Evaluation of Partial Discharge Signal Propagation Using Finite Element Method in Power Transformer

Muhammad Alleef Abd Jalil
Faculty of Electrical Engineering and Technology,
Universiti Malaysia Perlis (UniMAP),
Perlis, Malaysia
alleefjalil@studentmail.unimap.edu.my

Mohamad Nur Khairul Hafizi Rohani
Faculty of Electrical Engineering and Technology,
Universiti Malaysia Perlis (UniMAP),
Perlis, Malaysia
khairulhafizi@unimap.edu.my

Afifah Shuhada Rosmi
Faculty of Electrical Engineering and Technology,
Universiti Malaysia Perlis (UniMAP),
Perlis, Malaysia
afifahshuhada@unimap.edu.my

Abdullahi Abubakar Mas'ud
Department of Electrical Engineering,
Jubail Industrial College,
Jubail, Saudi Arabia
abdullahi.masud@gmail.com

Firdaus Muhammad-Sukki
School of Computing, Engineering and the Built Environment,
Edinburgh Napier University,
Scotland, United Kingdom
firdaus.sukki@gmail.com

Kumuthawathe Ananda-Rao
Faculty of Electrical Engineering and Technology,
Universiti Malaysia Perlis (UniMAP),
Perlis, Malaysia
kumuthawathe@unimap.edu.my

***Abstract*— Partial discharge (PD) is a phenomenon that can occur in power transformers which can lead to the degradation of the insulation system that resulting the failure of the power transformer. The power transformer uses oil as its insulation medium. An acoustic pressure wave generated by a partial discharge in oil can be detected by using Acoustic Emission (AE) sensors. However, the position of AE sensors needs to be determined to ensure that the sensors can effectively detect and capture the signals produced by partial discharges occurring within the transformer. The acoustic emission sensor can identify the PD between 10 kHz and 300 kHz. This paper presents the simulation of acoustic waves for oil propagation in a model transformer tank and its pressure that is detected by AE sensor using the finite element method (FEM) approach. In this research, two locations of AE sensors are simulated which is on the wall of the transformer and inside the power transformer tank. Based on the acoustic pressure and time of arrival, the propagation of the acoustic PD signal is being examined. The result shows that the acoustic pressure wave is getting bigger as the time increase. Its amplitude decreases when the radius of the acoustic pressure wave increases. The placement of the sensor either inside or outside of the transformer tank does not affect the amplitude of pressure detected by the acoustic sensor.**

Keywords—Partial discharge, power transformer, oil propagation, finite element method, insulation system.

I. INTRODUCTION

Partial discharge is a source of electrical discharges that contain voids, cavities, or insulation defects which can lead to transformer failure. According to IEC-60270, PD is an electrical discharge that only partially bridges the insulation between conductors and could occur close to a conductor [1]. PD signal must be identified at an early stage before serious damage occurs in the power transformer and interrupt the operation of the power transformer.

Partial discharge can be detected using different techniques such as optical detection, chemical detection, electrical detection, electromagnetic detection and acoustic emission (AE) detection [2], [3]. In this research, Acoustic emission is selected because of its advantage that gives electromagnetic noise immunity. The acoustic emission sources can be detected and characterised using the identification of acoustic signals produced by partial discharge PD in a frequency range from 10 kHz to 300 kHz [4].

Finite Element Method is a numerical technique used to solve complex engineering and scientific problems[5]. In this research, FEM software is used to evaluate the oil propagation of the PD signal in power transformer. The acoustic pressure transient module is already defined with a partial differential equation (PDE) in FEM software.

Thus, this paper is identified and evaluates the partial discharge signal in a power transformer using acoustic pressure with Finite Element Method to obtain more accurate detection and PD localisation.

II. ACOUSTIC DETECTION IN POWER TRANSFORMER

Acoustic PD measurement is a usual method for figuring out where PD occurs in insulation systems in power transformers. When a PD signal occurs, it produces pressure waves that can be seen as waves of sound. Acoustic sensors are usually placed on the surface of the transformer tank to detect these sound waves.

The exact position of the PD source by using time of arrival for acoustic signal to travel from the PD source to the sensors. One of the AE detection applications is a piezoelectric sensor that converts mechanical strain-induced vibrations from acoustic signals into corresponding electrical signals [6]. When a sound wave or vibration hits a piezoelectric material, it causes vibration, which makes the material produce an electric charge.

FEM has been widely used in evaluating the propagation of partial discharge signals in the oil of power transformers[7], [8]. FEM software provides the acoustic pressure transient module for the simulation of acoustic wave propagation in power transformer [9]. This paper presents a review of the use of FEM in evaluating the oil propagation of partial discharge signals in power transformers.

III. Simulation Of Signal Propagation

The FEM software is used to generate a simulation model that will be used to analyse the propagation of partial discharge acoustic waves in a model transformer tank[10]. There are two cases analysed in this research. The first case focuses on the effect of the sensor's distance from the PD source and the second case is to study the influence of the sensor placement inside and outside the transformer tank.

In this research, the 2-dimensional (2D) geometry of the transformer tank filled with transformer oil is simulated using the FEM software. The pressure acoustic wave equation is defined in the software using transient pressure acoustic module. The point source of pressure which is the Flow of Energy, Q(t) [11], [12]can be expressed as :

$$Q(t) = Ae^{(-\pi^2 f^2 (1-\tau)^2)} \quad (1)$$

Where A is the amplitude of the pulse, f is the frequency of the pulse and τ is the time offset for the peak pulse of the tank.

A. Transformer Model

The prototype modelling of geometry for power transformer is modelled in this design as shown in Fig. 1 with the dimension of the transformer tank is 50 cm X 30 cm and the thickness of the wall is 1 cm. Square 1 is adding as steel material on it for the outer area of the transformer. Square 2 adding as transformer oil for the interior of the transformer.

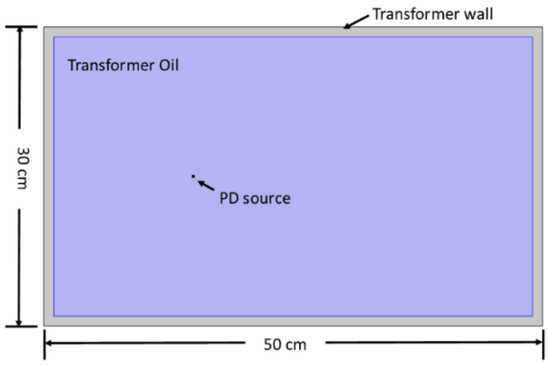
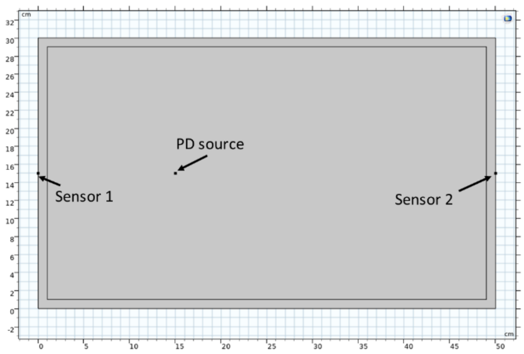
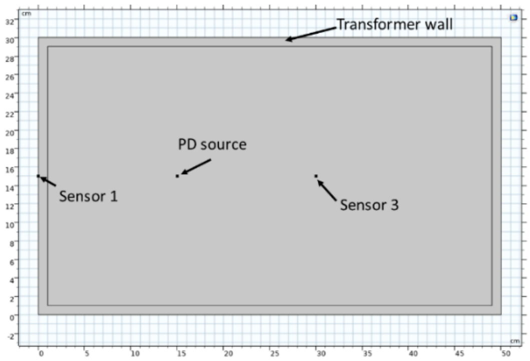


Fig. 1. The geometry of the power transformer

The transient pressure acoustic is placed inside the power transformer to act as PD source. The measurement probe which is the sensor was placed at the wall of transformer for case 1 to measure the acoustic wave, while for case 2, the sensor is placed at the wall of transformer and inside the transformer oil with the same distance as shown in Fig. 2.



(a)



(b)

Fig. 2. The location of the sensor for (a) Case 1, (b) Case 2

The location of the PD source is fixed at coordinate (15,15) for case 1 and case 2, while the sensor location is changed, as shown in Table I.

TABLE I. Location coordinate of PD source and sensors

Probe	Coordinate (x,y)
PD source	(15,15)
Sensor 1	(0,15)
Sensor 2	(30,15)
Sensor 3	(50,15)

B. Material Properties

Several factors were considered when simulating the oil propagation in the transformer tank. The simulation frequency in this research is selected at 100 kHz as the frequency of acoustic partial discharge frequency range from 20 kHz to 300 kHz[13]. Table II shows the material properties of the transformer filled with transformer oil and its wall is from steel AISI 4340.

TABLE II. Material Properties of the transformer

Material	Density (kg/m3)	Speed of sound (m/s)
Transformer oil	0.92	1390
Steel (ASAI 4340)	7850	5850

C. Meshing

After the design structure is completed, the meshing part is important to understand the behaviour of PD. The meshing process will analyse each element in the project design. To well resolve the propagating of the wave, 5 to 6 mesh elements per wavelength are required. The typical mesh size [11] is given by:

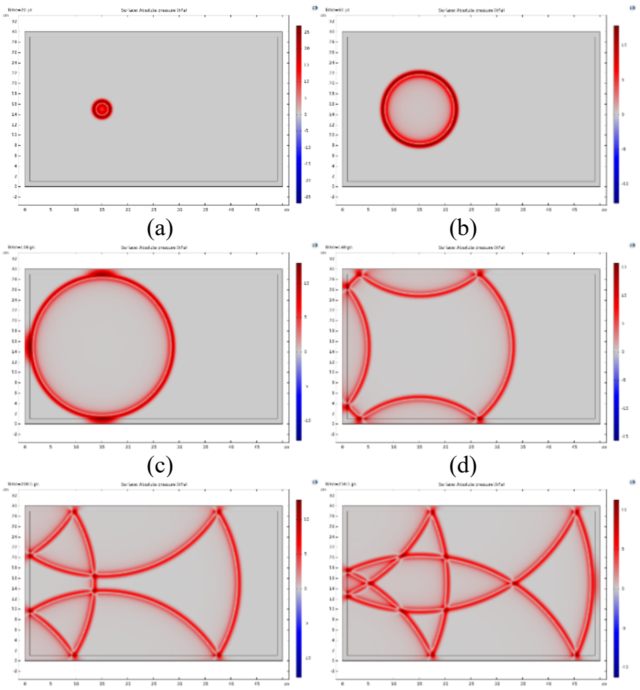
$$h_{\max} = \frac{\lambda_{\min}}{N} = \frac{c_{\min}}{f_{\max} N} \quad (2)$$

Where $hmax$ is the typical maximum mesh element size, λmin is the minimum wavelength computed at the highest frequency and $cmin$ is the minimum speed of sound and N is the number of elements per wavelength. s

IV. Result And Discussion

The PD oil propagation is being recorded in this research. The acoustic pressure wave generated by the PD source propagates in space with a spherical wave front. The wave travels along in the power transformer at different times after the PD source is triggered. Fig. 3 shows the behaviour of acoustic pressure waves from 20 µs to 250.5 µs.

The acoustic pressure wave progressively increases over time becoming bigger. However, the amplitude of the wave decreases as it expands and propagates outward. Its amplitude decreases when the radius of the acoustic pressure wave increases because of the effect of energy conservation within the wave. The energy is as the wave expands out and covers a larger area resulting in the amplitude of the wave is decrease.



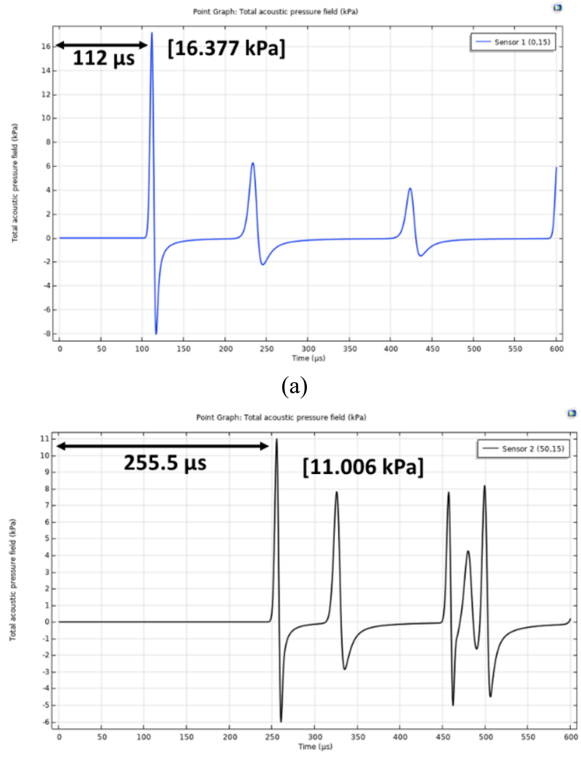
(a) (b) (c) (d) (e) (f)

Fig. 3. Acoustic pressure wave at; (a) 20 µs, (b) 60 µs, (c) 108 µs, (d) 140 µs, (e) 200.5 µs, (f) 250.5 µs

At 108 µs, the wave reaches the area of the steel tank and it reflects the wave due to a change in the impedance from oil to steel. The transformer oil and steel have different acoustic impedance values that cause some of the wave energy to get bounced back and reflected from the steel surface.

A. Case 1 – The effect of the sensor's distance from the PD source

The PD source is placed at a distance of 15 cm along the x-axis from sensor 1, while sensor 2 is positioned at a distance of 35 cm. The result of the peak amplitude of pressure and time of arrivals between the sensor and PD source is shown in Fig.4.



(a)

(b)

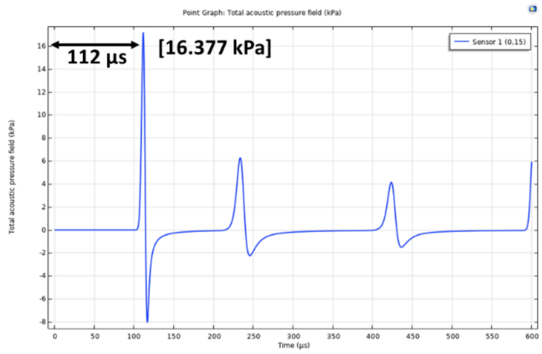
Fig. 4. Acoustic pressure signal detected by (a) Sensor 1, (b) Sensor 2

Sensor 1 detected the pressure wave faster with the time of arrival was 112 µs compared to sensor 2 with 255.5 µs. This result proves that the closer the sensor with the PD source allowing it to detect pressure wave faster. However, sensor 2 was located at a longer distance from the PD source that cause the delay before detecting the pressure of PD wave.

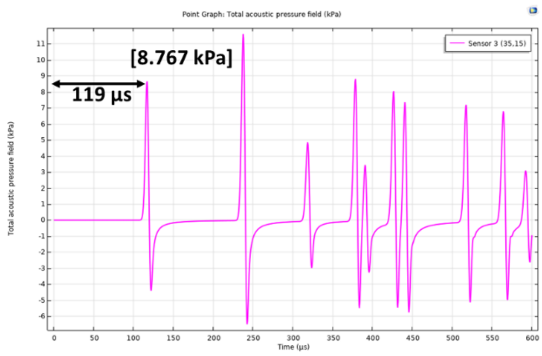
Moreover, the peak pressure for Sensor 1 is higher than the Sensor 2 which is 16.377 kPa and 11.006 kPa respectively. The difference in pressure shows that the pressure wave experiences attenuation or a decrease in strength as it travels from the PD source to the sensors. The longer the distance between the sensor and PD source, the pressure becomes lower because of energy losses and dispersion of wave pressure that propagates through oil.

B. Case 2 - The influence of the sensor placement inside and outside the transformer tank

The simulation is repeated with the PD source remaining constant at its coordinate (15,15). The location of sensor 1 and sensor 3 have the same distance which is 15 cm. Fig. 5 shows the comparison between sensor 1 outside the transformer tank and sensor 3 inside the transformer tank.



(a)



(b)

Fig. 5. Acoustic pressure signal detected by (a) Sensor 1, (b) Sensor 3

Sensor 1 showed a shorter time of arrival of 112 µs than sensor 3 which recorded a time of arrival of 119 µs. There is some difference of time which is 7µs because of the propagation of the pressure waves that took to reach the sensor. The wave propagation hit the inner wall of the transformer tank first at sensor 1.

Next, sensor 1 showed a peak pressure reading of 16.377 kPa which is higher than sensor 3 with 8.767 kPa. This is due to the reflection of the oil with the tank's wall reflected back into the tank. When the transformer oil hits the wall and comes to stop, the energy of the wave pressure transformer into potential energy that resulting higher pressure at the transformer tank.

V. Conclusion

In this study, acoustic pressure propagation inside a power transformer using FEM software has been investigated. A new method for locating the acoustic sensor in the transformer tank is evaluated and compared with external placement.

Based on the results, the pressure waves generated by the PD source inside the tank travel through the oil before reaching both sensors. The bigger pressure of acoustic is detected by the sensor when the sensor location is near the PD source. Moreover, the sensor for internal placement detected lower pressure compared to the sensor located at the wall of the tank because of the reflection between the transformer oil and the tank. However, the sensor inside the tank will be shielded from external noise. In addition, the time of arrival of the first peak amplitude for sensor inside and outside the transformer tank does not affect much for it time.

Acknowledgment

The authors would like to acknowledge the support from the Fundamental Research Grant Scheme (FRGS) under a grant number of FRGS/1/2019/TK04/UNIMAP/02/20 from the Ministry of Higher Education Malaysia.

References

[1] S. N. Meitei, K. Borah, and S. Chatterjee, "Modelling of Acoustic Wave Propagation Due to Partial Discharge and Its Detection and Localization in an Oil-Filled Distribution Transformer," *Frequenz*, vol. 74, no. 1–2, pp. 73–81, Jan. 2020, doi: 10.1515/freq-2019-0050.

[2] M. A. A. Jalil *et al.*, "Partial discharge signal measurement based on stand-alone and hybrid detection technique for power transformer," *Journal of Advanced Research in Dynamical and Control Systems*, vol. 12, no. 7 Special Issue, pp. 1302–1312, 2020, doi: 10.5373/JARDCS/V12SP7/20202230.

[3] R. Ghosh, B. Chatterjee, and S. Dalai, "A method for the localization of partial discharge sources using partial discharge pulse information from acoustic emissions," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 24, no. 1, pp. 237–245, Feb. 2017, doi: 10.1109/TDEI.2016.006080.

[4] M. A. Abd Jalil *et al.*, "Piezoelectric Sensor using PZT Material for Partial Discharge Detection on Power Transformer," *IOP Conf Ser Mater Sci Eng*, vol. 864, no. 1, 2020, doi: 10.1088/1757-899X/864/1/012204.

[5] Z. Wang *et al.*, "FEM Simulation and Test Verification of PD Ultrasonic Signal Propagation in a Power Transformer Model," *Journal of Electrical Engineering & Technology*, no. 0123456789, 2020, doi: 10.1007/s42835-020-00545-z.

[6] K. N. Khalid *et al.*, "Influence of PD source and AE sensor distance towards arrival time of propagation wave in power transformer," *J Phys Conf Ser*, vol. 1432, no. 1, 2020, doi: 10.1088/1742-6596/1432/1/012006.

[7] M. A. M. Isa *et al.*, "Investigation on partial discharge activities in cross-linked polyethene power cable using finite element analysis," in *Journal of Physics: Conference Series*, Institute of Physics Publishing, Jan. 2020. doi: 10.1088/1742-6596/1432/1/012024.

[8] K. N. Khalid, M. Nur, K. Hafizi, and B. Ismail, "Analysis on acoustic sensor placement for PD location in power transformer," *Turkish Journal of Electrical Engineering & Computer Sciences*, 2020, doi: 10.3906/elk-1907-187.

[9] A. S. Rosmi, M. Isa, B. Ismail, M. N. K. H. Rohani, and Y. Wahab, "An Optimization of Electrical Output Power for Piezoelectric Energy Harvester using Different Micro-Cantilever Beam Geometries," *J Phys Conf Ser*, vol. 1019, no. 1, 2018, doi: 10.1088/1742-6596/1019/1/012033.

[10] S. N. Meitei, K. Borah, and S. Chatterjee, "Finite Element Method Based Modelling and Analysis of Partial Discharge Acoustic Wave Propagation in an Oil-Filled Power Transformer," in *4th International Conference on Condition Assessment Techniques in Electrical Systems, CATCON 2019*, Institute of Electrical and Electronics Engineers Inc., Nov. 2019. doi: 10.1109/CATCON47128.2019.CN0111.

[11] V. B. Rathod, "Simulation of Partial Discharge Acoustic Wave Propagation Using COMSOL Multiphysics and Its Localization in a Model Transformer Tank," 2020.

[12] K. Liu, L. Guo, B. Chen, Y. Bao, J. Ma, and T. Feng, "Analysis of Ultrasonic Propagation Characteristics of Partial Discharge in Oil Immersed Power Transformer," in *Proceedings - 2020 7th International Forum on Electrical Engineering and Automation, IFEEA 2020*, Institute of Electrical and Electronics Engineers Inc., Sep. 2020, pp. 66–70. doi: 10.1109/IFEEA51475.2020.00022.

[13] H. R. Mirzaei, A. Akbari, M. Zanjani, K. Miralikhani, E. Gockenbach, and H. Borsi, "Investigating suitable positions in power transformers for installing UHF antennas for partial discharge localization," in *Proceedings of 2012 IEEE International Conference on Condition Monitoring and Diagnosis, CMD 2012*, 2012, pp. 625–628. doi: 10.1109/CMD.2012.6416223.