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A novel acoustic method of partial discharge allocation considering structure-borne waves

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ABSTRACT

For partial discharge, PD, allocating utilizing acoustic emission, AE, sensors, the arrival time of acoustic waves to the sensors forms the calculation basics, therefore, it is crucial that distance calculations are based on direct acoustic path. Considering structure-borne waves of higher speed, this would imply an incorrect distance between the source and sensor, because, AE signals of indirect path me be considered as AE signals of direct path. Therefore, a heuristic algorithm has been developed to consider the possible indirect paths. By comparing the time taken in each path of propagation, to reach the specified sensor location, the indirect path of shortest time for AE signal is determined. For experimental verification, a test oil chamber has been fabricated. PD signals are generated at different points inside the tank. The estimation results of algorithm have been compared with results of classic Time Difference of Arrivals method, TDOA. The proposed method considerably increases the PD allocation precision.

Introduction

The age of a power device is mainly the age of its insulation structure and the monitoring of the partial discharges, PDs, considerably reduces the failure risk and the progressive deterioration of the insulation system in any power devices [1,2]. All the partial discharges generate acoustic signals in a specific frequency band [3]. Piezo-electric transducers may be mounted on tank walls to catch the acoustic emission, AE, waves that travel from the PD source. This method is sensitive to PDs higher than 500 pC [4], and is more advantageous than the electrical methods. Besides the PD amplitude measurement, they are capable of simultaneously allocating the PD. Furthermore, in addition to their easy installation, they are immune to the electromagnetic interferences. Also, their sensitivity is independent of the capacitance of the object [5]. The method of the Time Difference of the Arrivals, TDOA, is used for the PD allocation via AE sensors [6–10]. This method utilizes the differences in the arrival times of the AE signals to the sensors and solves the equation systems explaining these time differences versus the PD location coordinates. In the TDOA method it is assumed that the AE waves propagate directly from the PD origin to the sensor. However, the indirect paths of the AE wave complicate the calculation of the PD origins by the externally mounted piezoelectric AE sensors. Actually, the propagation of the acoustic waves within the transformer wall is complex. Structure-borne propagation paths within the tank wall present a technical challenge [11]. As the AE waves enter the tank wall and propagate through the tank, their speed of propagation changes. Because the propagation speed in steel is higher than the propagation speed in oil, the arrival time of the structure-borne signals would probably be earlier than the AE waves which propagate directly from the PD source to the sensor [11]. For the determination of the exact time difference between the PD source and the acoustic sensor, the path with the shortest travel time should be investigated. This may be done, acknowledging the fact that during the indirect mode of propagation, the AE signals can hit any one of the six tank surfaces and then reach the sensor. Thus, a heuristic algorithm has been developed to consider all the possible indirect paths and to compute the indirect path propagation times. As a result, the propagation path with the lowest arrival time is determined, and, the more precise allocation of the PD signals is made possible. A test oil chamber has been utilized and artificial PD signals are produced at various points inside the tank. The output results of the algorithm have been compared with the results of the TDOA method. It has been shown that the proposed method significantly increases the allocation precision.

The allocation methodology

Classic method of time difference of arrivals

If a partial discharge occurs at the coordinates (x,y,z), and four sensors are mounted at the coordinates (x_i,y_i,z_i), the distances between the PD origin and the sensor locations are as (1).

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0142-0615/

$$
\begin{aligned}
d_1 &= \sqrt{(x^2 - x_1^2) + (y^2 - y_1^2) + (z^2 - z_1^2)} = Ct_1 \\
d_2 &= \sqrt{(x^2 - x_2^2) + (y^2 - y_2^2) + (z^2 - z_2^2)} = Ct_2 \\
d_3 &= \sqrt{(x^2 - x_3^2) + (y^2 - y_3^2) + (z^2 - z_3^2)} = Ct_3 \\
d_4 &= \sqrt{(x^2 - x_4^2) + (y^2 - y_4^2) + (z^2 - z_4^2)} = Ct_4
\end{aligned} \tag{1}
$$

where d_i is the distance from the PD origin to the sensor i, t_i is the arrival time to sensor i, and C is the speed of the sound, which according to [11], in temperature of 20 °C is equal to 1431 m/s.

Coordinates of the PD source may be calculated by TDOA method, via solving the equations of (2), [6].

$$
\begin{aligned}
d_2 - d_1 &= \sqrt{(x^2 - x_2^2) + (y^2 - y_2^2) + (z^2 - z_2^2)} \\
&\quad - \sqrt{(x^2 - x_1^2) + (y^2 - y_1^2) + (z^2 - z_1^2)} = C(t_2 - t_1) = C\tau_{12} \\
d_3 - d_1 &= \sqrt{(x^2 - x_3^2) + (y^2 - y_3^2) + (z^2 - z_3^2)} \\
&\quad - \sqrt{(x^2 - x_1^2) + (y^2 - y_1^2) + (z^2 - z_1^2)} = C(t_3 - t_1) = C\tau_{13} \\
d_4 - d_1 &= \sqrt{(x^2 - x_4^2) + (y^2 - y_4^2) + (z^2 - z_4^2)} \\
&\quad - \sqrt{(x^2 - x_1^2) + (y^2 - y_1^2) + (z^2 - z_1^2)} = C(t_4 - t_1) = C\tau_{14}
\end{aligned} \tag{2}
$$

where τ_{1i}, is the time-difference of arrivals between the sensor 1 and the sensor i.

Determination of the path with minimum propagation time

In Fig. 1, a PD has occurred at a distance from the tank with a mounted AE sensor. There are three possible cases for the AE signal propagation to the sensor which should be investigated. The AE wave may propagate from the PD source to the sensor position on a straight line of length L, path 1 in Fig. 1. There is an angle of α between this line and the tank wall in this case. Another possibility for the AE wave is to propagate on a perpendicular line to the tank wall and entering the wall, propagate on the wall toward the sensor, as path 2 in Fig. 1. In the last case, the AE wave propagates on a path between the paths 1 and 2. One part of the path is on a line with the angle of β relative to the tank wall. The other part, continues its path on the wall.

The path 1 has an arrival time of $T_1 = \frac{L}{C}$. According to [11], the acoustic wave speed in the steel is $m = 3.64$ times the speed in the oil. Therefore, the path 2 has the arrival time as in (3).

$$T_2 = \frac{L}{C} \sin \alpha + \frac{L}{mC} \cos \alpha \tag{3}$$

According to Fig. 1, and utilizing trigonometric equalities, the path 3 has the arrival time of (4).

$$T_3 = \frac{L}{C} \frac{\sin \alpha}{\sin \beta} + \frac{L}{mC} (\cos \alpha - \sin \alpha \cot \beta) \tag{4}$$

Which, may be written as (5), after trigonometric simplifications.

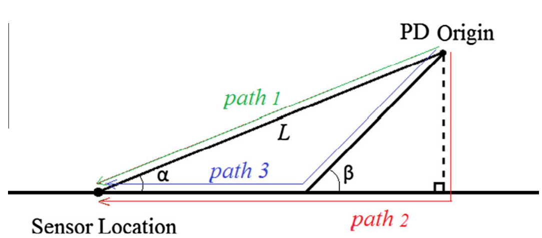

Fig. 1. Possible cases for AE wave propagation from a PD source to a sensor.

$$T_3 = \frac{L}{C} \left(\frac{\sin \alpha + \frac{1}{m} \sin(\beta - \alpha)}{\sin \beta} \right) \tag{5}$$

The variation of T_3 with β for different values of α is shown in Fig. 2. As evident from Fig. 2, each of the paths 1, 2 and 3 may be the minimum arrival time path. For $\alpha = 10$, the path 2 is the minimum time path, for $\alpha = 30$, the path 3 and for $\alpha = 70$, the path 1 are the minimum time paths. As a result, as long as the exact time calculations are intended, all these cases should be considered.

The allocation algorithm

The six sides of the tank wall and a sample PD source are shown in Fig. 3. The AE sensor is mounted on the side 1.

In order to calculate the path of minimum arrival time to the sensor, the projection of PD point on each side of the tank should be calculated at the first step. Knowing the projection point from the PD source to each side of the tank, the path of minimum length from the projection point to the sensor location should be determined. An algorithm has been developed to determine the path of shortest length among all the paths from the projected point to the AE sensor. The methodology of this algorithm is shown in Fig. 4, for projection relative to side 6. According to Fig. 4, the shortest path on the tank wall is the direct line from the projected point to the sensor position on the flat map of the tank walls.

According to Fig. 1, for each case in Fig. 4, three paths should be considered. These three paths for the OABS case in Fig. 4, are shown schematically in Fig. 5. Among these possible paths, the path with the least arrival time of the sensor is chosen according to the part III.

Any other possible paths would fall in the category of the projection relative to the other sides.

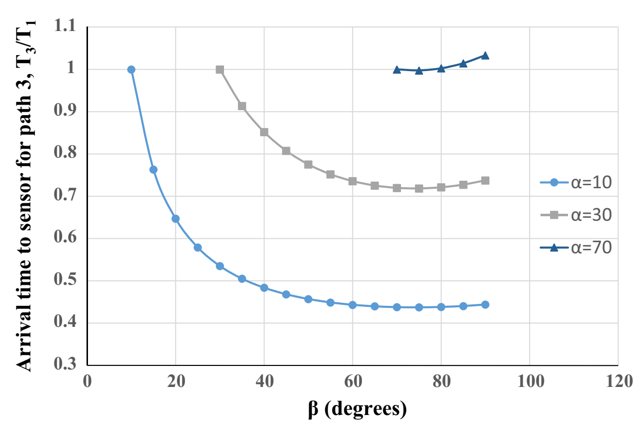

Fig. 2. The variation of the sensor arrival time for path 3, T_3, with respect to β.

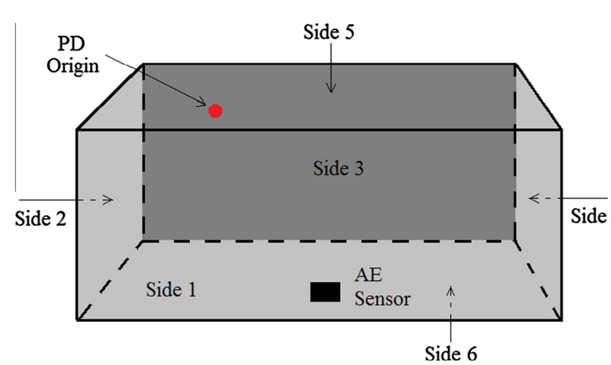

Fig. 3. The schematics of a PD source and a mounted sensor.