Study of Localization of Partial Discharges in Oil-filled Transformers using Acoustic Emission Signals

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ABSTRACT

The measurement of partial discharges (PD) in power transformers is crucial for fault detection and maintenance scheduling. In this paper, the relationship between detection intensity, type of PD source and propagation distance is investigated using an acoustic emission (AE) sensor. The AE wave intensity by the corona discharges are relatively strong. Creeping discharges were next, followed by PD in bubbles. Furthermore, two methods for calculating time difference of arrival (TDOA) in locate calculations, energy reference and generalized cross-correlation (GCC), were experimentally compared. The results showed that the energy reference method is suitable when sensors can be placed around the tank, while the GCC method is suitable when sensors are concentrated in specific parts of the tank. This finding may contribute to improving the accuracy of maintenance diagnostics.

1. ELECTRONIC SUBMISSION

Electrical insulation of power facilities plays an important role in ensuring the safe and proper operation of the power system. However, degradation of electrical insulation is accelerated by abnormal troubles caused by surroundings and manufactural errors, such as chemical, electrical and mechanical stresses and internal defects. This can lead to partial discharge (PD), which is a localized breakdown in the electrical insulation that occurs when stress is applied to a specific defective area. PD increases the intensity of the discharge and eventually leads to electrical insulation breakdown, causing significant economic losses and threatening the safety and stability of the power system. To prevent these incidents, it is essential to carry out PD diagnostic tests with appropriate PD source detection in the power system. This enables the scheduling of maintenance measures for power facilities.

PD detection sensors can be used for PD condition monitoring, including high frequency current transformers, Ultra high frequency (UHF) antenna and AE sensors. Sensing technology of AE, which is suitable for use in transformers due to its prevention to external electromagnetic interference, can detect PD non-invasively.

It is essential to carry out PD diagnostic tests with appropriate PD source detection, PD source location in the power system. This enables the scheduling of maintenance measures for power facilities. The use of AE sensors is widely adopted to identify the source of PD. Each AE sensor is mounted at a known location on the surface of transformer tank and measures the TDOA of sound waves travelling from the PD source to the AE sensor. If the speed of sound in the transformer oil or metal tank is known, the distance between the PD source and the AE sensor can be calculated from the TDOA; acoustic waves from the PD are detected by suitable sensors mounted on the wall of the transformer tank and their output can be analyzed by conventional data acquisition systems. There is an acoustic positioning system used combined acoustic/electrical. It uses a current, voltage or electromagnetic wave measuring device that can electrically detect PDs in combination with an AE sensor array.

In the case of the TDOA method, as many non-linear equations as the number of AE sensors need to be solved to estimate the coordinates of the PD source. Various researchers have used different methods to solve these equations (Gillette, M. et al, 2008), (Mirzaei, H., et al. 2013). Acoustic signals (sound waves) generated by PD events can propagate along many different paths to reach the AE sensor. Their waveforms are complex in nature, overlapping with other metamorphic waveforms due to reflection, refraction, attenuation, diffraction in different materials, complex structures in the transformer, etc.

In this paper, the TDOA technique for AE sensors was investigated to improve the accuracy of the discharge location technique, applying GCC method to the calculation of the location of multiple AE sensors. The effectiveness of the method was confirmed by experiments.

2. EXPERIMENTAL SETUP

Figure 1 shows the experimental configuration used to measure the PD in the model tank of a simulated transformer. The model tank, which is made of steel, has dimensions of 400 mm on each side and is 3 mm thick. Mineral oil is used to fill the tank.

Three PD sources were used: corona from protrusions, creepage discharge and PD in bubble. The specifications of each PD source are given in Table 1. The corona caused by protrusions simulates that generated in real transformers when metallic particles in oil adhere to the surface of a high-voltage conductor due to an electric field. It consists of an electrode with a diameter of 10 mm, a radius of curvature of 10 µm at the tip and an insulation distance of 10 mm. Creepage discharges, on the other hand, simulate PDs that occur when the support of the coil is reduced due to the deterioration of the insulating paper, resulting in a high electric field due to the H.V. conductor and the insulating paper. It consists of a PB electrode of 10 mm diameter and 2 mm thickness. PD in bubble simulates PD in a bubble generated by the attraction of dissolved air in oil to a high electric field point. Bubbles were introduced between flat electrodes with a diameter of 10 cm using a syringe.

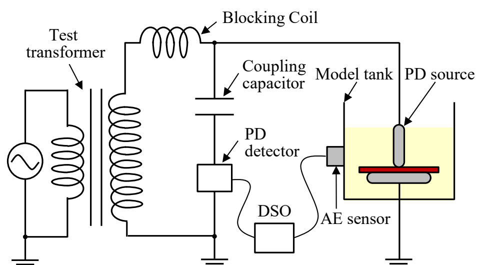
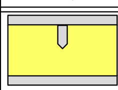
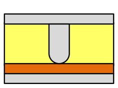
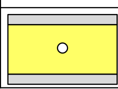
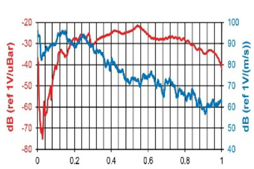


Figure 1. This is an example of figure caption.

Table 1. PD sources.

PD source	Image	Assumed event
Corona from protrusion		Metal particle in the oil adhere to the surface of H.V. conductor due to the electric field, causing a PD.
Creepage discharge		Deterioration of the insulating paper reduces the coil support. Discharge occurs due to proximity and high electric field between the charging section and the insulation paper.
PD in bubble		Dissolved air in the oil is attracted to high electric field points. Discharge occurs in the bubble.



(a) Appearance of AE sensors (b) Detection characteristics.

Figure 2. AE sensor (Physical acoustic, WD AH 17).

At each position on the surface of the model tank, an electrode and five AE sensors (Physical acoustic, WD AH 17) were placed. Figure 2 shows used AE sensors. AC voltage at 60 Hz was applied to the electrodes to generate PD, and the resulting PD current pulses were measured using a digital oscilloscope, a coupling capacitor, and a PD detection circuit. Simultaneously, the acoustic waves generated by the PD were detected using five AE sensors and measured on an oscilloscope through an amplifier with a 40 dB gain. The digital data were recorded at a sampling rate of 20 MS/s and 50 k points for each measurement.

3. EMISSION AND PROPAGATION OF AE WAVE

Figures 3 show experimental results of PD signals using the creepage discharge model. The signals of the two sensors are shown here. AE Sensor A is 440 mm away from the PD source and it can be seen that AE sensor A detects the signal 370 µs after the PD detector detects the PD signal. Similarly, AE sensor B is 200 mm away from the PD source and AE sensor A detects the signal 170 µs after the PD detector detects the PD signal. From these, it can be calculated that the propagation speed of AE waves is 1.2 km/s. The propagation speed of AE waves in oil depends on the oil temperature but is generally between 1.1 km/s and 1.5 km/s, which is also consistent with these results.

The detected signal strength of AE sensor A is 13 mV and that of AE sensor B is 20 mV, and the detected signal strength varies according to the PD strength, the trend of which is shown in Figure 4. The figure shows the relationship between PD intensity and detection intensity when the creepage discharge model is used and the distance from the PD source to the AE sensor is 150 mm, 300 mm and 450 mm. It also shows that the larger the distance between the PD source and the AE sensor, the smaller the detection intensity.

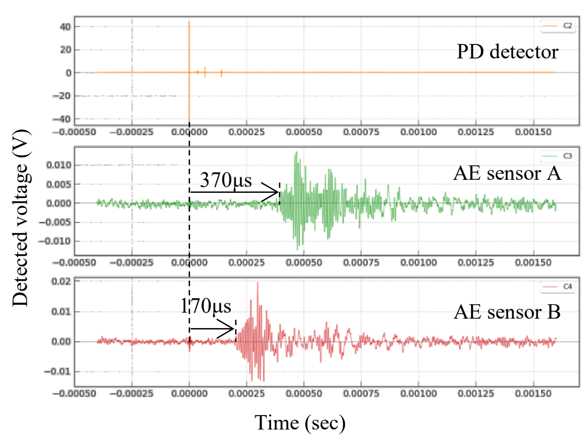


Figure 3. AE signal waveform
(using the creepage discharge model).

A comparison of detection sensitivity for different PD sources is shown in Table 2. The AE sensor sensitivity was obtained experimentally when a PD occurred at each PD source. In this table, the sensitivity at a PD intensity of 100 pC is compared here. The AE wave intensity by the corona discharges are relatively strong. Creeping discharges were next, followed by PD in bubbles. Corona discharges are considered to produce stronger AE waves because the discharge space is concentrated at the tip of the needle electrode. In creepage discharges, the AE wave intensity is smaller because the discharge spreads radially from the electrode over a wide area and the propagation speed of the discharge is slow. In PD in bubbles, the discharge space is within the bubble and the AE wave intensity is considered to be small.

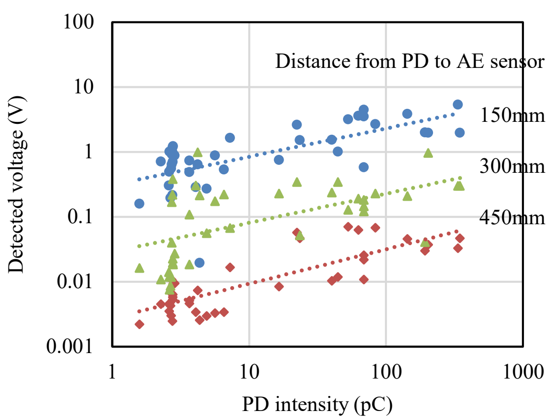


Figure 4. AE signal waveform
(using the creepage discharge model).

Table 2. Comparison of Detection Sensitivity of Different PD sources.

PD source	Corona from protrusion	Creepage discharge	PD in bubble
AE Sensors	1	0.54	0.23
UHF antenna	1	0.76	0.85

4. Localization Method

4.1. Overview

An AE signal is generated and detected by sensors located at different positions when a PD occurs. By measuring the TDOA of each sensor, the co-ordinates of the PD can be calculated using a geometric triangulation algorithm; in three-dimensional space, the TDOA of each sensor can be used with four or more sensors to construct the following non-linear equation. This equation can be solved numerically using the Newton-Raphson iteration method to calculate the discharge position (x, y, z).

$$\begin{cases} \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} = c*(T_1) \\ \sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2} = c*(T_1+t_{12}) \\ \sqrt{(x-x_3)^2+(y-y_3)^2+(z-z_3)^2} = c*(T_1+t_{13}) \\ \sqrt{(x-x_4)^2+(y-y_4)^2+(z-z_4)^2} = c*(T_1+t_{14}) \end{cases} \quad (1)$$

where (x_i, y_i, z_i) are the coordinates of the sensor, i = 1, 2, 3, 4, c is the propagation velocity of the AE wave, T_1 is the signal arrival time of sensor 1, t_{1n} is the time reference of the other sensors to sensor 1, n = 2, 3, 4. In the case of multiple PD sources. The predictive localization error can be calculated using the following equation, where (x_d, y_d, z_d) are the estimated positions.

$$e = \sqrt{(x-x_d)^2+(y-y_d)^2+(z-z_d)^2} \quad (2)$$

4.2. Calculation of TDOA using Energy Criterion Method

The energy reference method is used to calculate the time of arrival of the AE wave for each sensor; using S(t) as an indicator, the time at which the minimum value is obtained is determined by the formula below.

$$S(t) = \sum_{i=1}^{t} v_i^2 - t\delta \quad (3)$$

$$\delta = \frac{\sum_{i=1}^{N} v_i^2}{N} \quad (4)$$

In this equation, v_i represents the detected voltage, and N represents the number of samplings. The first term on the right side of equation (3) is the cumulative energy obtained by integrating the squared detected voltage up to any time t. The second term is the sum of the cumulative energy over the entire region, as shown in equation (4), and averaged over the region, denoted as δ. The difference between these terms yields S(t). The TDOA can be obtained from the difference in the calculated arrival times of the AE waves for each sensor.

4.3. Calculation of TDOA using GCC method

Acoustic signals propagate by reflection, because the interior of power transformers contains structures such as windings and insulating paper. Therefore, AE sensors are reached by reflected waves via multiple paths in addition to direct waves. However, only the difference in arrival time through the direct path from the PD source to the multiple receivers is used for positional targeting. Other components caused by reverberation need to be excluded as noise. One method to suppress the effects of reverberation is the TDOA calculation method using the GCC function (Chaogei, G. et al, 2018).

$x_i(t)$ and $x_j(t)$ are the time waveforms of these sensors. $X_i(\omega)$ and $X_j(\omega)$ are the coefficients obtained by the short-time Fourier transform. [*] denotes conjugation. The GCC function of the signals of these sensors is expressed as eq. (5). This is a coupled operation in the time domain, where the output is zero at frequencies where the components are different for the these sensors; $\Psi_{ij}(\omega)$ corresponds to a frequency filter, here a BPF centered at 100 kHz where the detected components are large.

$$R(\tau_{mn}(r_s)) = \frac{1}{2}\int \psi_{mn}(\omega) X_i(\omega) X_j^*(\omega) e^{j\omega\tau}\, d\omega \quad (5)$$

$\tau_{ij}(r_s)$ is the TDOA between these sensors. It quantifies the time difference between acoustic waves from the same source propagating to these sensors along the shortest path, respectively. According to the definition, it is described as follows:

$$\tau_{mn}(r_s) = (||r_d - r_i|| - ||r_d - r_m||)/v \quad (6)$$

where r_s is the positions of the PD source and r_i and r_j are the positions of these sensors, v is the propagation velocity of AE wave. The maximum likelihood estimation of position r_s is described as follows:

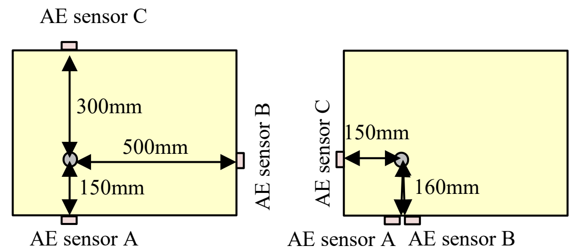
$$r_s = \text{argmax}_{r_s}\left(\sum_{i=1}^{M}\sum_{j=i+1}^{M} R(\tau_{ij}(r_s))\right) \quad (7)$$

4.4. Comparison of Two Methods to Calculate of TDOA

The effectiveness of the two TDOA calculation methods was experimentally compared: the AE sensors were evaluated under two different conditions: a dispersed arrangement and a centralized arrangement, as shown in Figure 5. In the dispersed arrangement, AE sensors were placed around the simulated tank, while in the centralized arrangement, AE sensors were placed in one corner of the tank. The tests used corona from a protrusion, with discharge intensities ranging from 100 to 1000 pC.

The results are shown in Figure 6. The Energy Criteria method was found to be more accurate for dispersed placement, while the GCC method was more accurate for concentrated placement; the Energy Criteria method demonstrated a stable signal detection timing reading, although it is difficult to specify accurately. The GCC method, on the other hand, provides a more detailed TDOA calculation, but its calculation scheme may be compromised by the attenuation of each sensor's detection waveform with distance from the PD source, resulting in reduced similarity. It is expected that this can be improved by selecting a more detailed window function $\Psi_{ij}(\omega)$.

It was therefore concluded that the Energy Criteria method is suitable when sensors can be placed around the tank, while the GCC method is suitable when sensors are concentrated in a specific part of the tank. This finding may contribute to improving the accuracy of maintenance diagnostics.



(a) Distributed placement (b) Centralized placement
Figure 5. Experimental Configuration.

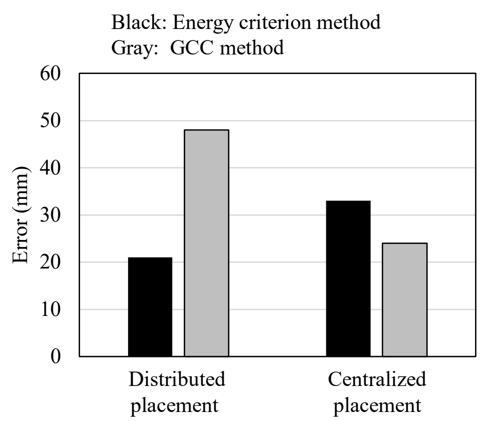


Figure 6. Experimental Result of Comparison of Two Methods to Calculate of TDOA.

5. Conclusion

The detection and localization of PD in power transformers is of great importance for maintenance scheduling: the discharge detection characteristics using AE sensors were investigated and the relationship between discharge source and propagation distance and detection intensity was clarified. Furthermore, two calculation methods for TDOA in locating calculations were experimentally compared. It was therefore concluded that the Energy Criteria method is suitable when sensors can be placed around the tank, while the GCC method is suitable when sensors are concentrated in a specific part of the tank. This finding may contribute to improving the accuracy of maintenance diagnostics.

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