Influence of PD source and AE sensor distance towards arrival time of propagation wave in power transformer

Khalid K N,2, Rohani M N K H,2, Ismail B,2, Isa M,2, Rosmi A S1,2, Wooi C L2 and Yii C C3

1Faculty of Engineering Technology, UniCITI Alam Campus, Universiti Malaysia Perlis, Sungai Chuchuh, Padang Besar, 02100 Perlis, Malaysia.
2High Voltage Transient and Insulation Health (HVTrans), Centre of Excellence Renewable Energy (CERE), School of Electrical System Engineering, Pauh Putra Campus, Universiti Malaysia Perlis, 02600 Pauh, Perlis, Malaysia
3School of Engineering (Electrical), International College of Advanced Technology, Kuching, Sarawak, Malaysia.

E-mail: nadiahkhalid@unimap.edu.my

Abstract: Partial discharge (PD) often begins with cracks or gas-filled voids in solid insulation or with gaseous bubbles in liquid insulation. These presences can degrade the quality of insulator. PD detection can identify these cracks at high voltage equipment such as power cables and power transformer at the early stage. One of PD detection methods is acoustic emission (AE) detection. PD produces an ultrasonic signal that can be captured by an AE sensor. The signal captured is then analysed by capturing the time of the receiving signal onto the sensor. The information related to time can be used for allocating the PD for maintenance purpose. This paper shows the influence of the distance between PD source and the AE sensor towards the arrival time of propagation wave in power transformer. In this study, the four placements of sensors were analysed by having three possible PD sources to represent the variety of distances between the PD source and the sensor. The simulated signal is generated by MATLAB and the arrival time is captured using time of arrival (TOA) method. The time captured and the distance between the PD source and arrival time showed that the relationship is proportional to one another.

Keywords: Partial discharge, AE sensor, arrival time, PD source, propagation wave.

1. Introduction

PD refers to electrical discharge occurring within a portion of dielectric material in between two electrodes that will open a circuit. PD can be initiated by floating microbubbles filled with methane or air in liquid dielectric and subjected to an electric field [1]. PD existence within the insulation is due to aging factor and electrical overstressing on the voids or cracks occurred during manufacturing. PD usually occurs in power transformer [2–12] and power cable [13–18] that lead to poor delivery of power supply to consumer. Thus, any sign of failure should be detected at earlier stage to avoid any economically destructive consequences. PD in power cable can effectively be detected by using a sensor called Rogowski Coi [19] and PD in power transformer is preferably detected using an AE sensor called piezoelectric [20–22].

The acoustical measurement of PD is based on the audible or ultrasonic noise generated from the PD. This technique uses piezoelectric sensors or transducers arranged outside the transformer wall [23,24]. For PD detection using acoustic method, some parameters must be observed and one of them is the velocity of wave propagation [25]. In allocating the PD source, it is commonly considered that the acoustic wave propagates in a direct line. In this paper, all the reflections and refractions of the acoustic waves in different materials that contribute to obstruction, are considered negligible.

To determine the PD location, the arrival time of propagation waves onto the sensor is referred to.
Hence, several sensors are installed on the external of the transformer wall. In this study, four AE sensors were installed to detect the signal. The arrival times of those sensors are then compared, and the location of the PD can be identified.

This simple acoustic system is more suitable for field use due to its immunity to electromagnetic interference [21]. However, the acoustic method is not noise-proof as the transformer itself will produce a mechanical vibration. Since the frequencies of these vibrations are smaller than those generated by the PD, hence their occurrences as well as other noises from outside of the tank are negligible in this study.

2. AE Sensor Placement

PD source is possible to occur in the transformer tank and can referred by using the coordinate \((x_{\text{act}}, y_{\text{act}}, z_{\text{act}})\) that is in meter (m). The three possible PD sources are identified as PD1 = (0.545, 0.68, 0.6) at core 1, PD2 = (0.258, 0.25, 0.35) at core 2 and PD3 = (0.248, 1.0, 0.55) at core 3. The analysis is based on the empty transformer tank filled with only transformer oil.

Based on suggestion from previous research [22], three different cases were defined for the placement of AE sensors mounted outside the transformer tank sized 0.936m\(^3\). Figure 1 shows the side of the transformer where all the sensors were placed.

![Figure 1. Illustration of the transformer tank include the side here the sensor are mounted, the dimension of the transformer and the possible PD sources.](image)

The sensors’ coordinates were shown in Table 1. As indicated in Table 1, the sensors for cases 1 and case 3 were placed at the four sides of the transformer in different heights. For case 2, the sensors were also placed at the four sides of the transformer but at the same height.

| Sensor Coordinate | Case 1 (x (m)) | Case 2 (x (m)) | Case 3 (x (m)) | Case 1 (y (m)) | Case 2 (y (m)) | Case 3 (y (m)) | Case 1 (z (m)) | Case 2 (z (m)) | Case 3 (z (m)) |
|-------------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| x (m)             | 0.00          | 0.40          | 0.20          | 0.00          | 0.00          | 0.00          | 0.40          | 0.40          | 0.40          |
| y (m)             | 0.00          | 0.40          | 0.20          | 0.00          | 0.00          | 0.00          | 0.40          | 0.40          | 0.40          |
| z (m)             | 0.20          | 0.70          | 0.20          | 0.20          | 0.70          | 0.20          | 0.45          | 0.45          | 0.45          |

3. Simulated PD Signal

PD signal was simulated using MATLAB software according to Equation 1 [14,17,26].

\[
s(t) = A[e^{-a_1t}\cos \omega_d \theta - e^{-a_2t}\cos \theta] / I
\]

Where, \(A\) is the magnitude coefficient assumed to be 0.01, \(a_1 = 1 \times 10^6s^{-1}\), \(a_2 = 1 \times 10^7s^{-1}\), \(\theta = \tan^{-1}\frac{\omega_d}{a_2}\), \(\omega_d = 2\pi f_d\), and \(f_d = 1 MHz\). The simulative sampling frequency, \(f_s = 100 MHz\).

From previous research [27], it was found that the propagating velocity in the transformer oil differed
according to the temperature of the oil. The study showed that at a low temperature, a limiting maximum velocity appeared thus as the temperature rises, the propagation velocity drops off dramatically [27].

Propagation velocity of oil used in this paper is \( V_{oil} = 1431 \text{ms}^{-1} \) at 20\(^\circ\)C oil temperature [21,22,28]. The propagation velocity is used in computing the time delay for the simulated PD signal. The PD pulse was simulated by using mathematical model as shown in Equation 1. The time delay was recorded and measured in Table 2, based on the first arriving signal at the sensor.

| PD Location | Case | Arrival Time (\(\mu\)s) |
|-------------|------|------------------------|
|             |      | T1    | T2    | T3    | T4    |
| PD1         | Case 1 | 420.41 | 481.89 | 500.72 | 559.89 |
|             | Case 2 | 207.80 | 395.57 | 457.13 | 497.15 |
|             | Case 3 | 332.16 | 450.41 | 472.89 | 490.88 |
| PD2         | Case 1 | 208.55 | 384.01 | 683.36 | 774.50 |
|             | Case 2 | 212.72 | 339.89 | 475.89 | 743.72 |
|             | Case 3 | 316.53 | 348.75 | 482.26 | 779.78 |
| PD3         | Case 1 | 236.78 | 458.08 | 603.78 | 748.22 |
|             | Case 2 | 245.19 | 307.80 | 462.06 | 710.28 |
|             | Case 3 | 257.33 | 386.88 | 518.11 | 714.57 |

Figure 2 and Figure 3 shows the simulated signals of PD1, PD2 and PD3 occurring at core 1, core 2 and core 3 for cases 1, 2 and 3. Each case comprises four sensors and each sensor is denoted as T1, T2, T3 and T4. The signals captured using 100MHz sampling frequency at 10000 sampling length and the amplitude of the PD signal for every case is set approximately at 4.16m \( V_p \).

Figure 2d - 2f show the simulated signals of PD2 that occurred at core 2 for cases 1, 2 and 3. Case 1 as shown in Figure 2d and case 2 in Figure 2e suggesting the distance between PD source and sensor were alike as the captured signals are almost identical. But for case 3 as shown in Figure 2f, the PD2 source is closer to T1, T2 and T3 but further away from T4.
Figure 2. Simulated PD1 signal (a-c) and PD2 signal (d-f) at each sensor for case 1, case 2 and case 3

Figure 3 shows the simulated PD3 signal that occurred at core 3 for cases 1, 2 and 3. Based on the arrival time for all the four sensors in case 1, 2 and 3, the PD source can be estimated as not far from all the four sensors in four different cases.

Figure 3. Simulated PD3 signal at each sensor for (a) case 1, (b) case 2 and (c) case 3.

4. Distances between PD Source and AE Sensor

This section analysed the distances between the PD source and the sensor. The distance between two nodes which are PD source and the sensor, is shows by Equation 2.

\[
\text{Distance} = \text{Velocity (ms}^{-1}\text{)} \times \text{Arrival Time (s)}
\]  

(2)

According to Equation 2, velocity is the wave propagation of light in the oil which is \(1431\text{ ms}^{-1}\) within \(20^\circ\text{C}\) [22] and the arrival time is recorded in Table 1, the distance between the PD source and the sensor is shown in Table 3.

| PD Location | Case   | Distance (m) |
|-------------|--------|--------------|
| PD1         | Case 1 | 0.6016       |
|             | Case 2 | 0.5661       |
|             | Case 3 | 0.6445       |
| PD2         | Case 1 | 0.2974       |
|             | Case 2 | 0.4864       |
|             | Case 3 | 0.4991       |
| PD3         | Case 1 | 0.3388       |
|             | Case 2 | 0.4056       |
|             | Case 3 | 0.3065       |
Based on Table 2 and Table 3, the value of time is increased based on the distance. The increment of the values can be further determined based on Figures 4a, 4b and 4c for PD1, PD2 and PD3, respectively.

The further the distance between PD source and the sensor, the longer the signal took to arrive to the sensor. Hence, the arrival time indicates that the PD source is further away from the sensor.

5. Conclusion

This study theoretically investigated the relationship between the distance and the arrival time of the PD propagation wave. In particular, the study focused on the correlation between the different arrival time due to the distance between the PD source and the AE sensor. The propagating wave speed is set constantly at $1431 \text{ m s}^{-1}$ at $20^\circ C$. Consequently, this study found that the results of the arrival time is proportional to the change of distance. Therefore, the time of signal arrival is depending on the distance between the PD source and the AE sensor placement. However, the accuracy of this study strongly depends on the cumulative energy captured by the AE sensor since the AE sensor converts the signal into an electrical energy.

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