A Strategy to Locate Partial Discharges in Power Transformers using Acoustic Emission

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Abstract. This paper presents a solution for the problem related to Partial Discharges (PD) source localization in oil-isolated transformers, using Genetic Algorithms. As known in literature, the simple PD detection is not enough to take a decision about intervening, so the localization is necessary to assess the risk and to plan corrective actions. The parameters extracted from the acoustic signals collected by piezoelectric sensors installed outside of the transformer, provide the correct position of PD. From parameters extracted of acoustic signals collected from piezoelectric sensors installed outside the transformer, the proposed algorithm provides the position where the PD is occurring. This work compares the performance of the method using Genetic Algorithms and those using iterative method, which is normally used to solve this problem. The conclusion describes the advantages of the proposed solution.

Key words

Power quality, Power transformers, Acoustic emission, Reliability, Maintenance

1. Introduction

The partial discharge is a phenomenon that occurs in a wide variety of electric equipments and it develops slowly as time passes by, resulting in the total flaw of the isolation system. The transformers are among the most affected equipment by this kind of flaw, specially the high power ones.

Due to its tricky behavior, there is a great need to monitor and to control the partial discharges in transformers, which shall consist of an effective predictive maintenance of those equipments. There are many techniques for the detection of partial discharges, which depend on the type of equipment to be monitored. Among those used in transformers, the acoustic technique shall be highlighted.

The acoustic method is based in the fact that when a Partial Discharge (PD) occurs, an acoustic wave, in the range of the ultrasound, is emitted. Therefore, it can be detected by one or more sensors spread on the walls outside the isolated oil transformer. The detected sign shall be processed to extract useful parameters for the flaw diagnosis. Among these parameters, there is the instant in which the front of the wave reaches the sensor when going through a straight line between it and the origin of the emission, needed to perform the localization, which is essential for the estimation of the flaw risk, as well as to plan the repairs.

The localization of the source of partial discharges by the use of acoustic signals can be modeled through a system of non-linear equations. As already known, to numerically solve a non-linear system is not simple, and normally it depends on a deep knowledge of the problem to get to an algorithm able to rapidly converge into a solution.

The proposal for this work is to use a Genetic Algorithm (GA) to solve this non-linear system. For this purpose, the equations of the system are reformulated as an optimization problem and an optimal solution with the GA is sought. The main advantage of the GA use is in its capability of obtaining the solution with no initial estimation, which is the weak point of the iterative methods. Beyond that, a wide range of sensors (at least 4) can be used without any need to change the algorithm.

This work does not approach the processing of the acoustic emission (AE) signal needed to obtain the parameters used by the GA. The problem of the localization is initially turned into an equation and some strategies are presented to solve it. Then the proposed solution shall be compared to the iterative method of Newton. Therefore, this work does not approach the acoustic technique for the detection of partial discharges as a whole, but only the part referring to their localization.

2. The Problem Related to the Localization

A way of turning into an equation the localization of the AE source is illustrated in the Figure 1. Many sensors are spread on the walls of the tank [1], which adopts any point as the origin of a rectangular coordinates system in three dimensions.

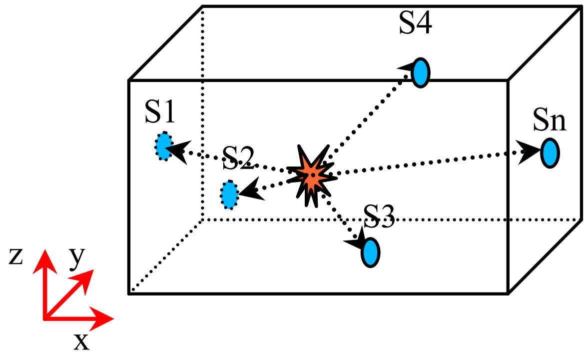

Fig. 1. Scheme for turning the problem into an equation

A system of non-linear equations can be obtained considering each sensor as the center of a sphere whose radius is the distance of this sensor to the AE source (Figure 2). The value of the radius shall be given in terms of propagation speed v_s of the acoustic wave in the transformer oil and in terms of the time Δt in which it took to reach the point where the sensor is [2]. The equation of the sphere is written in the following way:

$$(x - x_{S1})^2 + (y - y_{S1})^2 + (z - z_{S1})^2 = r^2 \qquad (1)$$

where (x_{s1}, y_{s1}, z_{s1}) are the coordinates of the sensor *S1*. When the sound propagation speed is v_s and the time interval between AE source and the arrived of the wave is Δt we can write that:

$$(x - x_{S1})^2 + (y - y_{S1})^2 + (z - z_{S1})^2 = (v_s \cdot \Delta t)^2 \qquad (2)$$

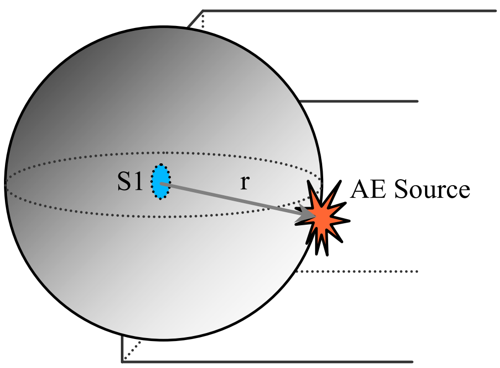

Fig. 2. Sphere with the center in the sensor to turn into an equation the problem of the localization of the AE source.

However, the time intervals in which the acoustic wave takes to reach the sensors cannot be directly obtained without the simultaneous electric detection. Therefore, a scheme with many sensors shall be used to monitor the transformer when an AE occurs due to a PD [3], in case the only method used is the acoustic one. Differences of time in relation to the first sensor that detected the AE were recorded. Stated that, the unknown factors of the problem shall be the time interval *T* between the occurrence of the PD and the detection of the acoustic wave by the nearest sensor and the coordinates (*x, y, z*) of the position of the AE source, that is, the position of the PD. Therefore, a non-linear system with four equations is obtained:

$$(x - x_{S1})^2 + (y - y_{S1})^2 + (z - z_{S1})^2 = (v_s \cdot T)^2 \qquad (3)$$

$$(x - x_{S2})^2 + (y - y_{S2})^2 + (z - z_{S2})^2 = [v_s \cdot (T + \tau_2)]^2 \qquad (4)$$

$$(x - x_{S3})^2 + (y - y_{S3})^2 + (z - z_{S3})^2 = [v_s \cdot (T + \tau_3)]^2 \qquad (5)$$

$$(x - x_{S4})^2 + (y - y_{S4})^2 + (z - z_{S4})^2 = [v_s \cdot (T + \tau_4)]^2 \qquad (6)$$

where the τ_i are the time differences in relation to the first detection.

3. Solution through an Iterative Method

An iterative method is relatively simple of being implemented. Initially, an initial estimate should be supplied, and then, it is evaluated if this estimate is satisfactory; in case it is not, it owes are refined her until that it is satisfactory and the algorithm can be contained.

A disadvantage of the iterative method is the divergence possibility. In spite of there being a "continuous refinement" of the solution, this process it can start to produce a worse solution, taking the algorithm to present a very bad final solution. The divergence (or convergence) depends a lot on the quality of the initial estimate and of the refinement method.

For nonlinear systems, elimination algorithms don't exist for approximation of the values of the initial estimate. Then, the procedure to arrive to a solution goes by locating the roots.

This location depends on the knowledge of the problem. The suggestion of [1] to use iterative methods in the location of the source of AE it is to position the origin of the system of coordinates in such a way that all of the possible positions are of positive coordinates. Like this, it is used (0; 0; 0; 0) as initial estimate.

Starting from the initial estimates, refinement algorithm starts. It will be approached Newton's method here. Considering a nonlinear system:

$$
\begin{aligned}
&f_1(x_1, x_2, x_3, ..., x_n) = 0 \\
&f_2(x_1, x_2, x_3, ..., x_n) = 0 \\
&f_3(x_1, x_2, x_3, ..., x_n) = 0 \\
&\vdots \\
&f_n(x_1, x_2, x_3, ..., x_n) = 0
\end{aligned}
\tag{7}
$$

the solution will be given by:

$$
\begin{aligned}
&x_1^1 = x_1^0 + h_1 \\
&x_2^1 = x_2^0 + h_2 \\
&x_3^1 = x_3^0 + h_3 \\
&\vdots \\
&x_n^1 = x_n^0 + h_n
\end{aligned}
\tag{8}
$$

where the super-index indicates the iteration, being the zero corresponding to the initial estimates. The h_i can be obtained being solved the following linear system of equations:

$$
\begin{aligned}
&\frac{\partial f_1}{\partial x_1} h_1 + \frac{\partial f_1}{\partial x_2} h_2 + ... + \frac{\partial f_1}{\partial x_n} h_n = -f_1 \\
&\frac{\partial f_2}{\partial x_1} h_1 + \frac{\partial f_2}{\partial x_2} h_2 + ... + \frac{\partial f_2}{\partial x_n} h_n = -f_2 \\
&\frac{\partial f_3}{\partial x_1} h_1 + \frac{\partial f_3}{\partial x_2} h_2 + ... + \frac{\partial f_3}{\partial x_n} h_n = -f_3 \\
&\vdots \\
&\frac{\partial f_n}{\partial x_1} h_1 + \frac{\partial f_n}{\partial x_2} h_2 + ... + \frac{\partial f_n}{\partial x_n} h_n = -f_n
\end{aligned}
\tag{9}
$$

where partial derivation and the functions are calculated for the estimates of the variables x_i of the previous iteration.

As stop criterion, a solution can be considered satisfactory when the difference among two successive solutions is inferior to a predefined tolerance.

4. Solution through a Genetic Algorithm

The solution of a non-linear system can be obtained with a Genetic Algorithm [4]. Then, a brief description of the developed algorithm shall be made.

The variables involved when turning problem into an equation are all real. Moreover, they need some precision records. The ***codification*** used in this algorithm is the ***real*** one. The structure of the chromosome (the genes) presents the following form:

x	*y*	*z*	*T*

where each one of the variables is a real number.

The equations of the non-linear system are used to build the ***fitness function***. Taking the expressions from (3) to (6), the following functions are obtained:

$$(x - x_{S1})^2 + (y - y_{S1})^2 + (z - z_{S1})^2 - (v_s \cdot T)^2 = f_1 \tag{10}$$

$$(x - x_{S2})^2 + (y - y_{S2})^2 + (z - z_{S2})^2 - [v_s \cdot (T + \tau_2)]^2 = f_2 \tag{11}$$

$$(x - x_{S3})^2 + (y - y_{S3})^2 + (z - z_{S3})^2 - [v_s \cdot (T + \tau_3)]^2 = f_3 \tag{12}$$

$$(x - x_{S4})^2 + (y - y_{S4})^2 + (z - z_{S4})^2 - [v_s \cdot (T + \tau_4)]^2 = f_4 \tag{13}$$

Applying the variables of the chromosome (the genes) to the equations (10) the (13) and taking the square root of the sum of the values f_i, it is obtained a value that should be minimized (the ideal is that it is reduced to zero) to arrive to a optimal solution [5] – this is the *objective function*. In this GA, the authors decided to change objective function for a strip of fitness values between 0 and 10 so that to smallest value of objective function should be close to 10 (a good chromosome) and the largest one, close of 0 (weak chromosome) [6].

Like this, the algorithm will look for to maximize the fitness values. The authors decided, then, to do an exponential conversion, so that:

$$A = b \cdot e^{-a \cdot F} \tag{14}$$

where it is A the fitness value, F is the objective function, the a and b are parameters of the exponential function. The parameter b defines the maximum fitness value, once there won't be smaller values than zero for the objective function. The parameter a controls it the curvature, so that as larger its value, more restricted it is the group of good fitness values. This conversion is illustrated in the Figure 3, where a=0.8 and b=10.

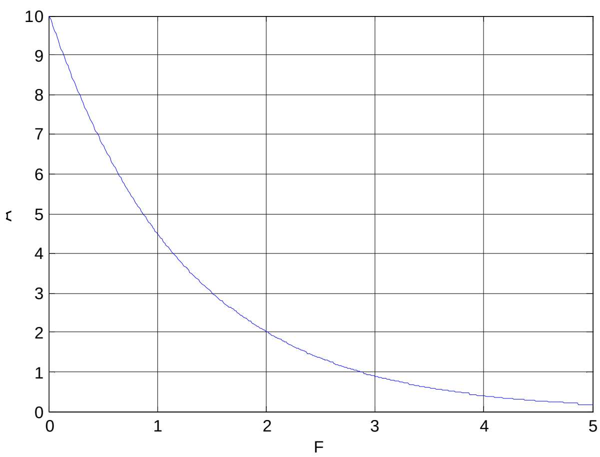

Fig. 3. Error Conversion Graphic

The type of ***selection*** used for the recombination was the *roulette wheel*, which choose individuals for the reproduction in a random way but it takes into consideration the fitness value in a way that the best shall be benefited in the choice.

As the *real* codification was specified, that determined the possible types of ***recombination***, which shall be operations with real numbers. In this case, the *in line* BLX_a recombination is used.

The ***mutation*** applied to the chromosomes with a very small probability belongs to the *creep* type. In it, the gene suffers the addition of a small random value with normal distribution.

5. Simulations and Results

To test the GA for the PD localization in isolated oil transformers, we initially used computer-simulated data. Sooner, in the next stage, situations of partial discharges simulated in an oil filled tank shall be performed, followed of field experiences, in real cases.

TABLE I - Positions of the sensors for the simulation

Sensor	Position [m]
Sa	(1.8; 1.0; 0.5)
Sb	(3.0; 0.5; 0.5)
Sc	(1.2; 0.5; 1.0)
Sd	(0.9; 1.0; 0.2)

For the fictitious tank of 3(m) x 1(m) x 1(m), and the sensors in the positions in Table I, we obtained the data for the simulation, which appear in the Table II for a PD occurrence in the position (0.3; 0.1; 0.7) and the speed of sound in the oil of 1400m/s. The origin of the coordinates system was placed in one of the corners of the tank.

Applying the values τ_i, and the positions of the sensors in the GA for the localization of the PD, we got to the result in Table IV. The parameters used for the GA are in Table III.

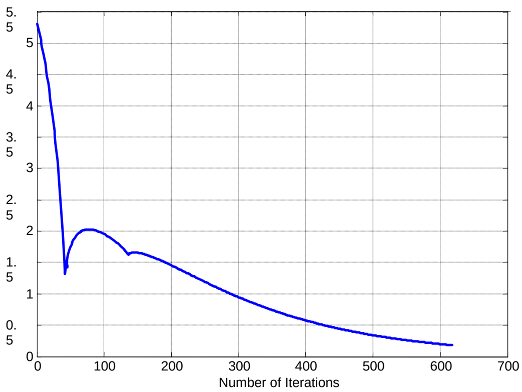

Fig. 4. Convergence of the Iterative Method

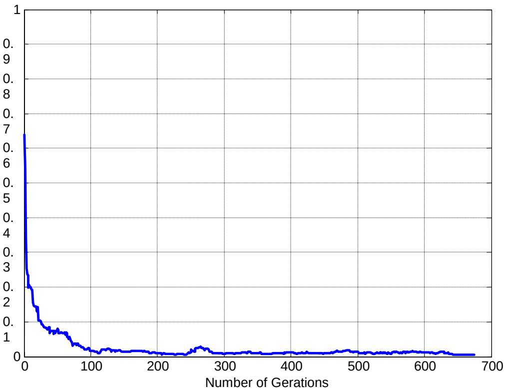

Fig. 5. Convergence of the GA

To compare, we implemented the iterative method of Newton to solve the non-linear system. After 618 iterations and using (0.1; 0.01; 0.2; 0.0005) as the initial estimation, we got to the results in Table V.

TABLE II - Results of the simulation

Sensors in the order in which they were reached	Sc, Sd, Sa, Sb
Time *T* between the PD occurrence and the first detection	0.735 ms
τ_1	0.116 ms
τ_2	0.522 ms
τ_3	1.219 ms

Graphics with a convergence curve for each algorithm can be checked in the Figures 4 and 5. In these graphics, the ordinate represents the flaw to be minimized, that is, the adding of the square root of the results of functions f_1, f_2, f_3, and f_4 in the equations from (6) to (9).

We can note that the GA converges very fast although the solution obtained took a long time to be achieved due to the demand related to precision.

TABLE III - Parameters of the Genetic Algorithm

Size of the Population	120
Maximum Number of Generations	1250
Recombination Probability	0.98
Mutation Probability	0.050

TABLE IV - Result of the Genetic Algorithm compared to the exact solution

Exact values			
x [m]	*y [m]*	*z [m]*	*T [ms]*
0.30	0.10	0.70	0.735
Values found by the GA			
x [m]	*y [m]*	*z [m]*	*T [ms]*
0.300	0.100	0.700	0.7353

TABLE V - Result of the iterative method compared to the exact solution

Exact values			
x [m]	*y [m]*	*z [m]*	*T [ms]*
0.30	0.10	0.70	0.735
Values found by the iterative method			
x [m]	*y [m]*	*z [m]*	*T [ms]*
0.301	0.100	0.699	0.7352

6. Conclusions

The solution for the localization of the origin of a partial discharge in an isolated oil transformer using acoustic emission techniques and Genetic Algorithms is satisfying, as the results show. The great advantage of this method is the lack of need of an initial estimation, as in the case of iterative methods. However, whether it is interesting, we can provide one or more initial estimations for the GA, which, if they are good, can speed up the obtainment of a result.

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