Improvements in an Iterative Method for Localization of Partial Discharge Source in Oil Insulation

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***Abstract*— An acoustic emission partial discharge (AEPD) system modelled mathematically gives a system of non-linear equations describing spheres. The existing algorithms, used for solving this system of sphere equations, have some limitations in a rapid and a precise localization of the partial discharge (PD) source. The mathematical model of an AEPD system is solved in the literature using Newton's method. The major challenges when implementing Newton's method are the difficulty in choosing an efficient initial guess, and the enormous computational time when a bad initial guess is chosen. In the present work, an efficient initial guess is located for Newton's method by using the Genetic Algorithm (GA). Numerical experimentations are carried out to confirm the improvements in performance of Newton's method. When proposed improvement is used for the PD source localization, the maximum percentage deviation error is few orders less than Newton's method. When a good initial guess is located for Newton's method by using GA, it is found that most of the PD source positions can be located within 60 seconds on a personal computer running at a clock speed of 2.53 GHz. This proves the high accuracy and reduced computational time in PD source localization when using the proposed improvement in Newton's method.**

I. Introduction

The partial discharge (PD) measurement is a dominant basis for the electrical quality control testing of the high voltage (HV) apparatus. Many manufacturing and assembly problems such as the metallic contaminants, cavities in solid insulation, and insulation surface contamination are detected by using the PD tests [1]. The discharge signals are strongly correlated with the contamination level, conductivity, and significant damage of the insulation [2]. The PDs are one of the causes of aging phenomena in transformers [3]. Detecting the presence of the PD alone is not useful in the case of large test object such as a power transformer or a distribution class switchgear cubicle, unless some indication of the PD source location is given [4]. A significant amount of time can be saved in the subsequent repair of insulation, if the discharge source is located accurately. Moreover, the information on the location of the PD is essential to estimate the severity of any insulation problem [5]. Many manufacturers prefer acoustic PD detection to electrical methods because of its ability to locate any discharges that occur in the transformer.

A PD results in an instantaneous release of energy [6]. The acoustic waves produced because of PD, propagate through the transformer oil and these waves can be detected at the transformer tank wall. The location of the PD source within the transformer can be detected by measuring the relative acoustic signal arrival time at multiple acoustic emission (AE) sensors [7]. The accuracy of the PD localization depends greatly on the algorithms used for solving the mathematical model of the AEPD system.

One of the earlier methods of the acoustic emission partial discharge (AEPD) source localization comprises of two AE sensors. In this iterative method, the two sensors should be placed equidistant from the PD source such that there is no time delay between the signal receptions by the two sensors. In such cases the source can be located on the perpendicular bisector of the line joining the two sensors [5]. The disadvantage of this method is the difficulty in placing the two sensors at equal distance from the PD source [8].

The other iterative methods, which use a minimum of four AE sensors, for AEPD source localization are Newton's method and the least square algorithm [9], [10]. The large computational time requirement is the disadvantage of most of the iterative methods. Moreover, the convergence of these iterative methods largely depends on the quality of the initial guess [11].

The random search algorithms such as the Genetic Algorithm (GA) can be used for the AEPD source localization [12]–[14]. The GA rapidly locates the regions where the roots are likely to exist. But this method cannot guarantee the convergence to an exact solution [11]. The particle swarm optimization (PSO) algorithm is also used for the AEPD source localization [15], [16]. The pattern recognition method is another search method used for the PD source localization. In this method, the transformer tank is divided into several sub modules [17]. Larger the number of sub modules greater will be the accuracy in PD source localization, but at the same time, the data to be handled for implementing the method increases. Moreover, the information about the internal dimensions of the transformer tank is crucial in this method [13].

The Non-iterative methods such as intersection of sphere method and global positioning system (GPS) algorithm can be used for detecting the PD source location [8], [18]. The disadvantage of using these algorithm is that, the selection of an actual location from the available solutions is sometimes not possible [19].

From the above discussion, it is clear that the existing algorithms have some limitations in a rapid and a precise localization of the PD source. Therefore, the present work intends to suggest improvements in an existing iterative algorithm, 'Newton's method'. The major challenges while employing Newton's method are the difficulty in choosing an efficient initial guess and the enormous computational time when a bad initial guess is chosen. In the present work, an efficient initial guess is located for Newton's method by using the GA. In this scheme, the global search capabilities of the GA and the rapid convergence characteristics of Newton's method are combined. Newton's method will converge to an accurate solution and there is a significant reduction in the computational time required, when the initial guess is located by using the GA. Numerical experimentations are carried out to substantiate that, with a good initial guess Newton's method can result in a rapid and a precise PD source localization.

II. Mathematical Description of an AEPD System for the PD Source Localization

The AE techniques are based on detecting the signals emitted from the discharge by using multiple sensors located on the transformer tank wall. The sensors are named S_1, S_2 … S_n, where n is the total number of sensors used. The sensor nearest to the PD source first receives the acoustic signals [20]. This sensor is named S_1. Time delay in signal reception of the other sensors with respect to the sensor S_1 is calculated. The sensors are named S_2, S_3, S_4 etc., in the increasing order of their time delays. In the physical model of an AEPD system multiple sensors are placed on the transformer tank wall and the PD is considered as a point source inside the tank. To solve for the PD coordinates, the AEPD system is modeled mathematically. The non-linear sphere equations are formed by considering each sensor as the center of the sphere and the distance between the sensor and the PD source as radius. The product of the velocity of sound in transformer oil (v) and the acoustic signal arrival time (T) to the sensor gives the radius of the sphere. The spheres intersect with each other at the PD location [12], [21]. The sensors S_1, S_2 …S_n have their coordinates given by (x_1, y_1, z_1), (x_2, y_2, z_2), ……. (x_n, y_n, z_n), respectively. Difference in time t_{12} is the time delay in signal arrival at sensor S_2 with respect to the sensor S_1. Difference in time t_{13} is the time delay in signal arrival at sensor S_3 with respect to the sensor S_1 and so on. The ‘n’ nonlinear sphere equations are given in (1).

$$
\begin{gathered}
(x-x_1)^2 + (y-y_1)^2+(z-z_1)^2 = (vT)^2 \\
(x-x_2)^2 + (y-y_2)^2+ (z-z_2)^2=\{v(T+t_{12})\}^2 \\
(x-x_3)^2 + (y-y_3)^2+ (z-z_3)^2=\{v(T+t_{13})\}^2 \\
\vdots \\
(x-x_n)^2 + (y-y_n)^2+ (z-z_n)^2=\{v(T+t_{1n})\}^2
\end{gathered}
\tag{1}
$$

In the system of the non-linear sphere equations given in (1), the coordinates of the PD source (x, y, z) and the acoustic signal arrival time to the nearest sensor (T) are the unknown quantities. Since there are four unknowns a minimum of four sensors are required to locate the PD source. In numerical computation, solving the system of nonlinear equations is perhaps the most difficult task, and it is unavoidable in a spectrum of engineering applications. Many algorithms have been developed for the solution of the system of non-linear equation. The most commonly used and the oldest method is Newton’s method [11]. The following section addresses some of the challenges in using Newton’s method, which can be vanquished by combining GA with Newton’s method (GA-Newton method).

III. GA-Newton Method

The GA-Newton method combines the advantages of both the GA and Newton’s method. The GA can be used to locate an appropriate initial guess, which are then supplied to Newton's method for solving the system of nonlinear equations. The detailed implementation of the GA-Newton method is explained through a flowchart given in Fig. 1. The ability of the proposed GA-Newton method to overcome the challenges in Newton's method is discussed in the following subsections.

A. Locating initial guess

The characteristics and convergence of Newton's method is highly dependent on the quality of the initial guess supplied [11]. GA can rapidly locate regions where the solutions are likely to exist, though it cannot guarantee the convergence to exact solution. Newton's method, which is an iterative method, can solve nonlinear equations with a greater accuracy, if proper initial guesses are used [11]. It is highly unlikely to expect an exact detection of the PD location by using any of these algorithms alone. Combining GA and Newton's method is a good inkling to solve the problem of the PD source localization.

The GA implementation for the present work starts with creating a random initial population with uniform distribution. For selecting parents of crossover and mutation children, the algorithm lays out a line in which each parent corresponds to a selection of the line of length proportional to its scaled value. The algorithm moves along the line in steps of equal size. At each step algorithm allocates parents of crossover and mutation children. A random binary vector is created and genes are selected where the vector is a 'one' from the first parent and the genes where the vector is a 'zero' from the second parent and combine the genes to form the crossover child. A random number taken from a Gaussian distribution is added to each entry of the parent vector to form the mutation child. The parameters of genetic algorithm used for the present study are given in Table 1.

TABLE 1: PARAMETERS OF GENETIC ALGORITHM

Maximum number of Generations	400
Population size	120
Population Initial range	Upper and lower bounds of transformer tank
Crossover Fraction	0.8
Elite count	6
Stall generation limit	50
Tolerance function	$1\text{x } 10^{-6}$

B. Computational time

Newton's method, which is an iterative method, can solve nonlinear equations with great accuracy. However, a bad initial guess can result in enormous computational time or non-convergence to the solution. GA can rapidly locate regions where the solutions are likely to exist, though it cannot guarantee the convergence to exact solution. Newton's method will converge to an accurate solution in lesser time when initial guesses are located by using the GA. The computational overhead of additional GA operation is negligible when compared to the computation involved in finding the inverse of the Jacobian matrix [11]. Therefore, combining GA and Newton's method is a good hunch to solve the issue of enormous computational time requirement.

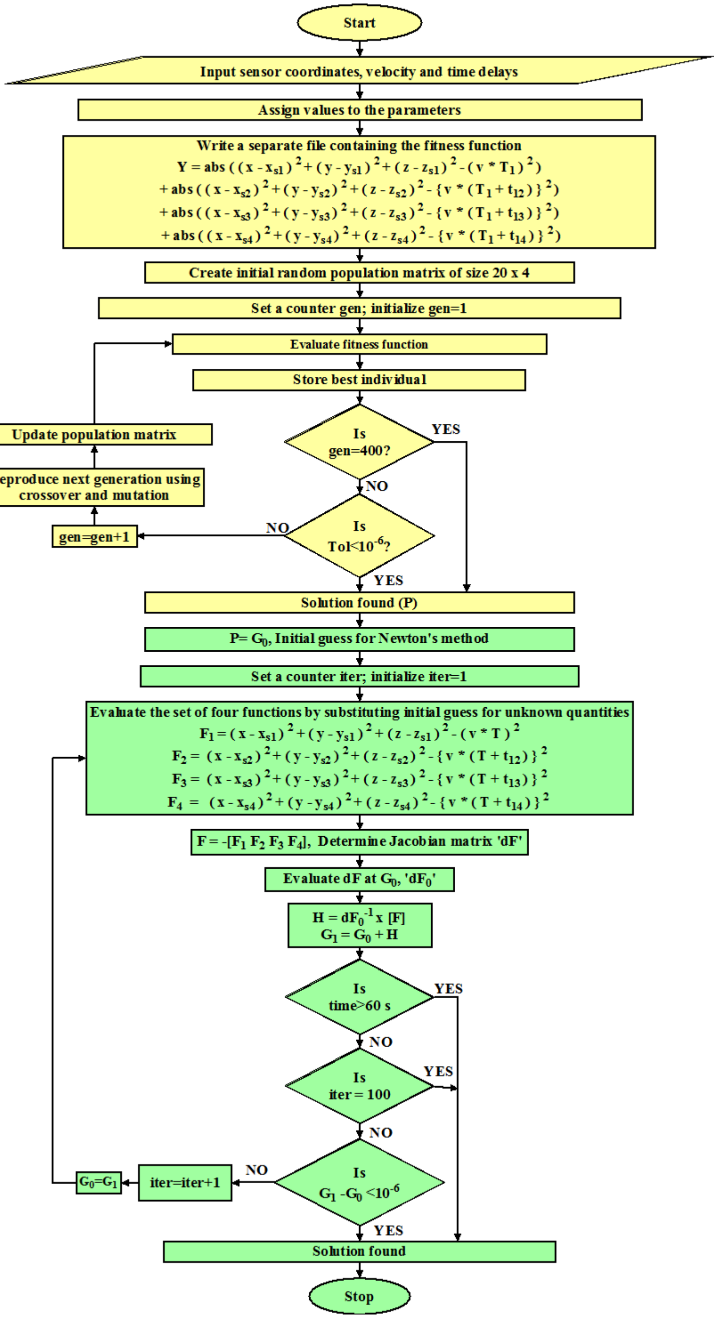

Fig. 1. Flowchart showing the implementation of the GA-Newton method

IV. NUMERICAL EXPERIMENTATION

A transformer tank of size 1m x 1m x 1m is considered for the numerical experimentation. Four AE sensors are placed on four side walls of the transformer tank. The coordinates of the sensors used for the implementation of algorithm are given in Table 2. Newton's method with initial guess (IG-1) as zero vector, Newton's method with a random initial guess (IG-2) as (0.1, 0.5, 0.9, 0) and GA-Newton method are implemented in MATLAB, on a personal computer with Intel® core™ i3 processor running at a clock speed of 2.53 GHz, for locating the PD sources.

Good initial guesses are specific to a given PD location and the sensor positions. Three randomly chosen PD source locations are considered within the transformer tank. They are PD-1 (0.8, 0.5, 0.7), PD-2 (0.9, 0.1, 0.1) and PD-3 (0.5, 0.7, 0.2). As the exact location of the PD source is known, the percentage deviation error in the located PD source can be calculated by using (2). The maximum tank dimension can be found by using (3).

$$\text{Percentage deviation error} = \frac{\text{Distance between actual and located PD source}}{\text{Maximum tank dimension}} \times 100 \qquad (2)$$

$$\text{Maximum tank dimension} = \sqrt{(x_{max} - x_{min})^2 + (y_{max} - y_{min})^2 + (z_{max} - z_{min})^2} \qquad (3)$$

The improvement in time consumption when using the proposed GA-Newton method is also analyzed. The transformer tank is divided into sub modules of size 0.1m x 0.1m x 0.1m. Each vertex of the sub module is considered as a PD source. In this way, 729 PD sources are considered. These PD source positions are located by using Newton's method with initial guesses IG-1 and IG-2 and the GA-Newton method. The stopping criteria are chosen as: (i) maximum number of iteration = 100; (ii) tolerance = 1 x 10^{-6}; and (iii) maximum time limit = 60 seconds. The computational time in the case of converging solutions is normally in the range of few tens of seconds. However, the non-converging solutions may take enormous time in the range of hours. Hence, the maximum time limit is chosen as 60 seconds. The number of PD sources that are converging or non-converging within 60 seconds out of the 729 PD source positions are analyzed.

TABLE 2: SENSOR COORDINATES USED FOR THE IMPLEMENTATION OF ALGORITHM

Sensor number	Sensor coordinates (m)		
	X	Y	Z
1	0.000	0.345	0.435
2	0.735	0.525	0.000
3	1.000	0.745	0.725
4	0.325	0.435	1.000

V. Results and Discussion

The PD coordinates (PD-1, PD-2 and PD-3; see section 4) located, by using Newton's method with two different initial guesses (IG-1 and IG-2) and GA-Newton method, are shown in Table 3. From Table 3, when Newton's method with an initial guess as zero vector is used, the PD source location PD-1 is located outside the tank with a percentage deviation error of 83.6%. Newton's method with a random initial guess also results in high percentage deviation error for the PD locations PD-1 and PD-2. All the three PD sources are located with greater accuracy using GA-Newton method. The PD source co-ordinates are computed to a precision of 15 decimal places, in the present numerical experiments, for estimating the percentage deviation error.

Table 3: The PD source located by using Newton's method with initial guesses (IG-1 and IG-2) and the GA-Newton method

Algorithm	PD source	Actual PD coordinates (m)			Located PD coordinates (m)			Percentage deviation error (%)
		x	*y*	*z*	*x*	*y*	*z*	
Newton's method with IG-1	PD-1	0.8	0.5	0.7	1.397	1.641	1.366	83.6
	PD-2	0.9	0.1	0.1	0.900	0.100	0.100	2.16×10^{-13}
	PD-3	0.5	0.7	0.2	0.500	0.700	0.200	1.43×10^{-14}
Newton's method with IG-2	PD-1	0.8	0.5	0.7	1.011	0.903	0.935	29.5
	PD-2	0.9	0.1	0.1	0.707	0.450	0.210	23.9
	PD-3	0.5	0.7	0.2	0.500	0.700	0.200	2.75×10^{-11}
GA-Newton method	PD-1	0.8	0.5	0.7	0.800	0.500	0.700	1.63×10^{-3}
	PD-2	0.9	0.1	0.1	0.900	0.100	0.100	2.16×10^{-13}
	PD-3	0.5	0.7	0.2	0.500	0.700	0.200	1.43×10^{-14}

The bar chart in Fig. 2 shows the number of PD sources that are converging or non-converging within 60 seconds out of the 729 PD source positions. From Fig.2, there is considerable increase in the number of PD sources that can be located within 60 seconds when using GA-Newton method, compared to Newton's method with initial guesses as IG-1 and IG-2.

VI. Conclusions

The present work analyses the major challenges when using Newton's method for AEPD source localization.

For some initial guesses, Newton's method results in high percentage deviation error in the located PD source positions. However, when GA-Newton method is used for the PD source localization the maximum percentage deviation error is of the order of 10^{-3}. This proves the high accuracy in PD source localization when using the proposed (GA-Newton) method.

When a good initial guess is located for Newton's method by using GA, most of the PD source positions can be located within 60 seconds and thus the enormous computational time requirement of Newton's method can be vanquished when using the GA-Newton method.

The good initial guesses are specific to a given PD location and the sensor positions. Hence, for such situations GA-Newton method that identifies a good initial guess for Newton's method via GA (being parallel search) is proved useful.

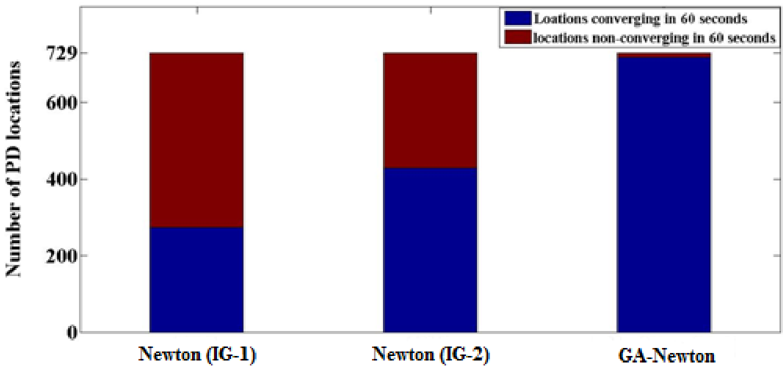

Fig. 2. Comparison of number of PD sources converging or non-converging within 60 seconds by using Newton's method with different initial guesses and GA-Newton method

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