Determination of PD Source Location inside Power Transformer Based on Time Difference of Arrival

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Abstract:- The Partial Discharge (PD) leads to a cat astrophic failure of the transformer insulation. Determination of the PD source location is very necessary to start the maintenance procedures and isolate the reason for occurring PD. In this paper, PD location can be determined by measuring the acoustic signals that emit from the PD source. The proposed technique is based on the computation of the time difference of arrival (TDOA) between the signals. The location of PD can be accurately determined depends on the precision degree of the TDOA. An experimental work is built to develop a PD using point to plane gap configuration in the insulation oil that fills the Acrylic tank, in addition to four piezoelectric (PZT) sensors. These sensors are mounted on the Acrylic tank to receive the acoustic signals. Therefore, the sensors are coupling with acoustic PD detector and the PD detector outputs are applied to four-channel digital oscilloscope to measure the acoustic signals. The signal is converted to digit numbers to express the characteristic of the signal and then the time difference between the reference signal and the other signal is estimated using the cross correlation function. The proposed algorithm results demonstrate the ability of the algorithm to determine the PD location.

Keywords: Partial discharge location, Acoustic, Time difference of arrival.

1 Introduction

Partial discharge (PD) is an indicator of the status of the insulation of the power transformers. An incipient and frequent occurrence of PD results in degradation and aging of the transformer insulation. PD detection is carried out to provide information about the occurrence of PD and therefore, determine its location to assess the insulation performance [1]. Then online monitoring of the PD can reduce the risk of the undesirable outage of the power transformer to ensure the continuity of the system. PD in the transformer insulting oil causes oil decomposition to the oil byproducts which are used as dissolved gas ratios such as [acetylene, C_2H_2]/[Ethylene, C_2H_4], [Methane, CH_4]/[Hydrogen, H_2], and [Ethylene, C_2H_4]/[Ethan, C_2H_6] [2, 3]. The dissolved gas analysis [4-6] is used as a d iagnostic tool to give an evidence of occurring PD but it can't determine the location of it. In addition, PD can be utilized as an aging marker; hence, their measurement is considered a non-destructive way of characterizing electrical insulation conditions.

Electrical, optical, acoustic, opto-acoustic and ultra-high frequency are the common methods that are used to measure PD. PD generates the acoustic pressure pulse which spreads and propagates in the oil and hence to the tanks' wall. The acoustic signals that captured via the piezoelectric sensor convert to voltage signals. These signals are amplified to be measured and transferred to multi-channel oscilloscope and then stored for the analysis purpose [7]. The evidence of the PD occurrence in large power transformer is not sufficient unless an indication to PD location is associated. Recently, acoustic PD detection over electrical detection is due to, it is immune to electromagnetic interference (EMI), therefore, it can be applied for online detection. Moreover, it can provide an indication of PD source location within a co mplex system like transformer [7-9]. The main drawback of the acoustic method is its lower sensitivity when the PD source is internal to solid (paper) insulating system.

Kundu, et al. [7], presents a non-iterative PD source location algorithm with Four Acoustic Emission sensors. The proposed algorithm is applied to experimental data, in addition to published data to compare its results with that obtained by iterative methods. The disadvantage of the proposed algorithm comes from the errors related to the arrival time calculation. In order to reduce these errors different arrival time calculation are discussed and a proposed comprehensive method is presented.

Markalous et al. [10], used the acoustic and electromagnetic signal for detection and location of the PD that occurred in the insulating system of the power transformer due to external stresses such as short circuits, lightning strokes or transients of switching operations. They presented a new location approach works with pseudo-times; in addition, permit the use of robust direct solvers instead of earlier iterative algorithms.

A phase resolved PD patterns with high frequency pulse waveform analysis are emerged to determine the discharge sources. The acoustic techniques are also developed to locate the PD inside the power transformer. In this paper, an inductive loop sensor was used to specify two different PD sources. These PD sources were located using Acoustic measurements with an electrical reference [2].

Búa-Núñez et al. [11], presented a multichannel system to locate the PD in power transformer. This system was based on detection of the acoustic emissions from PD in oil using piezoelectric (PZT) and fiber optic sensors. The location of PDs was developed based on a time reference that given by one fiber optic sensor installed inside the tank and the times of arrival to several other PZT sensors that placed outside the tank. The proposed system is tested using experimental work and the PD location was evaluated. The errors that developed from the times of arrival and the influence of the sensors number and their sites were analyzed.

In [1], the errors developed by noises have a great impact of the PD location. In this work, a new PD location algorithm is presented based on the time difference of energy accumulation curve of multiple signals. The algorithm is applied on the transformer model in the laboratory and it is proved to be a more effective way to locate the PD source compared to the single signal method. The results reveal that the errors of time difference are in 0.1 ns range and for PD source positions are in centimeter range.

The paper presents a mathematical algorithm to locate the PD source based on computing the time difference of arrival (TDOA) among the signals that received by four piezoelectric sensors which are placed on the oil tanks' walls. The sensors capture the signals and send it to the acoustic PD detector and these signals are reading and storing via multi-channel oscilloscope. The PD signals are developed using point to plane gap configuration that immersed in the oil that fills an acrylic tank. The High voltage is applied to the point electrode until the PD is generated and before, the occurrence of the breakdown.

2 PD location based on acoustic signal

When the acoustic signal develops, hence the acoustic wave reaches the closest sensor and then captures by the other sensors. If the PD initiates at point P with (x, y, z) coordinates and if the four sensors are mounted on the tanks' wall at S1(x1, y1, z1), S2(x2, y2, z2), S3(x3, y3, z3), and S4(x4, y4, z4). The origin O (0, 0, 0) is assumed at center of the tank as in Fig. 2. Therefore, the PD location can be expressed as follows [7];

$$(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 = (vT)^2 \quad (1)$$

$$(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2 = \{v(T + \tau_{12})\}^2 \quad (2)$$

$$(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2 = \{v(T + \tau_{13})\}^2 \quad (3)$$

$$(x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2 = \{v(T + \tau_{14})\}^2 \quad (4)$$

Where, T is an acoustic wave propagation time from PD source to the closest sensor. The sensor number 1 is taken as a reference and then the time delay for the signal that captures by the other sensors is τ12, τ13, and τ14 respectively. ν is considered as the signal velocity in m/s. the coordinates (x, y, z) refer to the PD location point and (xi, yi, zi) refer to the location of sensor Si.

Each equation from 1 to 4 represents a sphere that the each sensor location is its center and each sphere passes with the PD source.

The subtracting of every two equations from 1 to 4 gives the equation of the intersecting plane equation between (1, 2), (1, 3), and (1, 4) which is expressed as follows;

$$2x(x_2 - x_1) + 2y(y_2 - y_1) + 2z(z_2 - z_1) + 2v^2\tau_{12}T = k_1 \quad (5)$$

Where, $k_1 = (x_2^2 - x_1^2) + (y_2^2 - y_1^2) + (z_2^2 - z_1^2) - v^2\tau_{12}^2$ (5a)

$$2x(x_3 - x_1) + 2y(y_3 - y_1) + 2z(z_3 - z_1) + 2v^2\tau_{13}T = k_2 \quad (6)$$

Where, $k_2 = (x_3^2 - x_1^2) + (y_3^2 - y_1^2) + (z_3^2 - z_1^2) - v^2\tau_{13}^2$ (6a)

$$2x(x_4 - x_1) + 2y(y_4 - y_1) + 2z(z_4 - z_1) + 2v^2\tau_{14}T = k_3 \quad (7)$$

Where, $k_3 = (x_4^2 - x_1^2) + (y_4^2 - y_1^2) + (z_4^2 - z_1^2) - v^2\tau_{14}^2$ (7a)

Equations 5 t o 7 c ontains the unknown variables (x, y, z and T), eliminating T from equations 5 t o 7 and solve the generating equations can help to determine x, y and z and then determine T. the computation of the coordinates of the PD location and the acoustic wave propagation time is mentioned in details in [7].

3 Experimental Setup and details

The experiments are carried out for non-homogenous field (point-plate electrode) to develop PD signal and capture it using four piezoelectric sensors (PZT) that mounted on outside the tank. The experimental setup consists of an Acrylic tank with dimension (25cm×25cm×35cm) filled with the insulating oil, high voltage Transformer type (PGK HB) is up to 100kV AC, measuring capacitance that is used as a capacitor divider, connecting wires, the acoustic PD detector and the four-channel digital oscilloscope (Tektronix, TDS 410A). Figure 1 illustrates experimental setup with the complete devices. Each sensor is mounted on one face of the oil tank and the sensor that mounted on t he face with the high voltage electrode is placed far away to avoid the breakdown on it. The type of the insulating oil is the insulating oil type is Diala B with the dielectric strength of > 30 kV (Un-treatment) and > 70 kV (after treatment) according to IEC 60296 and IEC 60156.

The signal that developed due to the PD is captured by the PZT sensors that are mounted outside the transformer on its walls to the acoustic PD detector via cables with the same length and then transmitted to the oscilloscope to acquire for analysis purpose. The sound velocity in oil varies between 1240 m/s to 1300 m/s [10, 12]. Figure 2 illustrates the schematic diagram of the tank with PZT sensors and the virtual PD point at P.

The partial discharge is developed using point to plane gap configuration. The piezoelectric sensor type is 150 Hz resonant peak type. They are fixed on the tank walls using magnetic and silica gel as an acoustic couplant that used between the sensor and the tank to get better acoustic contact. The sensors coordinates are illustrated in Table 1. The applied voltage is increased gradually by 2 kV till a noise is heard, after that the spark is appeared and the acoustic signals are appeared on the oscilloscope. Then, the WFM signals are recorded on a floppy disk. These WFM signal are converted to ASCII data via ConverterWFM software code from Tektronix Company. These signals are drawn as in Fig. 3.

Table 1: Coordinates of the acoustic sensors

	x (m)	y (m)	z (m)
Sensor 1	0.125	0	-0.10
Sensor 2	0	-0.125	0
Sensor 3	-0.125	0	-0.10
Sensor 4	0	0.125	0

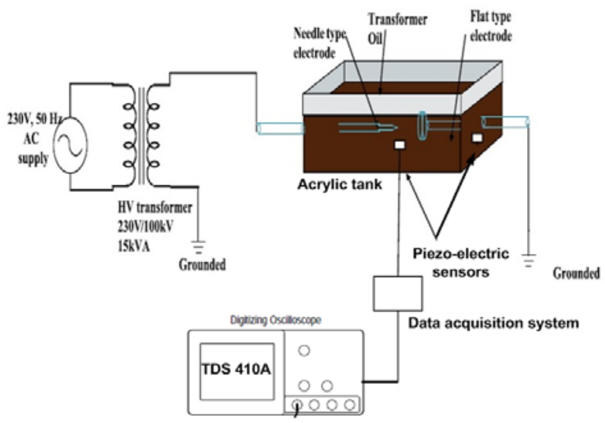

Fig. 1. Experimental setup

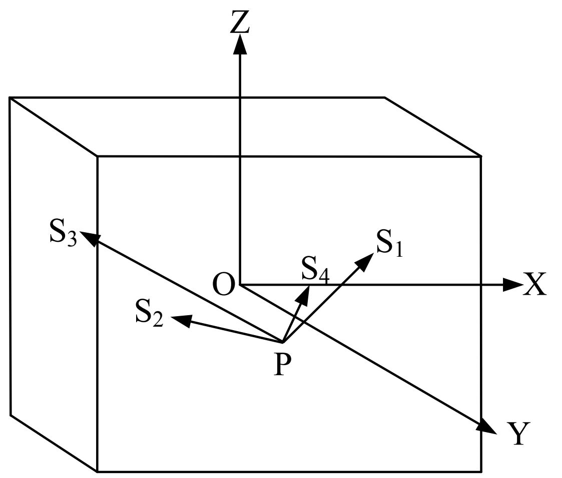

Fig. 2. Schematic diagram of the tank with the PZT sensors and PD at point P

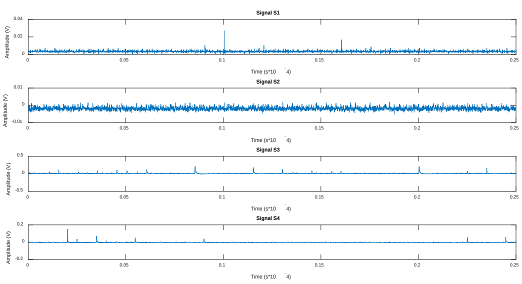

Fig. 3. The recorded acoustic signals which explained the PD event

4 Time difference between the recorded signals

The Matlab Code is built to find the PD location which based on equations of section 2. Reading the recorded data from ASCII file is the first step. The second step is determining the time difference between the recorded signals. The signal captured by sensor 1 i s taken as a reference signal and the time difference is computing between the sensor 1 signal and the signals captured by the three other sensors (t12, t13, and t14). The time difference between the reference signal and the other signal is determined using the cross correlation function. This function measures the dependency of first signal values on another signal values. For two Wide Sense Stationary (WSS) processes the functions x(t) and y(t), it is described by [13]:

$$R_{xy}(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_{-T}^{T} x(t)y(t+\tau)dt \tag{8}$$

or

$$R_{xy}(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_{-T}^{T} y(t)x(t+\tau)dt \tag{9}$$

Where, T is the observation Time.

The sampled signal is defined as;

$$R_{xy}(m) = \frac{1}{N}\sum_{n=1}^{N-m+1} y(n)x(n+m-1) \tag{10}$$

Where, m=1, 2, 3, … …, N+1 and N is the recorded length (i.e. the number of samples). The cross correlation function has some properties that are addressed as follows [13];

- It is real value function which may be positive or negative,
- It may not necessarily have a maximum at m=0 nor an even function,
- $|R_{xy}(m)|^2 \le R_{xx}(0)R_{yy}(0)$,
- $|R_{xy}(m)| \le \frac{1}{2}[R_{xx}(0)+R_{yy}(0)]$,
- If Rxy(m)=0, x(n) and y(n) are said to be "uncorrelated" or be statistically independent (assuming they have zero mean),
- $R_{xy}(-m) = R_{xy}(m)$.

The Matlab command [r,lags] is used to return a vector with the lags which the cross correlation is computed. Figure 4 illustrates the flowchart diagram that demonstrates the program procedures.

The great issue for the PD location comes from the noise and initial oscillation, hence, it is difficult to determine the arrival time precisely. In order to avoid the errors in the arrival time estimation, cumulative energy is used. The calculation of the cumulative energy is formulated as (11) [7];

$$E = \sum_{i=1}^{n} x^2(i) \tag{11}$$

where, n refers to the number of samples, x(i) expresses the amplitude of each sample i belong to the acoustic signal. To compute the total energy the number of total samples n is equal to N which is the total number of data points in the signals. Based on the cumulative energy, the arrival time can be computed as the time corresponds 0.02 of the maximum cumulative energy

5 Results and Discussions

In order to construct the Experimental setup, some problems are encountered such as the old version of the four-channel oscilloscope (Tektronix, TDS 410A) since the data are collected via floppy disks which are not used today. There is no shielded room to avoid interfacing between the recorded signals and the noise from the external sources like mobiles and other devices. In addition, the protection of the sensor from the overvoltage during the application of high voltage to develop the PD in the oil tank is very difficult. Finally, the captured signals are shown as in Fig. 3.

Fig. 4 shows the PD location that assigned via the software code. The PD coordinates that result from the software code are (-0.0912, -0.047, -0.0046) in m. The location of the point to plane gap which is centered in the oil tank is determined as the coordinates of y and z are zeros and the position of the high voltage electrode and the plate electrode (5 cm in radius) are varied with x coordinate only). The plate electrode is far with 0.03 m from the tank wall which sensor S3 is located; hence the plate electrode is at 0.095 m from the origin of the coordinates. Therefore, the error for determining the PD location according to x coordinate is 4.2% (((0.095-0.091)/0.095)*100) which is acceptable. The y coordinate (-0.047) of PD point means the PD occurrence is at the plate electrode (its radius is 0.05 m). The PD location is shown as in Fig. 5. Figure 5 shows the PD location from running the software code, in addition to the location of the sensors on each tank faces.

Another case of actual transformer that has a PD is studied. The coordinates of the sensors on the transformer sides are in Table 2 and the measured signal is shown in Fig. 6. The PD location based on the measured acoustic signals is shown in Fig. 7. The coordinates of the PD location are (0.32, 0.11, and -0.028m) for x, y and z coordinates respectively.

Figure 8 illustrates the cumulative energy that is used to estimate the arrival time for the sensors location as in Table 2 and the PD location is at (0.32, 0.11, and -0.028m) for x, y and z coordinates respectively. The arrival time is the time corresponds 0.02 of the maximum cumulative time. The maximum cumulative energy is calculated as 0.008104, therefore, 1.6209E-04 corresponds the 0.02 of the cumulative energy and hence, the arrival time can be estimated as 106 microsecond.

6 Conclusions

PD detection inside the power transformer is very important but determining the PD location is more important to be able to eliminate the source of PD in order to avoid the undesirable outage of the transformer from the power network. The constructed software code is based on the cross correlation function to compute the time difference between the signal that captured by sensor (S1) and the other signals that captured by the other sensors. The software code that is used to locate the PD point gave 4.2 % error with the x coordinate since the point to plane gap is positioned at zero for y and z coordinates.

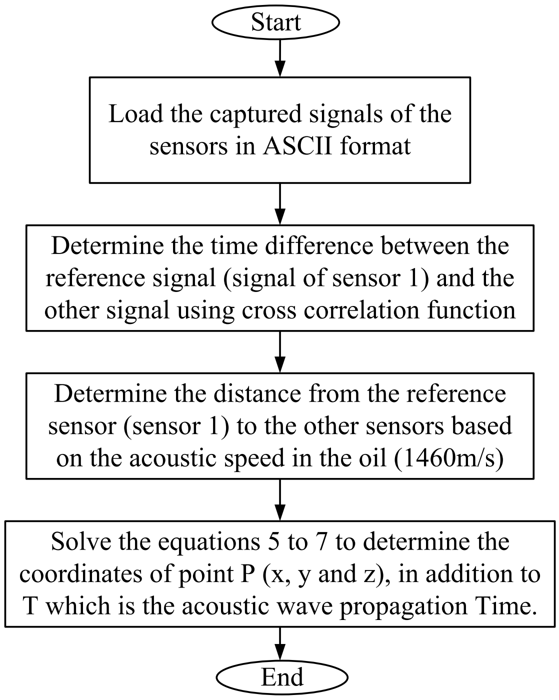

Fig. 4. The flowchart of the steps t xo determine the PD location

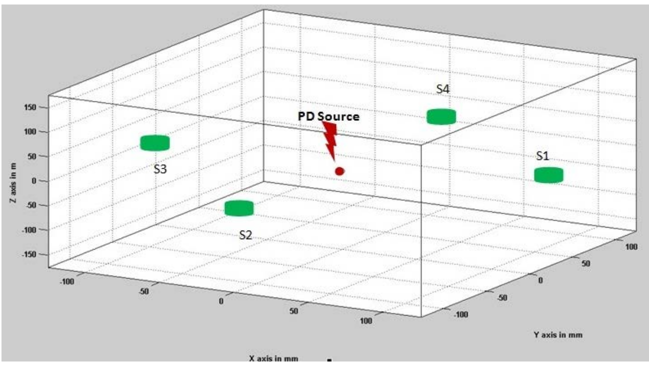

Fig. 5. The PD location inside the oil tank

Table 2: Coordinates of the acoustic sensors that placed on actual transformer sides

	x (m)	y (m)	z (m)
Sensor 1	1	0.06	0.2
Sensor 2	0.4	-0.4	0.25
Sensor 3	-1	0	0.1
Sensor 4	-0.3	0.4	0.3

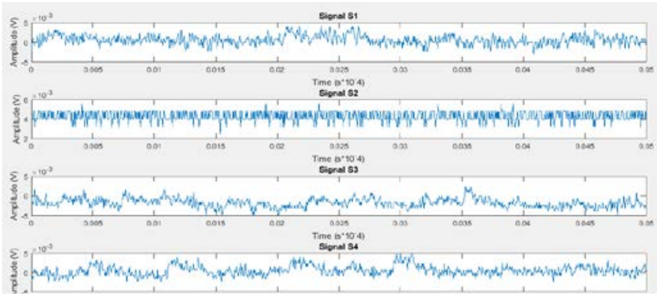

Fig. 6. The recorded acoustic signals for the actual transformer case

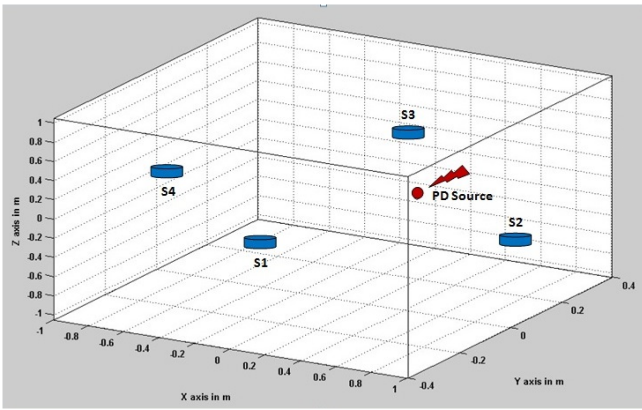

Fig. 7. The PD location inside the actual transformer tank

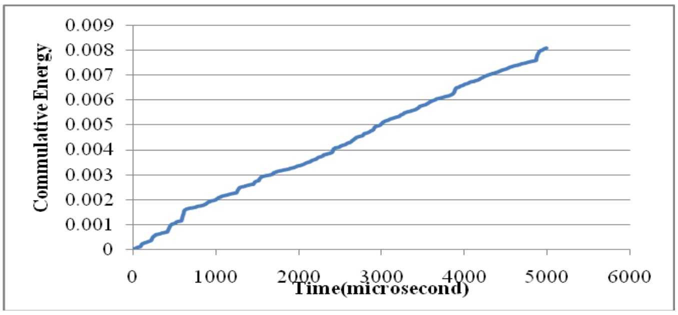

Fig. 8. The cumulative energy of the acoustic signal for the point-plane gap

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