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Proposed method of partial discharge allocation with acoustic emission sensors within power transformers

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A R T I C L E I N F O

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Employing acoustic emission sensors for detection of partial discharge, PD, introduces many advantages. Besides easy installation and replacement, they are non-invasive and immune to electromagnetic noise and interference and their sensitivity does not vary with object capacitance. For PD allocating utilizing AE sensors, distance calculations are based on the arrival time of acoustic waves to the sensors. Considering structure-borne waves of higher speed, the peaks of some of indirect path AE signals with significant contribution are mistakenly considered as peaks of direct path AE signals. Furthermore, the acoustic signals are propagating through certain parts of the transformer, such as the windings, and this complicates the partial discharge detection and allocation. These would imply an incorrect distance between the source and sensor. A method based on a heuristic algorithm has been proposed which considering all possible indirect paths with the relevant propagation times and all the barriers on the travel path of acoustic signal, calculates the more precise arrival times to sensors. A test chamber has been utilized and artificial PD signals are produced at various points. Output results of algorithm have been compared with results of classic method. It has been shown that proposed method significantly reduces the positioning errors.

1. Introduction

The partial discharges, PDs, have serious impact on the progressive deterioration of the insulation system in any power devices such as power transformers and may lead to ultimate failure [1]. Thus, the monitoring of the partial discharges is of significant importance, as it can help to reduce the failure risk. The Acoustic Emission, AE, method for the PD detection is based on the fact that all the partial discharges produce acoustic waves in a frequency range up to 150 kHz within a transformer tank [2]. Special piezo-electric sensors are mounted on the outer surface of the transformer tank to detect these waves that propagate from the PD origin to the tank through the dielectric medium. AE method is usually sensitive to PD levels of above 500 pC [3]. Acoustic methods of PD measurement are more beneficial than the electrical methods because they are non-invasive and immune to the electromagnetic noise and interference, their sensitivity does not change with the object capacitance, they offer the easy installation and replacement and besides the PD measurement, they can simultaneously provide an indication of the PD source location within a complex system [4–6]. For PD allocation with AE, generally the method of the Time Difference of the Arrivals, TDOA, is utilized [7–10]. In this method, the differences in the arrival times of the acoustic signals to the sensors are recorded and solving the nonlinear equations indicating these time differences, the PD location is estimated. This method necessitates a uniform medium for the propagation of the acoustic signals and it is assumed that the acoustic waves travel directly from the PD source through the oil to the sensor without any reflections and deflections. As a result, the disadvantage associated with an externally mounted piezo-electric acoustic emission sensor is that the multiple paths of the acoustic wave transmission and propagation through various media with different velocities make the estimation of the exact locations of the PDs difficult. Therefore, the accuracy of locating a PD source by this method is poor due to the structure-borne propagation paths within the tank wall [11] and the internal mechanical barriers [11,12].

Generally the locations of the PD likely to lead to failure, are in the areas where the PD signal should pass several barriers to reach the sensors, such as the areas within the windings and this would result in the erroneous readings of the acoustic emission sensors and would imply an incorrect PD coordinate. Also, as the acoustic waves collide with the tank wall and propagate through the steel of the tank, their propagation speed and mode of propagation change. Due to the higher propagation speed in steel, the

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structure-borne signals may reach the sensors earlier than the waves traveling the direct oil path [11]. This effect complicates the determination of the originating point of the PD signal.

In order to theoretically determine the real time difference between the PD origin and the AE sensor, the path of shortest time needs to be determined and the impact of various barriers inside the power transformer tanks on the arrival times of the sensors should be investigated.

In this paper a method has been proposed which simultaneously considers the impact of the structure borne waves on the tank wall and the barriers inside the transformer tanks on the arrival times of the sensors and the calculated position of PDs. This is implemented, firstly considering all the possible indirect paths and computing the indirect path propagation times. By comparing the times taken in each path of propagation, to reach the specified sensor location, the indirect path of shortest time for AE signal may be determined. Secondly, all the cylindrical objects inside the tank are formulized and the path lengths inside each object on the AE signal way to the sensor are calculated.

Utilizing a heuristic method, the PD origin is estimated with the least error. A test set up has been used to verify the proposed method via generating different PDs within a test chamber containing iron core, solid and liquid insulation and copper winding. Through comparison of output results of the proposed method with the TDOA method, the reduction of the positioning errors by this method is demonstrated.

2. Method of time difference of arrivals, TDOA

For a PD origin with Cartesian coordinates of (x, y, z), and at least four sensor coordinates of (x_i, y_i, z_i), the TDOA method, calculates the coordinates of the PD origin by solving the nonlinear equations of (1), [7].

$$
\begin{aligned}
r_2 - r_1 &= \sqrt{(x^2 - x_2^2) + (y^2 - y_2^2) + (z^2 - z_2^2)} \\
&\quad - \sqrt{(x^2 - x_1^2) + (y^2 - y_1^2) + (z^2 - z_1^2)} = C(t_2 - t_1) = C\tau_{12} \\
r_3 - r_1 &= \sqrt{(x^2 - x_3^2) + (y^2 - y_3^2) + (z^2 - z_3^2)} \\
&\quad - \sqrt{(x^2 - x_1^2) + (y^2 - y_1^2) + (z^2 - z_1^2)} = C(t_3 - t_1) = C\tau_{13} \\
r_4 - r_1 &= \sqrt{(x^2 - x_4^2) + (y^2 - y_4^2) + (z^2 - z_4^2)} \\
&\quad - \sqrt{(x^2 - x_1^2) + (y^2 - y_1^2) + (z^2 - z_1^2)} = C(t_4 - t_1) = C\tau_{14}
\end{aligned}
\tag{1}
$$

where r_i is the distance from the PD origin to the sensor i, τ_{1i}, being equal to $t_i - t_1$, are three time-differences of arrivals between the sensor i and the sensor 1 and the C is the speed of the sound in oil, assumed as 1431 m/s in temperature of 20 °C according to [11]. Corrections to the speed of sound for temperature and moisture content are not generally made to increase accuracy because the other uncertainties are usually much larger [11].

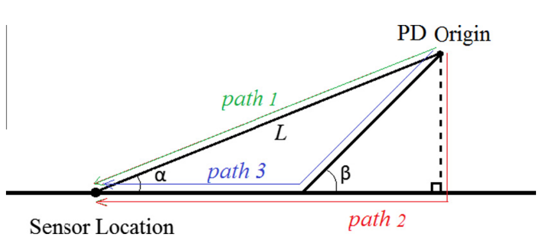

Fig. 1. Three possible paths for an acoustic wave from a PD origin to a sensor on the tank wall.

Numerically solving the equations in (1) results in the coordinates of the PD origin.

3. Proposed method to determine the path with minimum travel time of the acoustic wave to the sensor

Fig. 1 shows a PD origin at a distance to a steel wall on which an acoustic sensor is mounted. Three scenarios should be investigated to obtain the path yielding the minimum travel time of the acoustic wave to the sensor:

Case 1: the wave directly travels from the PD origin to the sensor position. The length of this path is taken as L and makes the angle of α with the tank wall. This path is shown as path 1 in Fig. 1.

Case 2: the wave travels along the perpendicular line to the wall and continues its path to the sensor on the wall. This path is shown as path 2 in Fig. 1.

Case 3: the wave travels along an intermittent path between the path 1 and the path 2. That means part of the path is in the oil, along a line making the angle of β with the tank wall, and, part of it is on the wall. This path is shown as path 3 in Fig. 1.

The arrival time for the case 1 would be as $T_1 = \frac{L}{C}$, where C is the sound speed in the oil.

Assuming the acoustic wave speed in the steel is m times the speed in the oil, the arrival time for the case 2 would be as (2).

$$T_2 = \frac{L}{C}\sin\alpha + \frac{L}{mC}\cos\alpha \tag{2}$$

The arrival time for the case 3 may be calculated as (3), utilizing trigonometric relations.

$$T_3 = \frac{L}{C}\frac{\sin\alpha}{\sin\beta} + \frac{L}{mC}(\cos\alpha - \sin\alpha\cot\beta) \tag{3}$$

After trigonometric simplifications, (4) would be obtained for the arrival time of the case 3.

$$T_3 = \frac{L}{C}\left(\frac{\sin\alpha + \frac{1}{m}\sin(\beta - \alpha)}{\sin\beta}\right) \tag{4}$$

The acoustic wave speed in the steel is 3.64 times the speed in the oil [11]. Fig. 2 shows the variation of T_3 with β for different values of α. it may be concluded from (2) and (4), that for $\beta = \alpha$, $T_3 = T_1$, and for $\beta = 90$, $T_3 = T_2$.

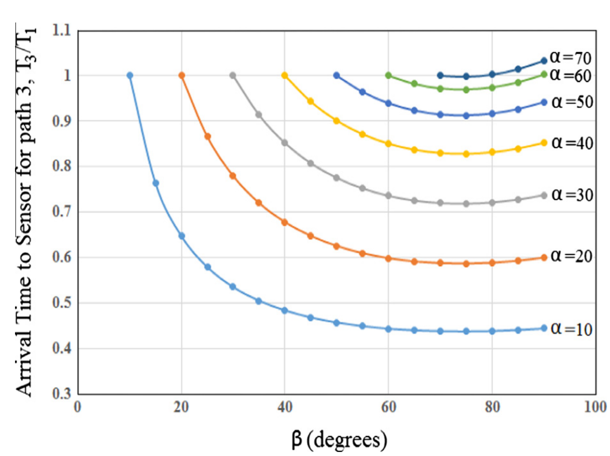

Fig. 2. The variation of the arrival time to sensor for path 3, T_3, with β for different values of α.

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