Acoustic and Electrical Detection to Localize And Measure the Partial Discharge in High Voltage Apparatus

Sobhy S. Dessouky
Electrical Engineering Department,
Faculty of Engineering
Port Said University
Port said, Egypt
Sobhy.serry@yahoo.com

Sherif S.M. Ghoneim
Electrical Department,
Faculty of Industrial Education
Suez University
Suez, Egypt
Sherif.ghoneam@suezuniv.edu.eg

Adel A. Elfaraskoury
Laboratories & Researches and Tests,
Egyptian Electricity Holding Company
Cairo, Egypt
Dr.adel_elfaraskoury@yahoo.com

Ramy. N. R. Ghaly
Mataria Technical College in Cairo
Ministry of Higher Education
Cairo, Egypt
ramyelectric@yahoo.com

***Abstract*—The occurrence of the Partial Discharge (PD) inside the high voltage apparatus especially in power transformer due to some defect in its insulation system results in a catastrophic failure. Determination the magnitude and location of the PD inside the transformer is very valuable to avoid the undesired outage. In this paper, two important issues will discuss. The first issue, measuring the magnitude of the PD by the electrical detection device (The partial discharge analysis system MPD 600) that has many kits to the acquisition and analysis for detecting, recording and analyzing the PD. PD Measuring the circuit of MPD600 connected to point to plane according to IEC60270 with an optical interface by computer that have Metronix software in case of partial prediction. The second issue is determining the PD location to start the maintenance process. In order to locate the PD inside the transformer the acoustic signals that emit from the PD source were measured and therefore, the Time difference of arrival (TDOA) between these signals is estimated. A point to plan gap configuration that is mounted in the acrylic tank that contains the insulating oil is used to develop the PD point source. In addition four piezoelectric sensors are fitted on the tank walls to receive the acoustic signals. The sensors are coupled with acoustic PD detector which outputs are applied to four-channel digital oscilloscope to measure the acoustic signals. The proposed algorithm results demonstrate the ability of the algorithm to determine the PD location.**

***Index Terms*—Partial discharge location, Acoustic, Time difference of arrival - PD electrical detection- partial discharge measuring system.**

I. INTRODUCTION

The degradation and aging of the insulation of the power transformer are the result of the generation of the frequent PD which acts as an indicator for the condition of the transformer insulation system. The insulation performance can be assessed by measuring and locating the PD [1]. Dissolved gas analysis (DGA) is one of the most important tools to detect the PD inside the transformer by measuring the decomposition of the dissolved gases that generated due to the electrical, thermal and mechanical stress that subjected on the insulating oil [2-4].

The PD measurement tool is very necessary to control of high voltage (HV) equipment. PD results in the loss in the insulation capacity of HV equipment. Therefore the electrical measurement of insulation ageing is very important [5].

Several methods were utilized to detect and measure the PD such as electrical, optical, acoustic, opto-acoustic, and ultra-high frequency.

PD measurements are often performed under noisy conditions. The PD signal is superposed by stochastic noise pulses or even multiple PD sources, which will lead to a complex phase resolved PD pattern that is not easy to analyze. The PD source separation must be the first step to de-noise PD data. In the future this will become even more important with the rising numbers of automated PD monitoring systems installed at critical network points [6].

Cristian Dan et. al., [5], presented a series of partial discharge measurements, reflecting the state of insulation of 110kV instrument transformers located in Sibiu county substations. The state of insulation of 110kV instrument transformers can be accurately assessed by PD measurements using MPD600. The system allows measurements of partial discharge on site, even in presence of strong electromagnetic interferences because it provides synchronous acquisition from all measurement points.

K. Rethmeier et al. [6], described the principle of synchronous multi-channel PD measurements and its benefits for PD data evaluation with four case studies (dry-type transformer, power transformer, GIS, generator). PD measurements are performed to evaluate the insulation condition of all types of HV apparatus. These measurements are possible under offline and online conditions, respectively.

Moreover, PD causes acoustic pressure pulse which propagates and spreads in the insulating oil reaching to the tanks' wall. The piezoelectric sensors captured the acoustic

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signals and convert them to voltage signals. These signals are amplified to be measured and transferred to multi-channel oscilloscope and then stored for the analysis purpose [7]. Measuring the magnitude of the PD signals inside the power transformer is not sufficient for maintenance purpose unless the location of PD is not identified.

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 complex 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], presented 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.

Dorin Popa [10], presented a PD source localization method that combines the results of the PD electrical measurement with the ones of the PD acoustic measurement. It is considered that a good approximation of the PD source was obtained when the positioning of the electrically measured impulse is the same or almost the same with the one calculated from the acoustic measurement.

Markalous et al. [11], 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 [12].

Búa-Núñez et al. [13], 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 the measurements of the PD using electrical detection method using PD digital measuring system MPD 600 from OMICRON. In addition, 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.

II. ELECTRICAL DETECTION OF THE PD

The classical measuring circuit for PD measurement according to the IEC Standard 60270 considers the PD circuit, the measuring instruments, the calibration and the measuring procedures as shown in (Fig. 1) [14].

Partial discharge measurements, requires a coupling capacitor for the connection of the PD measurement instrument and works at a measuring frequency of several hundred kHz up to one MHz.

The partial discharge analysis system MPD 600 offers high-resolution digital processing technology, which provides outstanding measurement accuracy.

MPD 600 is a modular, data acquisition and analysis system consisting of a PC-operated control unit.

The MPD 600 as a modern type of a fully digital PD measuring system is capable of performing synchronous multi-channel PD measurements as shown in (Fig.2) [5].

In order to perform the measurement by means of the electrical method it was used the PD digital measuring system MPD 600 from OMICRON. This is suitable for test facility measurements as well as for on-site measurements under strong electromagnetic interference conditions and thus provides an important contribution to maintaining the quality and value of expensive transformers [10].

The electrical measurements in power transformer to detect the partial discharge according to IEC 60270 by using MPD600, An experiment was conducted on a model transformer tank of 25 cm × 25 cm × 35 cm in size filled with transformer oil. A schematic diagram of the experimental model for non- homogeneous electric field (point to plane gap configuration) is shown in Fig. 3.

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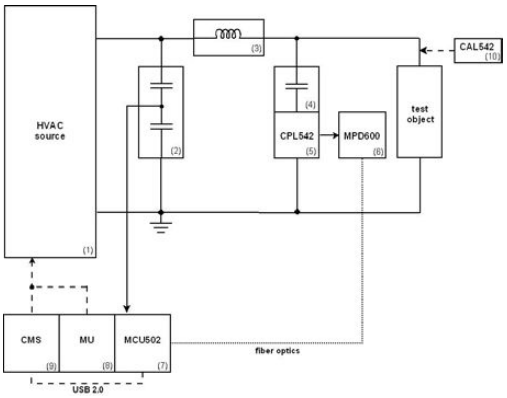


Fig 1. PD measuring circuit according to IEC 60270

(1) HV source
(2) Voltage divider
(3) Blocking impedance
(4) PD coupling capacitor
(5) Measuring impedance
(6) Acquisition unit
(7) Control unit
(8) Peak voltmeter
(9) Computer control
(10) Calibrator

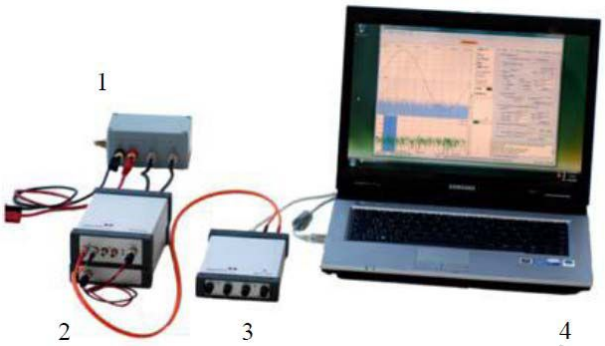


Fig 2. Components of a MPD system: measuring impedance (1), PD acquisition unit (2), optic-USB converter (3), notebook (4).

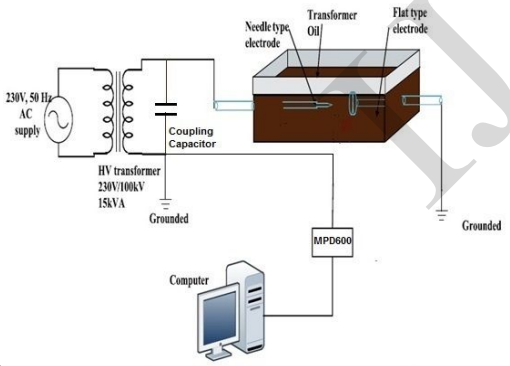


Fig 3. Experimental setup of electrical detection according to IEC60270

III. Electrical Detection Results

Case Study 1: The PD generated by applying HV across the point to plane gap configuration. As result non- homogeneous electric field is obtained. Therefore, the pre-arcing will located in tank oil and can be considered as a PD event. All PD events are taken at different distances across the point to plane gap configuration by increasing the HV applied between them.

The Pre- Arc voltage is less than the breakdown (BD) voltage. The relation between the pre-arc voltage (kV) and the PD value (pC) at distance 1 cm gap is indicated in Fig. 4. The results that are shown in Table 1 illustrated that an increase in the gap distance will lead to an increase in both pre-arc voltage and PD value.

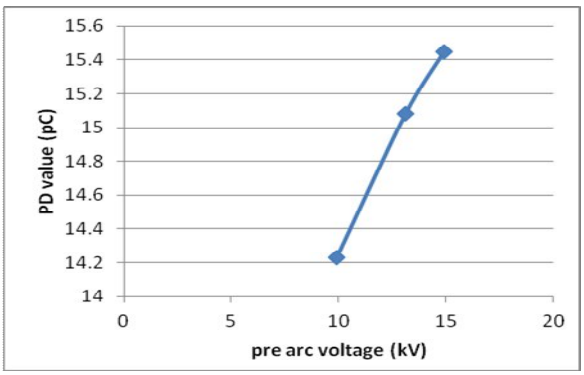


Fig 4. Relation between PD value and pre-arc voltage (kV) at distance 1cm gap

Table I: Effect of gap distance on the pre-arc voltage and PD value.

No	Distance (cm)	B.D voltage (KV)	Pre- Arc voltage (KV)	PD Value (PC)
1	1	19	9.9	14.23
2			13.1	15.08
3			14.9	15.45
4	2	36.8	20.3	968.5
5			25.3	1085
6			29.1	1189
7	3	48	32.9	1792
8			36.1	2230
9			39.8	2429
10	4	52.2	42.8	2431
11			45	2637
12			48.7	2718
13	5	64.5	53.4	2844
14			55.6	2953
15			59.2	3077
16	6	70	62.3	3300
17			64.7	3767
18			66.1	4213

Case Study 2: That is a real case of electrical measurement at faulted power transformer that located at the Egyptian power network. From the 3-Phase-Amplitude-Relation-Diagram (3PARD) that obtained from electrical measurements (outside PD measurements) according IEC 60270, the PD quantities as the following Table 2:

Table II: PD quantities of Egyptian faulted power transformer.

PHASE 1	80.45 Pc
PHASE 2	55.85 Pc
PHASE 3	73.04 Pc

In the 3 PARD, the orange color represented the PD event, while blue color is pre-arc noise, but any another color is the noise from other frequencies. As shown in Fig. 5 the PD concentrated at the phase 1 of transformer.

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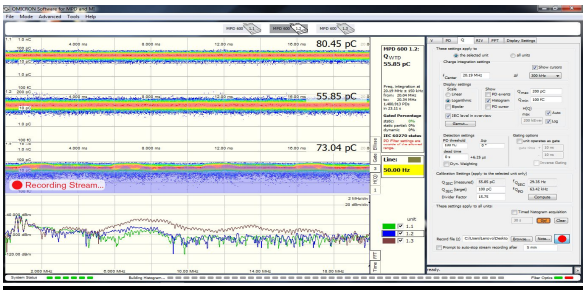


Fig 5. 3 PRPD pattern obtained, electrical PD measurement according to IEC 60270, for Egyptian faulted transformer 220/66 KV

IV. 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. 7. 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,

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

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

Where,

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

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

Where,

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

Equations 5 to 7 contains the unknown variables (x, y, z and T), eliminating T from equations 5 to 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].

V. EXPERIMENTAL SETUP FOR PD LOCATION

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 6 illustrates experimental setup with the complete devices. Each sensor is mounted on one face of the oil tank and the sensor that mounted on the 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 [11, 15]. Figure 7 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 3. 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 Converter WFM software code from Tektronix Company. These signals are drawn as in Fig. 8.

Table III: Coordinates Of The Acoustic Sensors

	x (mm)	y (mm)	z (mm)
Sensor 1	*125*	*0*	*-10*
Sensor 2	*0*	*-125*	*0*
Sensor 3	*-125*	*0*	*-10*
Sensor 4	*0*	*125*	*0*

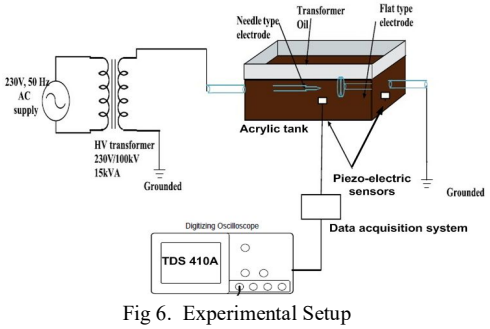


Fig 6. Experimental Setup

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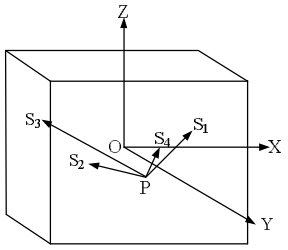


Fig 7. Schematic diagram of the tank with the PZT sensors and PD at point P

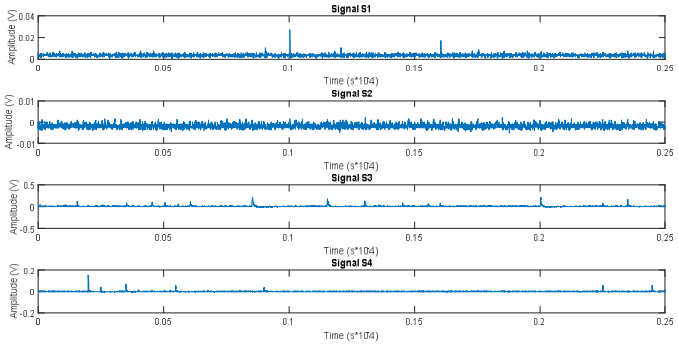


Fig 8. The Recorded Acoustic Signals Which Explained The PD Event

VI. PREPARE YOUR PAPER BEFORE STYLING

The Matlab Code is built to find the PD location which based on equations of section IV. 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 is 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 (τ12, τ13, and τ14). 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 [16]:

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

Or

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

Where, T is the observation Time.
The sampled signal is defined as;

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

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][16];

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,

$$|R_{xy}(m)|^2 \leq R_{xx}(0)R_{yy}(0),$$

$$|R_{xy}(m)| \leq \frac{1}{2}[R_{xx}(0)+R_{yy}(0)],$$

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 9 illustrates the flowchart diagram that demonstrates the program procedures.

VII. 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. 8.

Fig. 10 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. 10. Figure 10 shows the PD location from running the software code, in addition to the location of the sensors on each tank faces.

VIII. CONCLUSIONS

PD detection inside the power transformer is very important but determining the PD location is more important to be able to repair the source of PD in order to avoid the undesirable outage of the transformer from the power network.

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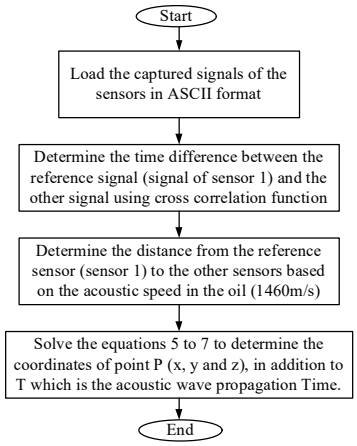


Fig 9. The Flowchart Of The Steps To Determine The PD Location

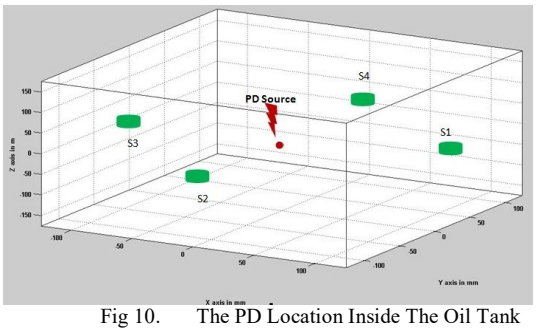


Fig 10. The PD Location Inside The Oil Tank

MPD600 is efficient and more reliable instrument for outside PD measuring. The experimental results exceeded the normal values that taken from any faulted power transformer due to PD simulation that obtained from the pre-arc in the tank oil that generated by increasing the HV applied between point to plane gap configuration in the experimental setup circuit. In the experimental setup circuit, the PD value is proportional with distance and pre-arc voltage.

The constructed software code is based on the cross correlation function to compute the time difference between the signal that captured by 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.

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