Effect of Hydrostatic Pressure on the Propagation of Partial Discharge Acoustic Signals in Transformer Oil

Syed Aqeel Ashraf[1], Brian G. Stewart[2], Parmal Singh Solanki[3], Khaliquzzaman Khan[4], Ch. Venkateswara Rao[1], Syed Moeen Ashraf[5]

Abstract – *In this research article an attempt is made to investigate the effect of hydrostatic pressure on the propagation behavior of Partial Discharge (PD) acoustic emission (AE) signals in a simple experimental tank. A mathematical model has been developed in the form of partial differential equations (PDEs) for PD acoustic wave propagation in transformer oil in a steel tank. A Finite Element Analysis tool (FEMLAB), has been used to simulate the propagation of the acoustic waves. The simulation results show that the speed of the acoustic signal varies with the depth of the source location demonstrating hydrostatic pressure affects AE wave propagation. Furthermore, the effect of hydrostatic pressure was investigated and conformed experimentally. It is concluded that the propagation speed is not constant within the tank and increases with tank depth. If the effect of increased acoustic velocities due to hydrostatic pressure is ignored then the possibility of practical PD location algorithms inferring the incorrect location in high voltage assets, such as oil filled transformers, will be increased significantly.*

Keywords*: Acoustic signals, High voltage equipment, Partial discharge and Wave propagation*

List of Acronyms: AE–Acoustic Emission, C–acoustic wave velocity, 3D–Three Dimensions, EMI–Electromagnetic Interference, f(t) –PD source function, FDTD–Finite Difference Time Domain method, FEM–Finite Element Method, FEMLAB–Finite Element Analysis tool, g–acceleration due to gravity, h–depth of the fluid, HV–High Voltage, HVAC– High Voltage Alternating Current, IEC–International Electro-technical Commission, P–pressure wave field, PDE–Partial Differential Equation, PD–Partial Discharge, R–Regression factor, S–propagation speed, TDOA–Time Difference of Arrival, UHF– Ultra-High Frequency, δ–Dirac Delta function, ρ_0–density of the fluid/solid, ω–angular frequency, β–attenuation factor, ρ–density of fluid and 'Δd'–path difference, V–speed of the PD AE wave.

I. Introduction

The High Voltage (HV) power apparatuses are the critical elements of the electrical power system, which requires continuous monitoring to prevent sudden catastrophic failures and also to maintain reliable power to the end users [1]. The most common failures in the HV equipment are due to Partial Discharge (PD) in electrical insulations which are the results of the insulation degradation over time [2]. The PD is like a cancer in power equipment.

The PD is defined by the IEC 60270 standard as an electrical discharge that only partially bridges the insulation between conductors and that may or may not occur adjacent to a conductor [3]. This usually occurs when insulation of electrical equipment is defective [4]. It is an indicator of abnormal insulation conditions and a further cause of insulation degradation, within power transformers, cables, switchgear, and windings in large motors and generators [5] & [6]. Thus PD measurement is a useful tool for quality assessment of electrical insulation during design, manufacture and in the prediction of the life span of HV equipment [8]. Therefore, early detection of PD activity is very important for condition monitoring engineers to avoid any expensive and unexpected failure in a power system. Hence, condition assessment of these power utilities at regular intervals is essential in order to ensure an uninterrupted power supply [9-11]. The detection of PD is an important process to evaluate the insulation status of power equipment [12]. When the location of its source is precisely determined, it can help to better identify the discharge type and the severity of the PD defect. Moreover, locating the PD source can assist in finding and repairing the discharge defect of HV power accessories [13] & [14].

The PD measurements have gained international acceptance by condition monitoring engineers, researchers and manufacturers of HV power system equipment and is used as a test method for non-destructive evaluation of the electric insulation properties [12]. Depending on the intensity, PD is often accompanied by emission of light, heat, electromagnetic radiation and Acoustic Emission (AE) signals [1]. There are varieties of technique available to detect and evaluate PD activity. The most common are electrical, electromagnetic, chemical, optical and acoustic techniques [14]. In recent years, the PD AE method has gained popularity. The reason behind is that acoustic emission techniques are non-invasive, immune to electromagnetic noise, relatively cheap and it is a convenient on-line diagnostic method for attempting to locate the discharge site [16] & [17].

The PD occurrence inside the insulation system can be explicated as a small explosion that excites the emission of acoustic pressure waves, which are propagated through the insulation material. The measurement of these mechanical waves by acoustic sensors that are sensitive to pressure changes can detect PD [18]. The AE sensor is not affected by external electrical interference and can be easily installed on the walls of HV equipment. Therefore, the AE method has been widely applied in PD localization [18] & [20].

Suitable AE sensors are mounted on the tank surface to pick up the signal. PD source location is based on time of flight measurement. First technique for PD source location is with simultaneous electrical and acoustic measurement. From the time difference between the two signals and velocity of acoustic signal, source distance from the sensor is calculated. For location, multiple sensor measurement with triangulation is applied. When electrical PD measurement is not feasible, an alternative method is applied with multiple acoustic sensors. From the time difference between the different sensor output and velocity of the signal, source location is calculated. In both methods of source location, it is assumed that the average speed of acoustic wave is constant [15] & [16].

In the earlier studies, researchers have located PD sources by continuously moving multiple sensors [1] & [4]. However, the time difference of arrival (TDOA) method is generally used nowadays. In the TDOA method, the differences in the arrival times of various AE sensors are calculated and the equations can be solved to obtain the PD coordinates [5] & [12].

Presently there is little published work related to modeling and simulation of the propagation modes of acoustic waves from PD activity [5] & [15]. Most of the research work on acoustic PD detection and its practical applications can be found in [16], [19] and [23]. There experiments were conducted to study characteristics of the PD acoustic signals as a function of position, propagation path, energy content, and signal attenuation [9] & [12].

In the current literature, detailed analysis and evaluation of propagated acoustic PD signals in HV equipment seems to be lacking [20]. Many experiments have demonstrated the viability of utilizing AE signals as warning indicators before any catastrophic failure occurs as a consequence of PD activity. Unfortunately the recent literature fails to address fully the modeling and the propagation behavior of these AE signals. The authors of [1] made an attempt to discuss some basic concepts of the acoustic wave-front and its practical applications. The theoretical model has discussed by [2] for ultrasonic wave propagation and methods of measuring the propagation time while [5] presented a basic three dimensional numerical simulation for PD acoustic waves. The researchers [9] have analyzed the behavior of the PD acoustic wave from the theoretical point of view using simplified 1-dimensional model. The results indicate that this method could extract the PD spike from the noisy measurement effectively. A simulation study of acoustic PD signal in a model Transformer using Finite Difference Time Domain (FDTD) method has described in [15]. The interpretation of PD results, development of remedial actions and numerical simulation models which would provide a better understanding of the emission and propagation processes of PD signals within typical HV plant insulations are subject yet to be developed.

Some scholars have utilized oil-filled tanks without transformer windings and cores in laboratory tests [12] and they assumed that the AE waves propagate directly from PD sources to AE sensors. Actually, since these sensors are mounted externally on the tank wall, the AE wave may travel via an indirect path and become the first to arrive at sensors. This process is complicated due to mixed wave-types and the existence of different wave speeds. These aspects also lead to inaccuracy in PD detection [14].

The technical literature [2-4] and [16-18] normally assume the speed of PD AE signals in oiled filled equipment to be constant but it is not correct. Specifically, this paper investigates the simulation and experimental study of PD AE wave propagation’s behaviour. The study is to visualize the influence of hydrostatic pressure and quantify the change of the hydrostatic pressure at deeper locations within the oil tank to understand better how it may be applied to practical oil filled transformers which are complex in nature. The experiments were conducted to determine the percentage change of the propagation speed at different heights within a model tank to demonstrate the physical changes in the PD AE waves which may be expected in real-life scenarios. A comparison between simulation and practical measurements is made to explore that the speed of propagation is not constant. It changes with depth in oil filled tank and will therefore influence any time of flight measurements made on oil filled power transformers when AE sensors are positioned at different locations. If the change in acoustic velocities due to hydrostatic pressure is ignored then the possibility of PD location algorithms based on TDOA of signals at AE sensors determining an incorrect PD location will be increased significantly [10].

The paper is organized as follows. Section I introduces the importance of PD, detection methods and the significance of acoustic PD detection. The authors have also documented the literature review on acoustic methods for PD detection. Section II highlights the significance of Partial Differential Equations (PDE) to model the AE signal. The PDEs describing the AE wave in an oil tank have been reported assuming the PD as a point source. Section III provides the proposed simulation method based on the propagation geometry. Section IV presents the simulation results. The changes in propagation speed of AE signals and the influence of hydrostatic pressure on propagation of acoustic waves have been explored. Whereas Section V illustrates the experimental investigation undertaken in order to validate the simulation studies discussed in section IV. Finally, section VI concludes the paper.

II. Formulation of the Problem

In transformer oil, PD emits light, heat, electromagnetic radiation and AE pressure signals as it excites the surrounding fluid medium. These signals can be considered as an impulse having a steep mechanical pressure wave front. In reality, the pressure waves may be more complex, but for an initial evaluation, the simplest form of an impulsive event generating signal emission is considered. These signals travel towards sensors through various propagation materials such as oil and metal. The PD propagation phenomena can be described mathematically by a set of coupled partial differential equations (PDE). A solution to these equations yields observable characteristics of the discharge. The standard PDE that governs the propagation of an acoustic wave within 3-D homogenous media is given by [1].

$$\frac{\partial^2 P}{\partial t^2} - C^2\left[\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} + \frac{\partial^2 P}{\partial z^2}\right] = \delta(x - x_0)\delta(y - y_0)\delta(z - z_0) f(t) \quad (1)$$

In equation (1), P is the pressure wave field (Pascal), t is the time (s) and C is the acoustic wave velocity (m/s). δ is the Dirac Delta function associated with the position of the PD source located at (x_0, y_0, z_0) in 3-D space and f(t) is the source function used in the numerical simulation of acoustic propagation. Equation (1) is a combination of three basic equations, which describe continuity, conservation of momentum, and elasticity of the medium [6] and [21] & [22]. The function f(t), which represents the PD source, is often expressed as follows [4]:

$$f(t) = -\rho_0 \beta t e^{-\beta * t} \sin(\omega t) \quad (2)$$

Where, ρ_0 is the density of the fluid/solid, ω is the angular frequency and β is the attenuation factor which determines how fast the peak amplitude of the signal decays. Equation (1) is simulated using Finite Element Methods (FEM) [6] & [15].

III. Materials and Methods

The proposed simulation is based on the propagation geometry presented in Fig. 1 which simulates a PD AE wave from a point source. The main objective is to demonstrate the 3-D propagation characteristics of the acoustic wave at different temperatures within the oil and the interface of the two media. In Fig. 1 the oil filled steel tank is designed to have a size of 30cm × 30cm × 30cm with steel wall thickness of 0.2cm.

The transformer oil is assumed to be filled up to a height of 23cm from the bottom of the model tank. A point-to-plane electrode is placed in the tank as shown in Fig 1. One of the electrodes is presumed to be a needle 16 mm long with and a sharp tip length of 40µm.

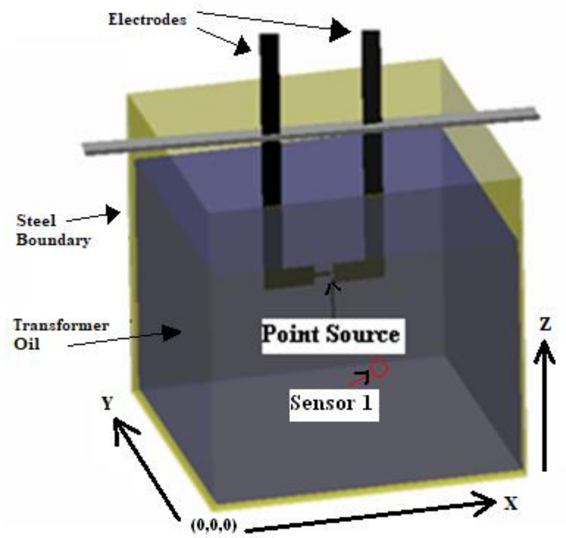

Fig. 1. Investigative 3-D oil filled steel tank

The oil within the steel tank is modelled as Class-I type transformer mineral oil according to the IEC60296 Standard [3]. The temperature is presumed to be 20^0C with corresponding oil and steel densities are 998 kgm^{-3} and 7900 kgm^{-3}, respectively. In the simulation study the propagation speed of the AE wave in oil is 1478 m/s and 5950 m/s in steel e.g. [1], [4] and [16]. It is also assumed that the pressure formula for the “explosion” of the PD moves with a spherical wave front at any time t expressed through equation (2) [4].

IV. Simulation Results and Discussions

The simulation results are presented in Figs. 2 to 7.Fig. 2 depicts a front side tank view of the simulated PD AE wave at 6 cm depth from the oil level (17 cm from bottom) of the tank. The PD source is located at coordinates x = 15cm, y = 15cm and z = 17 cm within the tank. The corresponding plot for acoustic pressure of the PD signal versus time is presented in Fig 3.

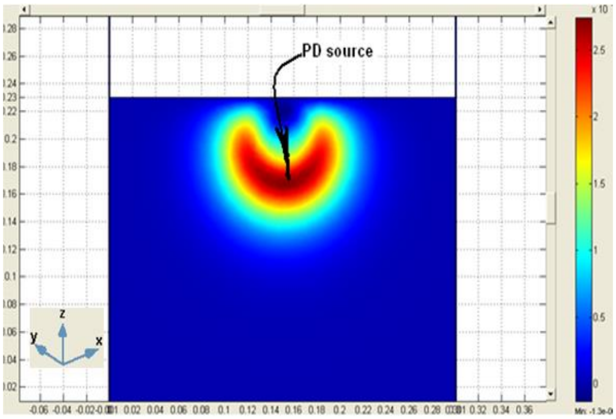

Fig. 2. Simulated PD AE wave at 6cm deep from top of the tank at (x=15cm,y=15cm, Z=17cm)

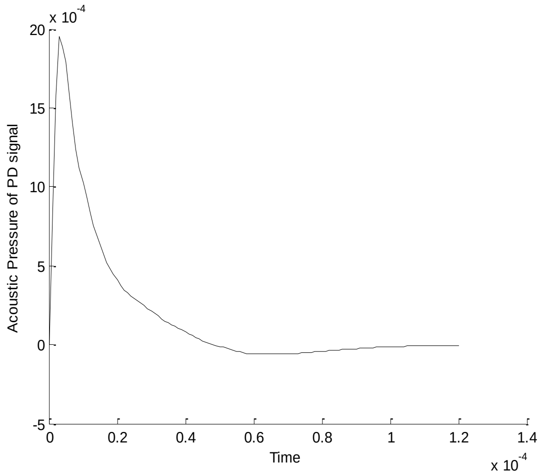

Fig. 3. Acoustic pressure of PD signal (arbitrary) versus time (μs)

Fig. 4 shows a front sides view of simulated PD AE wave at 11 cm depth from top of the tank. The PD source is at the position (15cm, 15cm, and 12cm) within the tank. The corresponding plot for acoustic pressure of PD signal versus time is presented in Fig. 5

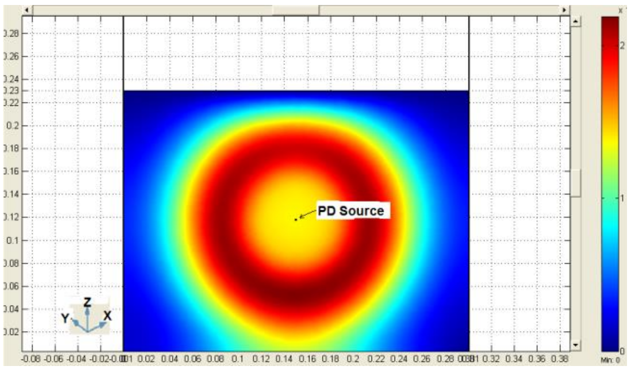

Fig. 4. Simulated PD AE wave at 11 cm deep from top of the tank at (x = 15cm, y = 15cm, z = 12cm)

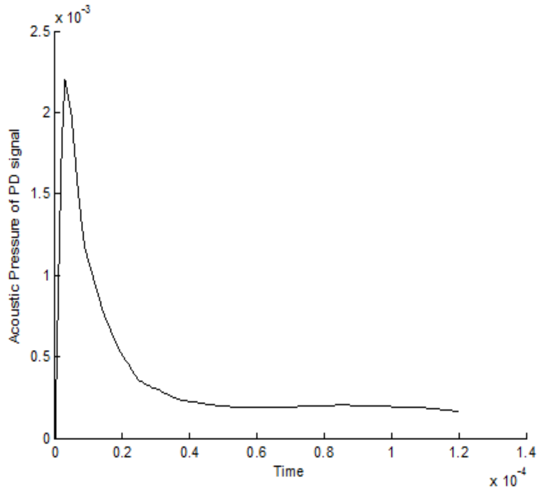

Fig. 5. Acoustic pressure of PD signal versus time (μs)

Fig. 6 shows a front side view of simulated PD AE wave at 18 cm depth from top of the tank. The PD source is at the coordinate (x=15 cm, y=15 cm, z=5 cm) within the tank. The corresponding plot for acoustic pressure of PD signal versus time is presented in Fig.7.

Figs. 2, 4 and 6 illustrate the propagation behavior of the AE signal as it propagates in deeper locations. The colour legend has provided at the right side of each figure to understand the change of PD AE wave as the spherical wave-front moves further from the point source. The red colour describes the highest pressure at start of PD. The broader wave-front with changing colour shows that the wave is moving. The colour changes from red to yellow to green to blue indicating that the wave-front is weakening. It weakens as the wave spreads out towards the boundaries of the tank within the oil as shown in the simulated result varying depth presented in Figs. 2, 4 and 6.

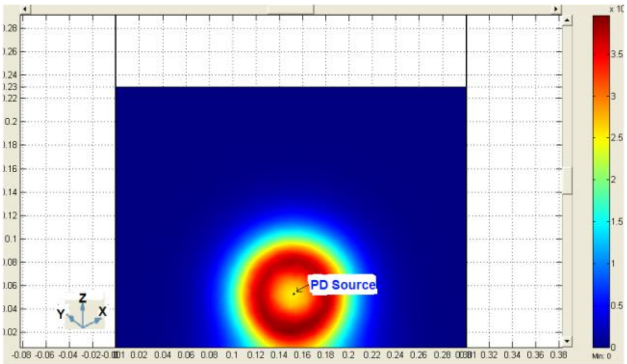

Fig. 6. Simulated PD AE wave at 18cm depth from top of the tank at (x = 15 cm, y = 15 cm, z = 5 cm)

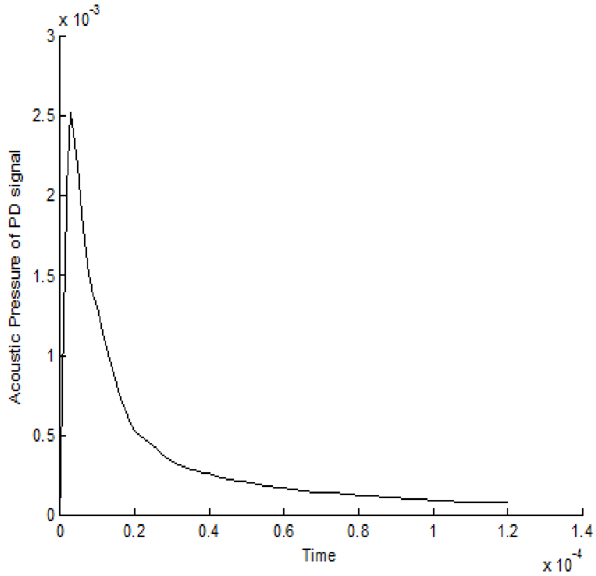

Fig. 7. Acoustic pressure of PD signal versus time (μs)

It is interesting to note that in Fig. 2, Fig. 4 and Fig. 6, the AE wave-fronts are non-circular. This is attenuated due to the influence of hydrostatic pressure at varying depth**.** When moving deeper within the oil tank, the effect of hydrostatic pressure distorts the circular nature of acoustic wave-fronts.

The acoustic pressure (P) at any level may be interpreted as the total weight of the fluid on a unit area at any elevation. The pressure exerted by a fluid depends only upon the depth of the fluid (h), the density of the fluid (ρ) and the acceleration due to gravity (g) as shown in equation (3) [7], i.e.,

$$P \propto \rho g h \qquad (3)$$

Since the density is a function of depth, the acoustic pressure is directly proportional to the product of depth of the source location and the acceleration due to gravity as described by equation (3). When moving deeper within the tank, the oil pressure increases which can be seen in Figs. 3, 5 and 7. The change of pressure of the acoustic signal with the depth of the tank is plotted in Fig. 8. The Fig. 8 illustrates that the peak pressure of the acoustic signal has non-linear relationship with the depth of the tank as given equation in Fig. 8. The peak pressure of the acoustic signal increases non-linearly at deeper locations because hydrostatic pressure affects the propagation of AE wave.

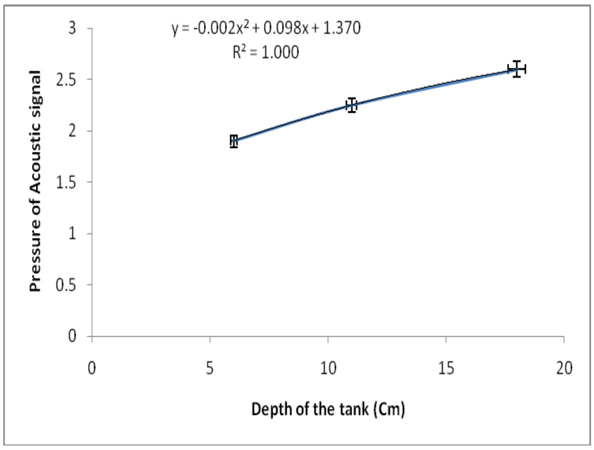

Fig. 8. Peak pressure of acoustic signal versus depth of tank

The oil pressure increases as moving down within the oil tank which would make the medium denser resulting decrease in radius of wave front. Since the amplitude of the spherical wave is inversely proportional to the radius of wave-front [10], the amplitude of the wave would increase resulting in increase in the speed of the AE signal.

As acoustic pressure is directly proportional to the speed of the PD AE wave (V) [7], i.e.,

$$P \propto V ,$$

Therefore, the speed of the PD AE wave can also be represented as,

$$V \propto \rho g h \qquad (4)$$

Hence it can also be said by equation (4) that the speed of the PD AE wave (V) depends upon the depth of the fluid (h), the density of the fluid (ρ) and the acceleration due to gravity (g). It has been observed in Fig. 8, that the peak pressure of the acoustic wave gradually increases by around 11% when going deeper by 10 cm in the tank. Hence it can be concluded that the propagation speed of the AE signal increases when going deeper in the oil tank. This outcome is an alarm in the field of PD study for the exact location of PD in HV equipment, because the researchers [1], [4] and [16] are assuming the speed of PD AE signal as a constant value, which is not correct.

V. Experimental Validation

In order to validate simulation studies discussed in section 4, experiments were conducted to investigate the relation of the propagation speed of PD acoustic signal with hydrostatic pressure in transformer oil to demonstrate the physical changes in the AE waves.

Fig. 9 illustrates the experimental layout of the laboratory setup based on six device (numbered 1to 6 in fig. 9) for detecting the acoustic signals produced by PD. To capture the AE signals, the experimental set-up consists of the HV transformer (1), HV coupling capacitor (2), Voltage divider (3), Electrode systems (4), Steel oil tank (5) and Four Piezo-electric sensors (6).

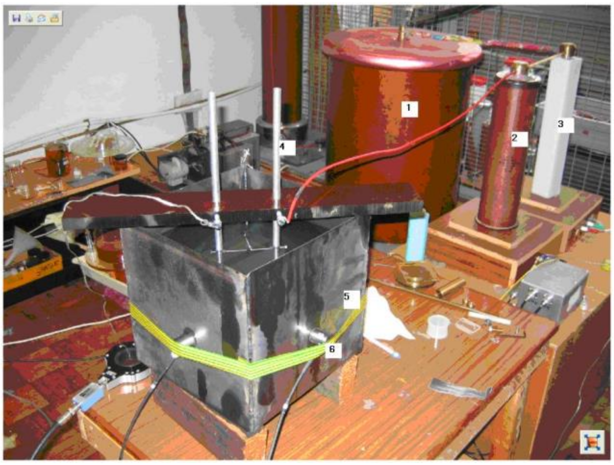

Fig. 9. Experimental layout of the laboratory setup

However Fig. 10 illustrates the circuit diagram of the experimental setup for detecting the acoustic signals produced by PD. The magnitude of the HV is increased gradually until the electrical stress is large enough to produce PD.

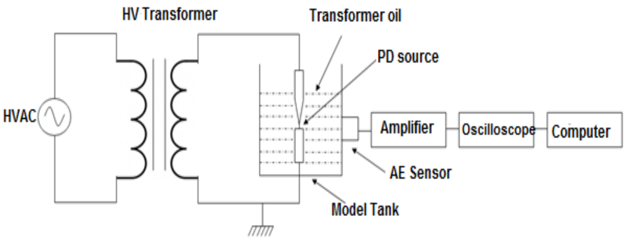

Fig. 10. Circuit diagram of the experimental setup

Two AE sensors positions are located directly opposite to each other with the PD source at the centre as shown in Fig. 11. PD source and the sensor are kept at the same height so that the sensor could capture the first peak of AE signal as a result of the direct propagation path which is to be quickest. A thin layer of silicon grease is applied on the surface of the sensors for maximum transmission of signals between the tank wall and the sensors. During the experiments, same as simulations, the tank top cover is kept open so that the PD source could be put inside the tank. The coordinates of the PD source and the sensors on the tank wall are as given in Table 1.

Transformer oil is filled in the tank up to the level of 23 cm from the bottom of the tank. The needle-plane electrode system is placed along the center axis of the tank and PD source is moved at the heights of 10, 15 and 25 cm from the top of the tank in different sets of experiments such that 1 to 9 specified locations are used as shown in Fig. 11.

TABLE I
THE POSITIONS OF THE DISCHARGE SOURCE AND THE SENSORS IN THE EXPERIMENT AS SHOWN IN FIG. 10

Components	x(mm)	y(mm)	z(mm)
PD Source	150±1	150±1	115±1
Source 1	150±1	0	115±1
Source 2	150±1	300±1	115±1
Source 3	300±1	150±1	115±1
Source 4	0	150±1	115±1

The temperature of the transformer oil in the model tank is kept around 20^{0}C. A stirrer is used to maintain constant temperature throughout the tank so as to maintain the consistency in the results of hydrostatic pressure at room temperature. The applied voltage is 15 kV.

The experiment will help to monitor the influence of location of the PD acoustic signals within the tank. It is critical to establish how the signals will vary depending on the location of the PD source due to any variations with density/pressure of the oil. A PD pulse creates a spherical pressure wave of a longitudinal nature in the oil which then excites a longitudinal wave and a shear wave in the transformer tank.

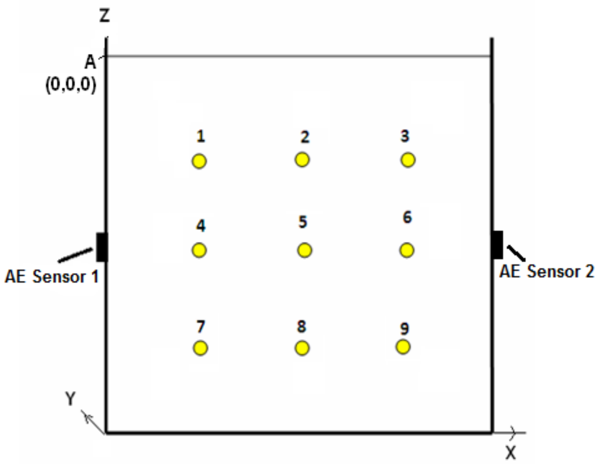

Fig. 11. Front view of model tank with 1 to 9 locations of PD and 'A' is a reference point with coordinates (0, 0, 0)

In general, there are three basic propagation paths from the source of the AE wave to the sensor as illustrated in Fig. 12. One is the direct path in the oil (straight line between the PD source and the sensor i.e. d_1 or d_2). The other is the mixed path; the acoustic wave propagates in oil first and then in steel tank wall and next one is the reflected paths.

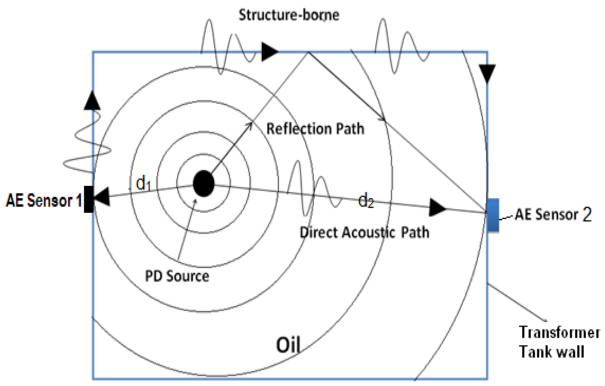

Fig. 12. Illustration of typical propagation paths for acoustic PD signals

To measure the speed of propagation of an acoustic pulse in oil, it is necessary to determine the TDOA between sensors required for the AE pulse to travel a known distance [4], [16-18] and [23]. Since the path difference 'Δd' between the PD source and the AE sensors is known, then one can estimate the propagation speed 'S' of the PD AE signal by using

$$S = \frac{\Delta d}{TDOA} , \qquad (5)$$

for example, the path difference between sensor 1 and 2 (i.e., d_1-d_2) as shown in Fig. 11, divided by the TDOA between sensor 1 & 2 (i.e., t_1-t_2) will produce the propagation speed over the difference in path length. Repeated measurements were taken for the TDOA of AE signal at sensors**.** Thirty sets of samples were measured at 9 locations as shown in Fig. 11. But due to limitation of paper size, the readings of only three locations, 2, 5 and location 8 are presented here. TDOA was measured taking sensor 1 as a reference. τ_{12} is the TDOA between sensor 1 and 2. The average propagation speed of PD AE signals were estimated (including standard deviation) using equation (5) on each location and presented in Tables 2 to 4.

TABLE II
PROPAGATION SPEED OF AE SIGNAL AT 20^{0}C AT LOCATION 2
(x=15 CM. y=15 CM, z= 10 CM)

Sr. No.	Temperature	Path Difference between PD source to the sensor 1&2	Average TDOA (τ_{12}) (including mean error) µs	Average speed of AE signal m/s (including standard deviation)
1	20^0 C	15.1	114±0.34	1324±0.29%

TABLE III
PROPAGATION SPEED OF AE SIGNAL AT 20^{0}C AT LOCATION 5
(x=15 CM. y=15 CM, z= 15 CM)

Sr No	Temperature	Path Difference between PD source to the sensor 1&2	Average TDOA µs (τ_{12}) (including mean error)	Average speed of AE signal m/s (including standard deviation)
1	20^0 C	15.1	106±0.63	1425±0.59%

TABLE IV
PROPAGATION SPEED OF AE SIGNAL AT 20^{0}C AT LOCATION 8
(x=15 CM. y=15 CM, z= 20 CM)

Sr No	Temperature	Path Difference between PD source to the sensor 1&2	Average TDOA µs (τ_{12}) (including mean error)	Average speed of AE signal m/s (including standard deviation)
1	20^0 C	15.1	99±0.28	1525±0.43%

The variations of the average speed of AE signals at locations 2, 5 and 8 at a temperature of 20^{0}C in oil are plotted in Fig. 13. Least squares curve fitting is also used for all three curves. The curve is second order parabola with the equation shown in the Fig. 13. The propagation speed can be computed by the equations at any depth between 10 cm to 20 cm within the tank.

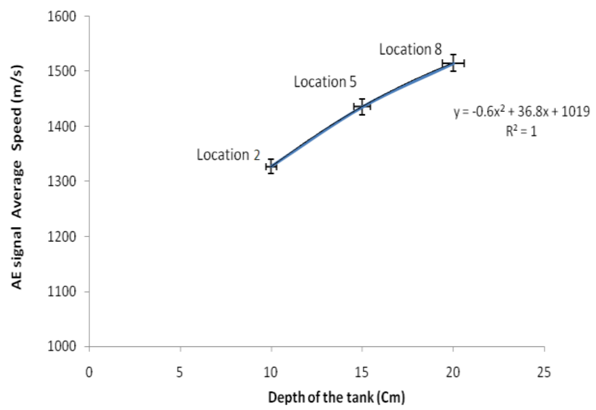

Fig. 13. Variation of average speed of AE Signal at location 2, 5 and 8 at temperature of 20^{0}C in oil

Fig. 13 shows that when the acoustic signal propagates from the top towards deeper locations within the tank, the speed of the AE signal increases. It illustrates that going deeper within the tank from locations 2 to 5 then to 8, the average speed of AE signals increases non-linearly. Hence it can be concluded that propagation speed of the AE signal increases with depth in the oil tank. This is due to increased density of the oil that is caused by hydrostatic pressure. Hydrostatic pressure will affect the acoustic velocities in such a way that the initial change in depth of just 5 cm produces an increase of around 6% in the speed of AE signals and nearly an 8% increase of the signal speed when going 10cm deeper within the tank at 20^0C temperature. Due to increased density influence, the oil pressure increases when moving down within the tank which makes the media denser (more viscous) resulting in an increase of speed of AE signals as seen in Fig. 11 at location 8 which is near to the bottom of the tank. Therefore, it can be concluded that percentage rise of propagation speed of PD; AE signals increases at deeper levels at room temperature. This result validates the simulation study explored in section 4.

Fig. 13 also illustrates that the speed of the AE signal increases around 30% with a change in depth of just 5 cm at 20^0C at location 2, nearly 20% at location 5 and around 15% at location 8. Since the location 8 is near to the bottom of the tank, therefore it has been seen that in Fig. 12 percentage of rise of speed of PD; AE signal due to rise in hydrostatic pressure is decreasing at deeper level. If the effect of increased density due to hydrostatic pressure is ignored then the possibility of having wrong PD location will be increased significantly since the speed of propagation cannot be assumed to be the same at each location within the HV plant equipment.

VI. Conclusions

A 3D simulation of PD acoustic signal propagation in a model transformer tank has been presented. The simulation study deals with the propagation of induced PD-AE wave through the oil using FEMLAB, a Finite Element Analysis tool. The investigations and results presented here are very interesting behavior to the field of PD. In order to estimate the propagation speed within the oil tank at different levels, experiments were also conducted. On the basis of the outcomes of experiments, it has been seen that propagation speed of AE signals is not constant within the tank. It was observed that the speed of the acoustic signal varies with the depth of the source location. The propagation speed increases with increasing depth in the oil tank at room temperature. This is because of the effect of hydrostatic pressure, the pressure increases as moving down within the oil tank. This makes the media denser (more viscous) resulting in an increase of speed of the AE signal.

By comparing the experimental results with simulation studies, the partial discharge acoustic emission signal speed increases around 10% theoretically and 8% experimentally when going 10 cm deeper within the tank. It was also observed that the amplitude of the peaks becomes larger with deeper locations.

The results explored here are for a small size model tank. So there is a great possibility of having significant effect on these outcomes with real size transformer tank. Neglecting these results may produce incorrect diagnostic conclusions for PD diagnostic engineers and practitioners.

Future research work may involve simulating a real transformer to study the effect of multi-wave propagation modes in deeper locations at different temperatures. Further investigations should consist of the effect of path obstacles on the propagation and signal attenuation of the PD AE wave within the transformer structures. Moreover, other important improvement is to include electrical detection along with the acoustic detection. The simulation on multiple PDs can be performed since the timing of the PD is available from the electrical detection. Therefore, the study will not be limited only to the well-defined reflection pattern recorded by the acoustic sensor.

These comprehensive investigations will therefore assist in PD diagnosis and aid in understanding more to determine sensor placement within the tank or on the tank wall and will also help the practical engineer to choose suitable AE sensor positions to monitor the PD activity.

Acknowledgements

The authors wish to express their sincere thanks to Dr. J. Mohammad Jahabar for his technical discussions.

References

[1] Lundgaard L.E., Berg G, Brede AP, Kyrkjeeide SL., Acoustic location of discharges in power transformer, *Proceedings of XIIIth international symposium on high voltage engineering*, Netherlands, 2003.

[2] Gao C., Yu L., Xu Y., Wang W., Wang S., and Wang P., Partial discharge localization inside transformer windings via fiber-optic acoustic sensor array, IEEE Trans. Power Del., vol. 34, no. 4, pp. 1251-1260, Aug. 2019.

[3] IEC 60270: INTERNATIONAL ELECTROTECHNICAL COMMISSION: High-Voltage Test Technique – Partial Discharge Measurement.

[4] Kundu P., , Kishore, N.K, Sinha, A.K., Simulation and Analysis of Acoustic Wave Propagation due to Partial Discharge Activity, *Proceedings of IEEE Conference on Electrical Insulation and Dielectric Phenomena*, Kansas-USA, pp. 619-622, 2006.

[5] Yan-Bo Wang, Yu-Hang Fan, Shao-Rui Qin, Ding-Ge Chang, Xian-Jun Shao, Hai-Bao Mu, Guan-Jun Zhang, Partial discharge localisation methodology for power transformers based on improved acoustic propagation route search algorithm, IET Sci. Meas. Technol., Vol. 12 (8), pp. 1023-1030, July 2018.

[6] Ashraf, S. A., Stewart, B.G., Khan K., Hepburn D.H. and Siddiqui S. A., Stochastic Behavior of Propagation of Partial Discharge Acoustic Signals in Transformer Oil, *Proceedings of International Journal of Applied Engineering Research* ISSN 0973-4562, 11(12), pp. 7702-7707, June 2016.

[7] Sears F.W., M.W. Zemansky and H.D. Young, University Physics (Narosa Publishing House), India, 6^{th} Ed, 1998.

[8] Al-Masri W. M. F., Abdel-Hafez M. F., and El-Hag A. H, ``A novel bias detection technique for partial discharge localization in oil insulation system," *IEEE Trans. Instrum. Meas.*, vol. 65, no. 2, pp. 448-457, Feb. 2016.

[9] Refaat S. S., Sayed M., Shams M. A., and Mohamed A., ``A review of partial discharge detection techniques in power transformers," in *Proc. 20th Int. Middle East Power Syst. Conf. (MEPCON)*, pp. 1020-1025, Dec. 2018,

[10] Syed Aqeel Ashraf, The theoretical modeling and Evaluation of Partial Discharge Acoustic Signals in oil, *PhD Thesis (Glasgow Caledonian University*), UK, July 2015.

[11] Mehdizadeh, S., Mohammadreza Y. and Mehdi N., A Novel AE Based Algorithm for PD Localization in Power Transformers, *Journal of Electrical Engineering Technology*, *Vol. 8*, pp.1487-1496, 2013.

[12] Rashid Hussain M., Shady S. R. and Haitham Abu-rub, Overview and Partial Discharge Analysis of Power Transformers: A Literature Review, IEEE Access, *Vol. 9*, pp. 64587- 64605, DOI: *10.1109/ACCESS.2021.3075288,* April 2021.

[13] Cao, W. M, Cao H. J. et al., An overview of state-of-the-art partial discharge analysis techniques for condition monitoring, IEEE Electr. Insul. Mag., Vol 31, (6), pp. 22–35, 2015.

[14] Yaacob, M.M, Alsaedi, M.A., Rasheed, J.R., *et al.*, Review on partial discharge detection techniques related to high voltage power equipment using different sensors, *Photonic Sens.*, *Vol.4*, (4), pp. 325–337, 2014.

[15] Ahmed Qiste, Simulation of acoustic partial discharge signals in a model transformer and a location algorithm, *PhD Thesis (University of Manchester*).UK, Aug 2007

[16] Ilkhechi H. D. and Samimi M. H., Applications of the Acoustic Method in Partial Discharge Measurement: A Review, IEEE Transactions on Dielectrics and Electrical Insulation Vol. 28, No. 1; pp. 42-51, February 2021.

[17] Dae-Won Park, Hyang-Eun Cho, Sang-Wook Cha and Gyung-Suk Kil, Positioning of Partial Discharge Origin by Acoustic Signal Detection in Insulation Oil, Proceedings of Journal of International Council on Electrical Engineering, , Vol. 2, No. 1, pp. 28~32, 2012.

[18] Sikorski W., Ziomek W., Detection, recognition and location of partial discharge sources using acoustic emission method. *Acoustic Emission, In Tech*, ISBN: 978-953-51-0056-0, pp. 49–74, 2012.

[19] Hussein R., Shaban K. B., El-Hag A. H., Denoising different types of acoustic partial discharge signals using power spectral subtraction, *IET HV Journal, Vol3(1),* pp. 44 – 50, ISSN 2397-7264, March 2018.

[20] Sorokhaibam N.M., Borah K., Saibal C., Modelling of Acoustic Wave Propagation Due to Partial Discharge and Its Detection and Localization in an Oil-Filled Distribution Transformer, Frequenz, Volume 74, Issue 1-2, pp. 73–81, eISSN 2191-6349, ISSN 0016-1136, DOI: https://doi.org/10.1515/freq-2019-0050, Oct 2019.

[21] Banumath S., Chandrasekar S, Analysis of Partial Discharge Characteristics of Olive and Castor Oil as Dielectric Medium for HV Applications, *International Review of Electrical Engineering (I.R.E.E.)*, Vol 8, No 6, 2013.

[22] Moosaviyan, I, Seifossadat Gh., Kianinezhad R., Fault Location in High Voltage Transmission Line with Current Traveling Wave, *International Review of Electrical Engineering (I.R.E.E.),* Vol 6, No 4, pp 112-117, 2018.

[23] SHUDONG WANG, YIGANG HE, BAIQIANG YIN, WENBO ZENG, YING DENG AND ZENGCHAO HU1., A Partial Discharge Localization Method in Transformers Based on Linear Conversion and Density Peak Clustering, IEEE Access, Vol 9, No 4, pp 7447-7458, DOI: 10.1109/ACCESS.2021.3049558, Jan 2021.

Authors' information

[1]Department of Electrical Engineering, University of Technology and Applied Sciences, Salalah, Sultanate of Oman.
[2]Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, Scotland, UK
[3]Department of Engineering, University of Technology and Applied Sciences, Suhar, Sultanate of Oman.
[4]Department of Maths, Aldar University, Dubai, United Arab Emirates
[5]National Cable Factory, Salalah, Sultanate of Oman.

Syed Aqeel Ashraf had received his Bachelor of Electrical Engineering, Master of Engineering from Aligarh Muslim University, India and PhD from Glasgow Caledonian University (United Kingdom). He is working as senior faculty of Electrical Engineering at the Department of Electrical Engineering, University of Technology and Applied Sciences, Salalah (Sultanate of Oman).

He has more than 30 years of academic and industrial experience. He is active reviewer of several reputed international journals and has published more than 23 papers in international journals and conferences. His field of interest includes the Power Systems, Partial Discharge, Industrial Instrumentation and Renewable Energy.

Dr. Ashraf is a life member of ISTE (India), IE (India) and Computer, Electrical & Electronics Engineering Society of India.

Brian G. Stewart has gained a BSc and PhD from the University of Glasgow and also holds a BD degree from the University of Aberdeen. He is currently Professor of High Voltage Engineering at the University of Strathclyde, Glasgow, Scotland, UK.

His research interests lie in the areas of high voltage engineering focusing on electrical condition monitoring, insulation diagnostics, HV asset management, data analytics and communication systems. He is also Co-academic lead for the Asset Management theme at Strathclyde's Power Network Demonstration Centre (PNDC). Recently funded research projects have focussed on power transformers, power cables, HVDC systems, GIS systems, electrical diagnostic measurements, power quality in rail systems and data analytics.

Prof. Brian's professional affiliations are CEng, MIET and MIEEE. He has previously served as an elected AdCom Member of the IEEE Dielectrics and Electrical Insulation Society (DEIS), held the position of IEEE DEIS Secretary during 2012-2017 and was Vice-President (Technical) of the IEEE DEIS Society for 2018 and 2019. He is currently serving as Vice-President (Administration) of the IEEE DEIS Society for 2020.

Parmal Singh Solanki had received his Bachelor of Electrical Engineering, Master of Engineering from Indian universities and PhD from Glasgow Caledonian University, (United Kingdom). He is working as Assistant Professor at Department of Engineering, University of Technology and Applied Sciences, Suhar, (Sultanate of Oman).

He has more than 25 years of academic and industrial experience. He has published more than 25 papers in international journals and conferences.

He is active reviewer of several reputed international journals. His field of interest includes the Power Systems Analysis, Demand Side Management of Electrical Power and Renewable Energy.
Dr Solanki is a member of ISTE (India) and IE (India).

Khaliquzzaman Khan did his Bachelor, Master and PhD from Indian Universities. He is working as an Assistant Professor in the Department of Mathematics & Statistics, Aldar University- Dubai, (United Arab Emirate).
He has more than 28 years of academic experience. He is active reviewer of several reputed international journals and has published more than 20 papers in international journals and conferences. His field of interest is Applied Statistics.
Dr. Khan is a member of Indian Mathematical Society.

Ch. Venkateswara Rao had received his Bachelor of Electrical Engineering, Master of Engineering and PhD from Indian universities. He is currently working as a Lecturer in Electrical Engineering at the Department of Engineering, Salalah College of Technology-Salalah (Sultanate of Oman). He has more than 24 years of academic and industrial experience. His major research interests are Power Systems, Energy Conservations and Smart Grids.
Dr. Rao is a member of ISTE (India) and CSI (India).

Syed Moeen Ashraf did his Bachelor of Technology in Electrical and Electronics Engineering from Aligarh Muslim University, India. He is working as PLC Maintenance Engineer in National Cable Factory, Salalah, (Sultanate of Oman). He has published papers in international conferences.
His research interests are Industrial Instrumentation, detection and localization of Partial Discharge in high voltage power cables. He is also associated with the design of single and multicore 0.6/1kV cables.
Engr. Moeen is a member of Institution of Engineers (India).