Electric Power Systems Research 143 (2017) 110–120

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Quantification of the performance of iterative and non-iterative computational methods of locating partial discharges using RF measurement techniques

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ARTICLE INFO

Article history:
Received 17 February 2016
Received in revised form 11 October 2016
Accepted 14 October 2016

Keywords:
Partial discharges
Iterative algorithms
Non-iterative algorithms
Radio frequency
Fault location
Time difference of arrival

ABSTRACT

Partial discharge (PD) is an electrical discharge phenomenon that occurs when the insulation material of high voltage equipment is subjected to high electric field stress. Its occurrence can be an indication of incipient failure within power equipment such as power transformers, underground transmission cable or switchgear. Radio frequency measurement methods can be used to detect and locate discharge sources by measuring the propagated electromagnetic wave arising as a result of ionic charge acceleration. An array of at least four receiving antennas may be employed to detect any radiated discharge signals, then the three dimensional position of the discharge source can be calculated using different algorithms. These algorithms fall into two categories; iterative or non-iterative.

This paper evaluates, through simulation, the location performance of an iterative method (the standard least squares method) and a non-iterative method (the Bancroft algorithm). Simulations were carried out using (i) a "Y" shaped antenna array and (ii) a square shaped antenna array, each consisting of a four-antennas. The results show that PD location accuracy is influenced by the algorithm's error bound, the number of iterations and the initial values for the iterative algorithms, as well as the antenna arrangement for both the non-iterative and iterative algorithms. Furthermore, this research proposes a novel approach for selecting adequate error bounds and number of iterations using results of the non-iterative method, thus solving some of the iterative method dependencies.

1. Introduction

Radio frequency (RF) measurement technique using receiving antennas can be used to detect the radiated energy from PD sources or any other electrical discharge activities, subsequently facilitating the discharge source triangulation. Using a receiving antenna array, which may be arranged in various forms, the time differences of arrival (TDOA) between received signals on each of the respective antennas allows the 3 dimensional position of the electrical discharge source to be deduced by processing of the TDOA values through iterative or non-iterative location algorithms. The location of partial discharges using emitted RF techniques in HV equipment has been widely investigated [1–5]. Research in this area has been carried out on cables [6–9], gas and air insulated switchgears [10–14] and transformers [15–17]. PD location in cables, and to a degree in gas-insulated substation (GIS), is a two-dimensional problem, while internal localisation within power transformers and localisation in three dimensions in wide-area HV substations requires robust computation algorithms [1].

There are two types of computational algorithm which can be used to locate partial discharges in three dimensions; (i) iterative methods and (ii) non-iterative methods. In this study, a non-iterative method was selected due to the large success of these methods in Global Positioning System (GPS) applications such as navigation and location systems. The choice of an iterative method was mainly due their efficiency in solving nonlinear problems involving large number of variables.

The iterative methods give an approximate solution to nonlinear equations based on a number of iterations and starting with an initial value, which is improved at each iteration by an error bound until a converged solution is found or until a maximum number of iterations is reached. Taylor expansion and Newton–Raphson tech-

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http://dx.doi.org/10.1016/j.epsr.2016.10.036
0378-7796/

niques are common iterative methods that can be used to solve the equations of nonlinear systems. These methods have been used in different studies to locate PD [1,18,19]. The study in Ref. [18] highlighted that the performance of the Taylor expansion method depends on the accuracy of the initial values and the number of sensors, whereas the study by Moore et al. [1] showed that the Newton–Raphson method successfully locates PD and that the location accuracy depends on the arrangement of antennas. Study [19] also used the Newton–Raphson method to locate PD and found that in some cases the algorithm did not provide a converged solution. It indicated that a solution called the "grid search method" which consists of using a range of values within a grid as initial values to determine a converged solution helped improve accuracy. Despite the fact that these studies highlighted the success of these iterative methods to locate discharges activities within a reasonable margin of error, a limited number of published studies have attempted to evaluate fully the performance of non-iterative and iterative methods in their ability to locate accurately the position of electrical discharge sources.

In order to evaluate the performance of iterative and non-iterative algorithms, the present study investigates through simulation the location performance of a well-established iterative method; the standard least squares (SLS) method, and a non-iterative method; the Bancroft algorithm [22]. Two antenna array configurations (Y and square shape), both consisting of 4 antenna positions were chosen for the investigations reported herein evaluating the performance of the respective location algorithms. The square and 'Y' array configurations are commonly used and were selected since they have been used in previous studies [1,4] to investigate electromagnetic (EM) wave propagation PD sources.

The paper is structured as follows: the mathematical formulation of the SLS and Bancroft location algorithms are presented in Section 2; Section 3 presents the methodologies used in the present study; Section 4 presents the results of PD location studies using the SLS and Bancroft algorithms respectively (in each case two different antenna arrangements were investigated). For simplification, the simulated PD location data points refer to any electrical discharge source emitting EM wave radiation; Section 5 compares the characteristics of both the iterative and non-iterative algorithms used; Section 6 proposes a new approach to select adequate error bounds and number of iterations using results of the non-iterative methods; Section 7 summarises the findings of the study.

2. Formulation of the SLS and Bancroft algorithms

A minimum of four spatially separated antennas may be used to triangulate the location of a PD event in 3 dimensions using RF methods (Fig. 1). Knowing the grid coordinates of each antenna in the array then allows the propagation time from the PD source to the respective antennas to be calculated using the basic formula $D = v \cdot t$, where D is distance, v is propagation velocity and t is propagation time. This technique, commonly referred to as 'triangulation', is described by Eq. (1):

$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = (V_e \cdot t_i)^2 \tag{1}$$

where (x_i, y_i, z_i) are the coordinates of the ith antenna in Cartesian space, (x, y, z) represent the true coordinates of the PD event, v_e is the speed of light (3×10^8 m/s) and t_i represents the 'time-of-flight' of the propagating PD signal from its source to the ith antenna. It should be noted that since the study is a simulation based investigation, the speed of light was considered to be in a vacuum and that this value changes depending on the insulating material.

Let the time-of-flight from the PD source to antenna A_1 be T and the time-difference-of-arrival between antennas A_1 and A_n

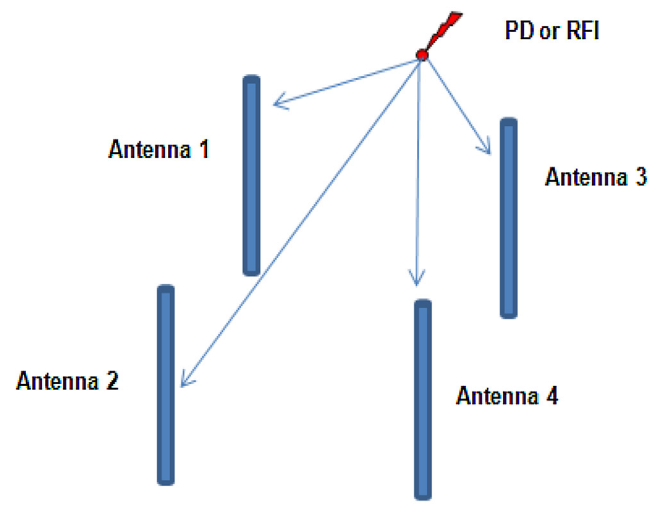

Fig. 1. Basic configuration of a typical RF PD location setup.

(n = 2–4) be τ_{1n}. Eq. (1) now expands into the following four formulae [20]:

$$\begin{aligned}
(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 &= (v_e \cdot T)^2 \\
(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2 &= (v_e \cdot (T + \tau_{12}))^2 \\
(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2 &= (v_e \cdot (T + \tau_{13}))^2 \\
(x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2 &= (v_e \cdot (T + \tau_{14}))^2
\end{aligned} \tag{2}$$

2.1. Standard least squares (SLS) algorithm

Using on the non-linear equations in Eq. (2), the position of a PD source (x, y, z) can be computed using the least squares method given in Eq. (3).

$$S(X) = \sum_{i=1}^{N} (Y_i(X))^2 \tag{3}$$

In least squares, the standard definition of $Y_i(X)$ is given in Eq. (4). Based on the definition of $Y_i(X)$, the least squares method minimises the sum of the square of the residuals.

$$Y_i(X) = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} - (v_e * (T + \tau_{1i})) \tag{4}$$

Since the aim is to compute the values of x, y and z which minimise $S(X)$, the partial derivative of $S(X)$ with respect to x, y and z is calculated with the equation set equal to 0 as shown in Eq. (5):

$$\frac{\partial S}{\partial x} = 0, \quad \frac{\partial S}{\partial y} = 0, \quad \frac{\partial S}{\partial z} = 0, \text{ and } \frac{\partial S}{\partial T} = 0. \tag{5}$$

Substituting p to represent x, y or z, the iterative solution for each coordinate and for T becomes:

$$p = \frac{1}{N}\sum_{i=1}^{N} p_i + \frac{1}{N}\sum_{i=1}^{N} \frac{(p - p_i)(T + \tau_{1i})v_e}{\sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2}} \tag{6}$$

$$T = \frac{\sum_{i=1}^{N} \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2}}{\sum_{i=1}^{N} v_e} - \frac{1}{N}\sum_{i=1}^{N} \tau_{1i} \tag{7}$$

where N is the number of antennae and τ_{1i} is the TDOA between a signal measured by the ith antenna and by antenna 1. For cho-