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Partial Discharge Localization in Transformers Using Monopole and Log-Spiral UHF Sensors

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Abstract: The location of a partial discharge (PD) source inside a transformer can be determined from the time differences of arrival (TDOA) between signals that are captured by an array of UHF sensors. From these, the PD location can be found by geometric triangulation which involves solving a set of non-linear equations. This can be achieved using an efficient software realization of the maximum-likelihood estimator. The recorded PD waveforms are affected by the type of sensor used to capture PD signals. In this paper, the accuracy of the PD localization using different sensors is investigated. Two types of sensor, i.e. short monopole and log-spiral are used to capture electromagnetic waves emitted from a PD source. To calculate the TDOA, two methods: first peak and cross-correlation were applied. The localization result shows the monopole sensor produces higher accuracy than the log-spiral and the first peak method achieves better result than the cross-correlation method.

Keywords: partial discharge location, ultra-high frequency (UHF) sensors.

INTRODUCTION

Knowing the exact location of partial discharge (PD) sources inside a power transformer not only provides information about the presence of PDs but can also help engineers in determining the severity of insulation defects and speeding up the repair process.

The ultra-high frequency (UHF) detection of PDs involves the use of UHF sensors (antennas) to capture the fast electromagnetic transients emitted from the discharge site. This detection method has proven viable in monitoring the insulation condition of GIS. It is now being extended and applied to transformer diagnostics [1,2]. In order to determine the PD location, a distributed array of 4 sensors is used to record PD signals simultaneously and enable triangulation. The received signals can be processed to determine the arrival time difference between them. Localization of the PD source then can be determined from the time difference of arrival (TDOA) between the sensors.

The captured PD waveforms pattern is affected by the particular sensor design. Different type of sensors has different frequency response thus they produce different waveforms even for the same PD excitation. This paper discussed PD localization by applying two types of sensors, i.e. monopole and log-spiral, to detect the PD source. For comparison, the sensors were installed at the same locations and captured signals emitted by a PD source inside an oil-filled transformer tank.

BACKGROUND THEORY

Time Difference of Arrival (TDOA)

The arrival time of PD signals at specific sensors can be acquired by selecting the first peak of the oscillating PD signals [3-5]. This method requires simple procedures and less calculation. However to determine the first peaks itself is not always an easy process, especially if the PD waveform has a lot of oscillations at its front.

The TDOA also can be determined by analysing the similarity of the PD waveforms. Due to the fact that the waveforms produced by the same PD source and sensors are similar, thus the PD waveforms should have similar pattern. By evaluating the similarity between waveforms, the TDOA can be determined.

Another method is to examine the cumulative energy of the PD signal [3-6]. From the energy curve, the time difference between signals is determined by finding the knee point where the change is sudden [3, 5]. The drawback is that human judgment is required to decide on the knee point [3]. To avoid ambiguity due to potential human error, the TDOA can be acquired from the similarity between the cumulative energy curves [3, 5, 6]. Due to the fact that PD signals may undergo multiple reflections during their propagation, it was proposed using only part of the PD waveforms to extract the energy curves [6]. This approach resulted in a higher degree of accuracy but it still relies on human judgment and thus possible interpretation error. In a previous study by the authors [7], it was found that the first two methods mentioned above give better result and also more computationally efficient. Thus in this paper, these methods are applied to determine the TDOA and used to locate the PD source.

Locating the PD source

The distance of the PD source to any sensor i such as the composition shown in Fig. 1 can be calculated using the Pythagorean theorem:

$$r_i^2 = (x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 \quad (1)$$

where (x, y, z) are the coordinates of the PD source and (x_i, y_i, z_i) are the coordinates of sensor i. To determine the PD source, it is necessary to operate at least four sensors to record PD signals at simultaneous times. When the signals arrive at each sensor, there will be an arrival time difference between the sensors. As the sensors' positions are known, the PD location can be calculated.

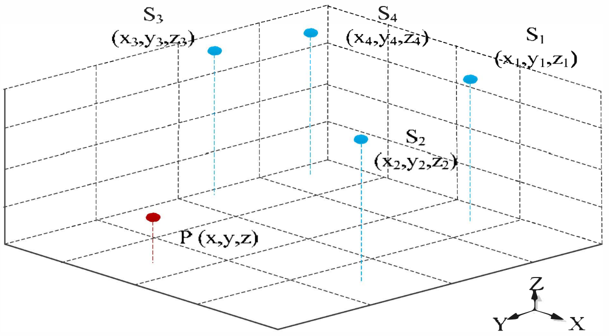


Fig. 1. Coordinate system of the PD source P (x, y, z) and sensor S_i (x_i, y_i, z_i).

When four sensors are applied to capture PD signals, the coordinate of the PD source can be written in terms of the distance between the PD source and a reference sensor [8]. Without loss of generality, choose (r_4) as the reference sensor, it can be shown that:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = -\begin{bmatrix} x_{14} & y_{14} & z_{14} \\ x_{24} & y_{24} & z_{24} \\ x_{34} & y_{34} & z_{34} \end{bmatrix}^{-1} \times \left\{ \begin{bmatrix} r_{14} \\ r_{24} \\ r_{34} \end{bmatrix} r_4 + \frac{1}{2} \begin{bmatrix} r_{14}{}^2 - K_1 + K_4 \\ r_{24}{}^2 - K_2 + K_4 \\ r_{34}{}^2 - K_3 + K_4 \end{bmatrix} \right\} \quad (2)$$

where (x,y,z) are coordinates of PD source, (x_{i4}, y_{i4}, z_{i4}) denote differences in coordinates between sensor i and the reference sensor (sensor 4), r_{i4} is the TDOA between sensor i and sensor 4 times the speed of the PD signal in oil, r_4 is the distance of sensor 4 to the PD source and K_i is calculated as $K_i = x_i^2 + y_i^2 + z_i^2$. Note that all the parameters on the right-hand side of Equation 2 are known except r_4. Utilizing this equation, one can substitute x,y,z in term of r_4 into Equation 1 and solve that quadratic equation. The positive root value of r_4 acquired from Equation 1 is then inserted back into Equation 2 to determine the PD source coordinates.

EXPERIMENT

Ultra-High Frequency (UHF) Sensor

Two types of UHF sensor were used to detect PD signals; they are monopole and log-spiral as shown in Fig. 2. The monopole sensor is a straight conductor mounted on a printed circuit board (PCB). The length of the conductor is 10 cm. The log-spiral sensor is a tapered log-spiral shape etched onto the surface of a single layer PCB and a six-section balun is used to connect the sensor to the coaxial cable. The diameter of the log-spiral shape is 10 cm.

Another important aspect of sensor characteristics for PD localization purpose is the pulse response. Knowing the step response means that the most suitable sensor for PD location application can be selected. For the purpose of PD localization, the sensor with the least oscillation response and therefore the fastest to reach maximum energy is the most suitable [3, 4]. The lowest level of oscillation means that the first peaks of the signals are easier to pick up. Thus error due to false determination of the peaks can be minimised. Fig. 4 shows the step-pulse response of both monopole and log spiral sensors. The monopole had a faster response with the least oscillation. A similar response was given by the conical with just slight oscillation. The spiral had the most oscillation in its response with the peaks of the signals distorted.

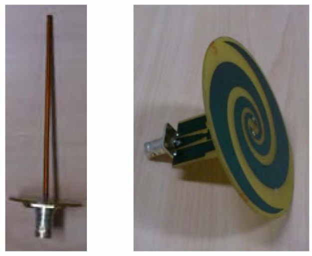
(a)  (b)

Fig. 2. Sensors used: (a) Monopole, and (b) Log-spiral

The sensor frequency response up to 2 GHz is shown in Fig. 3. The monopole has high response at lower frequency but decreases at higher frequency. The log-spiral has a better characteristic: the response is higher and flatter than the monopole's.

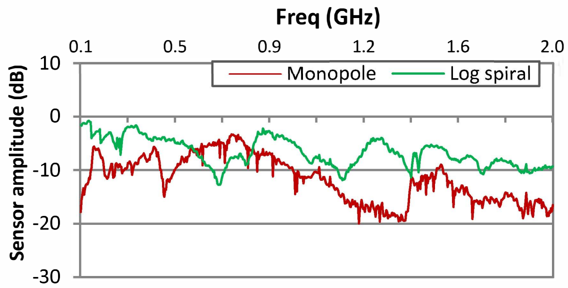


Fig. 3. Frequency response of the Monopole and Log-spiral sensors.

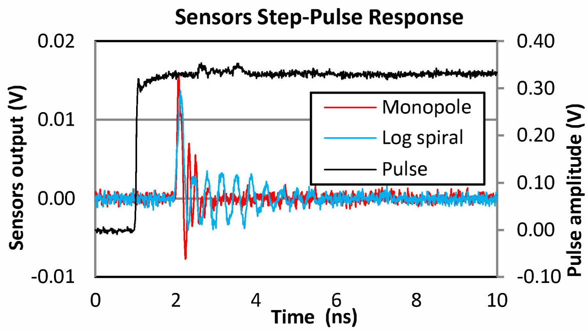


Fig. 4. The step-pulse response of both sensors.

Experimental Set-up

Fig. 5(a) shows the experimental diagram. Four UHF sensors of both types were used to capture PD signals. Their outputs were connected to a 4-channel digital oscilloscope via coaxial cables of identical length. The sensors and the PD source are immersed in an oil-filled transformer tank (71.5 x 118 x 95 cm), and their coordinates are shown in Table 1.

The PD source is a needle-plate electrode arrangement. To generate discharges, the voltage was raised to 19 kV. An oscilloscope was used to record the PD signals. It has 40 Gs/s sampling rate for each channel and has a built-in computer system to record the data.

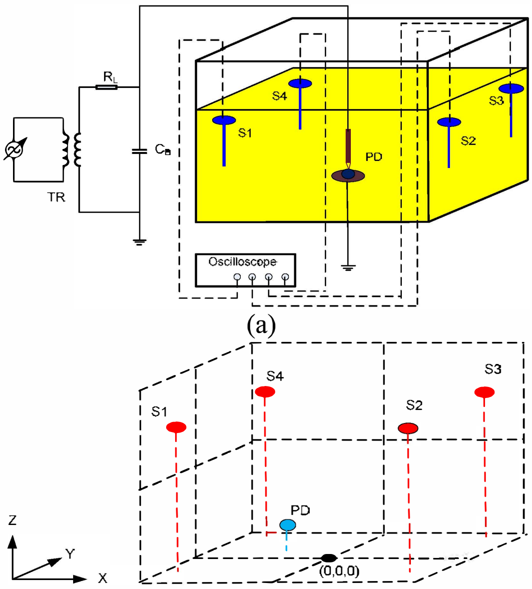


Fig. 5. Experimental setup: (a) layout and circuit for PD generation and detection, (b) coordinate system.

The coordinates of the sensors location are shown in Table 1. The origin of the coordinate system in relation to the transformer tank is shown in Fig. 5(b). The PD source is located at four different positions and their coordinates are shown in Table 2.

Table 1. UHF sensors position

	x (cm)	*y* (cm)	*z* (cm)
Sensor 1	-50	-25	48
Sensor 2	45	-20	46
Sensor 3	45	20	49
Sensor 4	-50	20	45

Table 2. PD source coordinates

Position No.	*x* (cm)	*y* (cm)	*z* (cm)
1	-11	5	37
2	-3	5	37
3	6	5	37
4	12	5	37

RESULTS AND DISCUSSION

PD Waveforms

Fig. 6 shows the typical waveforms recorded by both sensors. The waveforms show slight difference. As the log-spiral has more oscillatory pulse response, the PD waveform recorded using this sensor has longer oscillation than the monopole. The log-spiral sensor signal has slightly larger magnitude as this sensor has better sensitivity than the monopole. Since the purpose of the analysis is to determine the time difference of the arrival between signals, this is not essential but nevertheless a desirable characteristic.

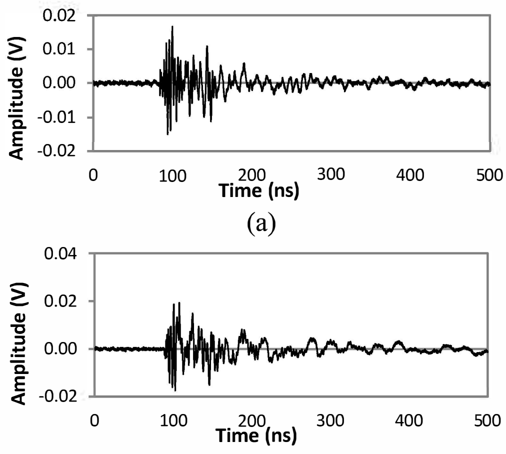


Fig. 6. Typical PD waveforms recorded by different sensors: (a) Monopole, and (b) Log-spiral

The First Peak Method

When signals in the transformer tank propagate in the same manner in all directions, sensors will capture the same PD pulse then produce similar waveforms. The time difference between signals can then be determined from the first peaks of the waveforms recorded by different sensors. To avoid error due to the presence of noise, waveform can be denoised [5] and/or a threshold value used as the minimum limit of the first peak [3, 5]. The first peak is defined as the first occurrence of a peak where the value exceeds a specific threshold.

The procedure to determine the time difference between the first peaks of two PD signals is as follows:

1. Denoise the original signal by applying multivariate denoising tool. The denoising process is done to the PD signals captured at the same time by the sensors.
2. Process both original and denoised signals to make the waveforms unipolar, achieved by taking absolute value of each point of the waveform.
3. Normalize so all waveforms have same magnitude.
4. Choose the same threshold setting, for example 25% of the signals maximum magnitude.
5. Pick the first peak point above the threshold value by applying the peak point detector. This point is then used to determine the arrival time.
6. Calculate the time difference between the two first peaks of PD signals.

The calculated TDOAs are then used to locate the PD coordinates. Table 3 shows coordinates of the PD location based on measurements by both sensors.

The Cross-Correlation Method

Cross-correlation can be used to measure the similarity of two waveforms as a function of a time lag applied to one of them. One waveform is considered in stationary position and the other is shifted toward the stationary one. Then, the similarity of the waveforms is calculated. The cross-correlation value is the largest when waveforms are most similar and aligned to each other. When both waveforms show high similarity then the product of the two functions is more positive. For perfectly uncorrelated, such as a random function, the cross-correlation value is zero. The cross correlation $f(n)$ of two discrete functions $g(m)$ and $h(n)$ which are time series of finite duration is defined as:

$$f(n) \equiv \frac{1}{N} \sum_{m=0}^{N-|n|-1} g(m)h(n+m) \tag{3}$$

where N is the number of data points.

The PD location coordinates calculated using the cross-correlation method are shown in Table 4. The location accuracy for both sensors is shown in Table 5.

Table 3. PD location calculated using first peak method.

PD loc.	Monopole x,y,z (cm)	Log-spiral x,y,z (cm)
1	-2.21, 0.58, 44.21	0.66, 7.5, 48.93
2	-1.51, 0.98, 33.36	-0.53, 1.22, 73.1
3	-1.59, 0.59, 40.97	-2.26, 8.6, 43.47
4	-1.79, 1.56, 61.11	-0.58, 4.34, 64.81

Table 4. PD location using cross-correlation method.

PD loc.	Monopole x,y,z (cm)	Log-spiral x,y,z
1	-3.58, 6.74, 68.85	-0.44, 0.3, 78.85
2	-3.56, 4.58, 64.46	-0.3, 2.3, 49.23
3	-4.35, -2.60, 8.66	-0.31, 0.48, 70.11
4	-4.64, 5.93, 16.63	-0.71, 2.66, 65.96

Table 5. Average errors of the PD localization: (a) monopole, (b) log-spiral.

PD Loc.	First Peak (cm)		Cross-correlation (cm)	
	(a)	(b)	(a)	(b)
1	12.20	16.86	32.75	47.28
2	5.62	36.38	27.47	16.67
3	9.63	11.09	31.12	37.91
4	27.99	30.53	26.31	35.40
Average	13.84	23.71	29.41	34.32

Localization Accuracy

It can be seen from Table 5 that the monopole sensor gives better location accuracy than the log-spiral sensor. For all PD source locations and methods, the monopole sensor has lower error except for location 2 using cross-correlation method. For both sensors, the first peak method gives higher accuracy than the cross-correlation method. The higher error of the log-spiral sensor is probably produced as a result of the oscillation near peaks of the pulse as shown by the step-pulse response and longer oscillation.

CONCLUSION

The sensor characteristic strongly affects the captured PD waveform. The monopole sensor has lower sensitivity but has less oscillation. The time difference of arrival (TDOA) of the PD signals can be acquired from the recorded PD waveforms. Based on the TDOA, the PD location then can be determined.

PD localization results show the monopole sensor produces higher accuracy than the log-spiral sensor. Using the first peak method, the average error resulted by the monopole sensor is 13.84 cm whilst the log-spiral sensor produces error up to 23.71 cm. The first peak method resulted in higher accuracy than the cross-correlation method for both sensors. The average errors of PD localization using the cross-correlation method are 29.41 cm and 34.32 cm for monopole and log-spiral sensors respectively.

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