: The sensors should be placed such that all three sensors should have distinct x-coordinate values and distinct y-coordinate values. Placing all the three sensors in the $z = 0$ plane helps in easily identifying the actual PD source location from the two available solutions by rejecting one of the solutions that has a negative z-coordinate value. All three sensors should not be placed in a straight line.

The noniterative method presented in this paper is independent of the relative distances between the sensors and the PD source and thus has an advantage over the prevailing noniterative method used in the all-acoustic system. The computational time required for the noniterative method is significantly less compared to Newton's method. The devised method being noniterative does not have any convergence problem and does not require any initial guesses.

The possibility of identifying the structure-borne-path wave or significant error in signal arrival time (from PD source to AE sensor) measurement by checking the discriminant value is an added advantage of proposed noniterative method.

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