UHF Sensor Array for Partial Discharge Location in Transformers

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***Abstract*—The application of the ultra-high frequency (UHF) partial discharge (PD) detection method has proven effective in GIS. This method is now also being applied to detect PDs in oil-filled power transformers. In this paper, the localization of the PD source in transformer is discussed. This is achieved by applying an array of four sensors to capture the PD signals at the same time. To determine the PD location, two methods (first peak and cross-correlation) are used to determine the difference in time of arrival between sensor signals and followed by numerical triangulation. The sensor positions and array size influence the PD waveform patterns captured, and thus the accuracy of the PD localization. Experimental results and analysis indicate the first peak method yields better location accuracy than the cross correlation method. However, the traditional external acoustic detection method performs better than the UHF detection method under the same test configurations.**

Keywords-Partial discharge; Ultra high frequency; Localization; Time difference of arrival (TDOA)

I. Introduction

The ultra-high frequency (UHF) detection of partial discharge (PD) has proven effective in checking the insulation condition of GIS. This technique is now being developed and applied to transformer diagnostics [1]. The PD detection involves the use of internal UHF sensors (antennas) to capture the fast electromagnetic (EM) transients emitted from the discharge site. This is in contrast to the traditional acoustic/ultrasonic detection method which employs piezoelectric sensors mounted externally on the transformer tank to detect the PD-induced pressure waves [2].

The UHF detection method offers a number of advantages over the traditional method. Apart from the reduced sensitivity associated with external sensors, the pressure waves propagate in different modes through liquids (transformer oil) as compared to solids (core, tank) and often a direct path is not the quickest path thus causing significant localization error. On the other hand, the installation of internal UHF sensors in a transformer can be an issue. Also, due to the very fast velocity of the EM waves, the UHF method requires a measuring system with much higher resolution than the acoustic setup.

To locate the PD location, a distributed array of four sensors can be utilized to record PD signals simultaneously and enable triangulation. The time of arrival (TOA) of the PD signals at each sensor can be used to calculate the time difference of arrival (TDOA) between each sensor pair. Localization of the PD source then can be determined from a set of three TDOA values.

In the transformer oil medium, the EM waves emitted by the PD source travel slower than the speed of light but still very fast (~$2x10^8$ m/s). This makes measurement difficult especially within the space limitation of a transformer tank. The transformer tank is usually limited to a few meters; hence the flight time of the electromagnetic signal lies within a range of nanoseconds only.

To increase the arrival time difference between sensors and thus facilitate accurate time difference determination, sensors can be installed at positions far apart, such as on opposing sides of the transformer tank. However, the physical characteristics of the paths through which the signals propagate are more likely to be different. The result is that the propagation time is no longer directly proportional to the distance. Also, complications arise from reflections and refractions. This can lead to higher location error. To combat this problem, the sensors can be installed in close proximity to each other [3]. By installing them in this manner, the PD signals can then be very similar. The tradeoff is that the time difference between signals will decrease which can be difficult to measure accurately.

In this paper, the PD signals were recorded by using UHF sensors arranged in a square array and positioned on one side of the transformer tank. External acoustic sensors with a similar arrangement were used for comparison. The signals were recorded in two conditions: with and without presence of a barrier between the PD source and the sensors.

II. Signal Time Difference of Arrival (TDOA)

The arrival time of PD signals at specific sensors can be determined based on the first peak occurrence in the PD waveforms [4]. The procedure is simple and requires little calculation. However, to recognize the first peak itself is not always straightforward, especially if the PD waveform is highly oscillatory and corrupted by noise.

The TDOA can also be determined by analyzing the similarity (correlation) among the PD waveforms. Due to the fact that the received signals are produced by the same PD source and the sensors are similar, the PD waveforms should have similar pattern. By time shifting to optimize alignment between waveforms, the TDOA can be determined.

Another method is to derive the cumulative energy from the recorded PD signal [5]. By examining this energy curve, the knee point where the change in value is sudden is then used to work out the TDOA [5]. The drawback is that human judgment is required to decide on the knee point [5]. To avoid ambiguity due to potential human error, the TDOA can be acquired by using software to perform cross-correlation between the cumulative energy curves [5]. Due to the fact that PD signals may undergo subsequent multiple reflections during their propagation, it would be better to select only the beginning part of the PD waveforms to extract the energy curves [3]. This results in better accuracy but again it requires visual inspection to truncate the waveforms.

A previous study conducted by the authors [6] found that the above first two methods give better location accuracy and also more computationally efficient. Thus, these two methods will be applied in this paper to determine the TDOA and used to locate the PD source.

III. LOCATING THE PD SOURCE

The distance of the PD source to any sensor i such as the composition shown in Figure 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 be able to determine the PD source from a single measurement, 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.

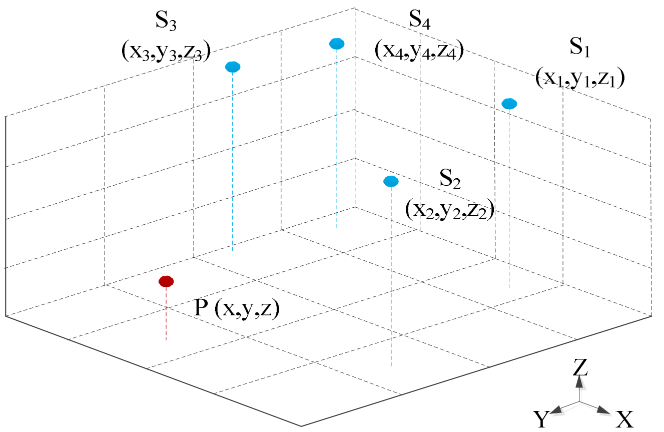

Figure 1. Coordinate system of the PD source P (x, y, z) and sensor S (x_1, y_1, z_1).

When four sensors are used for measurement, the coordinate of the PD source can be written in terms of the distance between the PD source and a reference sensor. 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 the coordinates of the 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 propagation velocity of the EM waves 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 input back into Equation 2 to determine the PD source coordinates.

IV. EXPERIMENT SET-UP

The experiments were conducted using a small transformer tank with dimension of 71.5 cm width, 118 cm length and 95 cm height. The tank was filled with mineral oil up to 50 cm of depth. The core and winding were removed from the tank.

Four UHF mono-pole type sensors were used to capture the PD signals [2]. Their outputs were connected to a 4-channel digital oscilloscope via coaxial cables of identical length. The sensors were installed in a square array arrangement with distance of 40 cm between them.

The PD source is a needle-plate electrode configuration. For testing purposes, it was moved to different locations with coordinates as shown in Table 1. The origin of the xyz coordinate system in relation to the transformer tank is shown in Figure 2.

The UHF sensor array was installed inside the transformer tank. For comparison, an acoustic sensor array was also used in the experiment to locate the PD source. These are PAC (type R15I) resonant sensors with built-in 40dB pre-amplifier. The typical operation range is from 100kHz to 450kHz and the resonant frequency is ~160kHz.The acoustic sensor array was mounted outside the transformer tank, with the distance of the sensor to each other similar to that of the UHF sensor array.

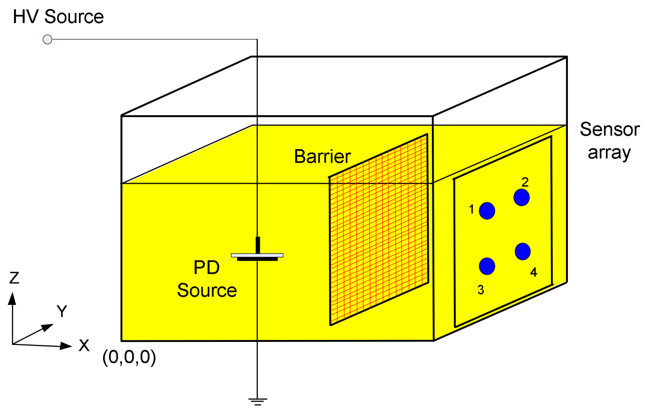

Figure 2. Experiment arrangement

TABLE I. PD SOURCE COORDINATES

Position No.	x (cm)	y (cm)	z (cm)
1	57	60	30
2	57	35	30
3	57	10	30

V. PD SIGNALS PROPAGATION AND WAVEFORM PATTERNS

According to the well-known Maxwell's theory, the propagation velocity of electromagnetic waves in a given medium is $v = 1/\sqrt{\mu\varepsilon}$ where μ is the permeability and ε is the permittivity of the medium. In air, the propagation velocity is the speed of light (i.e. $3x10^8$ m/s). In oil, it would be slower because of its higher permittivity as compared to air, the latter has a relative permittivity of 1. Due to lack of manufacturer data for the relative permittivity of the oil used, experiments were conducted to determine the speed of the electromagnetic waves emitted by the PD source and propagating in oil. This was found to be $2x10^8$ m/s (i.e. two thirds the speed of light). On the other hand, the velocity of acoustic pressure waves in oil is much slower compare to the electromagnetic signal. In transformer oil, it varies from around 1240 m/s to 1300 m/s at oil temperature of 30^0C to 50^0C [7]. Consequently, acoustic measurement does not need a very fast oscilloscope whereas the UHF system requires a sampling rate in excess of 5 Gs/s.

The electromagnetic and acoustic signals generated by the PD source inside the transformer tank will travel in all directions. During the course of propagation, the signals may encounter internal barriers or the transformer tank and thus reflection and/or refraction may occur. This can distort the signal waveforms, resulted in different waveform patterns and can lead to error in the TDOA values [6].

The PD signal patterns are also very much affected by the sensors location. Different locations may produce different patterns. This might be because the initial wavefront of the field radiated by the PD source may not be uniform in all directions. Also the PD signals may be attenuated along its path, and the density of the oil could be non-uniform and thus the velocity of the signals changes [6].

To reduce the effect signal propagating through different physical media on the received waveforms, the sensors can be installed in close position. Figure 3 and 4 show typical PD waveforms recorded by different sensors in the experiment. It can be seen that the waveforms produced by sensors in close position have quite similar pattern. However, as the sensors are closer the arrival time difference between signals is reduced accordingly. This will adversely affect the accuracy of measurement.

VI. TIME DIFFERENCE OF ARRIVAL CALCULATION

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A. First peak method

Assuming the signals in the transformer tank propagate in same manner toward all directions, the sensors will capture the same PD pulse and produce similar waveforms. The arrival time difference between signals then can be determined from the first peaks of the waveforms recorded by different sensors. The first peak is defined as the first time instant when the signal amplitude exceeds a certain level [6]. Requirement of a minimum finite threshold is necessary to counter the presence of noise in the signals which is unavoidable even after the application of software denoising.

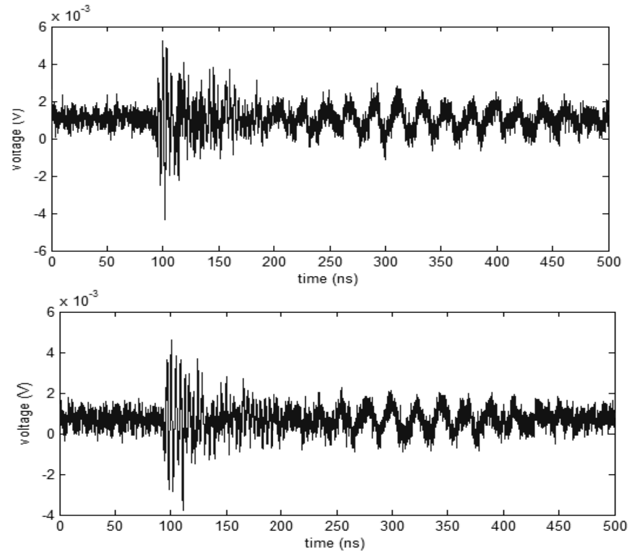

Figure 3. Typical time domain of PD waveforms captured simultaneously by two UHF sensors of the array

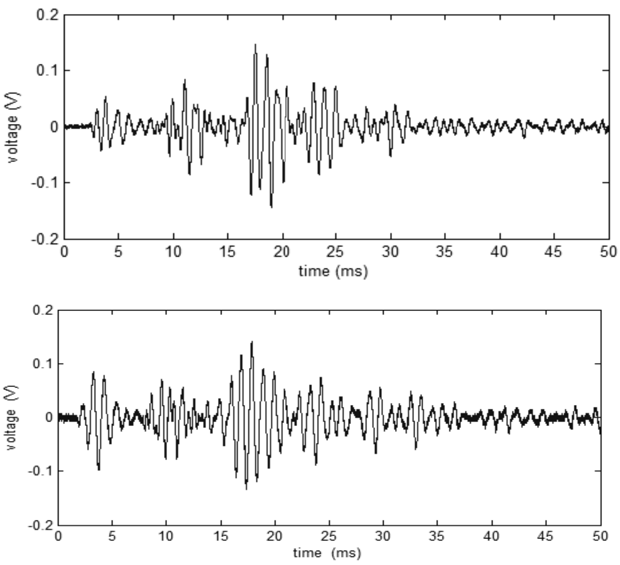

Figure 4. Typical time domain of PD waveforms captured simultaneously by two acoustic sensors of the array

The procedure to determine the TDOA between the first peaks of PD signals captured by 2 sensors is as follows [6]:

1. Normalize the signals so that all waveforms have the same maximum magnitude.
2. Choose the same threshold setting, for example 25% of the maximum magnitude.
3. Identify the first peak point above the threshold value (automatically determined with software). This point is then used to determine the arrival time.
4. Calculate the time difference between the two first peaks of the PD signals.

B. Cross-correlation method

The TDOA between two sensor signals also can be determined by applying cross-correlation between the signals. Cross-correlation measures the similarity between 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. The similarity between these two waveforms is then calculated. The TDOA is determined as the location where the cross-correlation curve reaches its peak. For perfectly uncorrelated such as random functions, the cross-correlation value is zero.

The cross correlation *f(n)* of two discrete functions *g(n)* and *h(n)* is defined as:

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

where N is the number of data points.

VII. PD LOCALIZATION ACCURACY

By placing sensors in a 40x40 cm square array arrangement, the recorded PD waveforms are very similar. This eliminates effect of dissimilarity of the signals due to the different propagation paths of the signals, and also the refraction and reflection affecting the electromagnetic signals during its traveling. However, this arrangement also makes the time difference between signals small and sometimes the recorded signals show no time difference. The error of the PD localization by using UHF PD detection method is shown in Table 2. The presence of barrier did not show significant effect, probably due to the small distance of the sensor to the PD source. The first peak method produces better accuracy than the cross correlation method. The average errors are 18.7 cm and 22.8 cm for the first peak and cross correlation method respectively.

Table 3 shows the calculated PD source coordinates using the acoustic method. The results show higher accuracy than the UHF method with average error as low as 7.8 cm for the first peak method and 10.9 cm for the cross correlation method. The accuracy of the acoustic method is relatively similar for the three PD locations with little variation. The acoustic signals travel in much longer time than the electromagnetic signals (over the same distance) thus produce larger time difference. Similar to UHF method measurement results, the acoustic waveforms captured by the sensors of the array have very similar patterns. The first peak method yields better accuracy than the cross correlation method for both PD measurements.

TABLE II. AVERAGE ERRORS OF THE UHF DETECTION METHOD (A) WITHOUT BARRIER,(B) WITH PRESENCE OF BARRIER

PD Loc.	**First Peak (cm)**		**Cross-correlation (cm)**	
	(a)	(b)	(a)	(b)
1	21.3	21.7	22.3	24.4
2	19.8	20.2	14.6	15.6
3	15.2	14.5	31.7	33.4
average	18.7	18.8	22.8	24.5

TABLE III. AVERAGE ERRORS OF THE ACOUSTIC DETECTION METHOD (A) WITHOUT BARRIER,(B) WITH PRESENCE OF BARRIER

PD Loc.	**First Peak (cm)**		**Cross-correlation (cm)**	
	(a)	(b)	(a)	(b)
1	8.5	11.3	9.1	16.5
2	7.2	12.6	12.2	15.5
3	7.9	12.3	11.4	19.2
average	7.8	12.1	10.9	17.1

VIII. CONCLUSION

PD sensors installed in an array arrangement with short distance between sensors will capture similar waveforms. This will help in the comparison of waveforms to work out the arrival time difference between the signals. However, the arrival time difference will become small as well and result in higher location error. By virtue of the much slower propagation velocity of the acoustic pressure waves, the relative time difference associated with the acoustic detection method is always higher than that of the UHF method and so the accuracy of the latter is inferior. For the particular experiment setup used in this work, the best average accuracy of the UHF method is 18.7 cm without presence of barrier whilst for the acoustic it is 7.8 cm, both with the first peak method.

REFERENCES

[1] M.D. Judd, L. Yang, and I.B.B. Hunter, "Partial discharge monitoring for power transformers using UHF sensors Part 2: Field Experience", *IEEE Electrical Insulation Magazine*, Vol. 21, No. 3, pp. 5-13, 2005.

[2] B.T. Phung, T.R. Blackburn, and Z. Liu, "Acoustic measurements of partial discharge signals", Journal of Electrical and Electronics Engineering, Australia, Vol.21, No.1, 2001, pp.41-47.

[3] Z. Tang, C. Li, X. Cheng, W. Wang, J. Li, and Jun Li, "Partial discharge location in power transformers using wideband RF detection", IEEE Trans. on Dielectrics and Electrical Insulation, Vol. 13, No. 6, 2006.

[4] H.H. Sinaga, B.T. Phung, P.L. Ao, and T.R. Blackburn, "Partial discharge localization in transformers using UHF sensors", 30th Electrical Insulation Conference (EIC), Annapolis USA, June 5-8, 2011, pp. 64-68.

[5] P. Kakeeto, M.D Judd, J. Pearson, and D. Templeton, "Experimental investigation of positional accuracy for UHF partial discharge location", Conf. on Condition Monitoring and Diagnosis, Beijing, China, pp.1070-1073, 2008.

[6] H.H. Sinaga, B.T. Phung, and T.R. Blackburn, "Partial discharge localization in transformers using UHF detection method", IEEE Trans. on Dielectrics and Electrical Insulation, paper 3436, accepted for publication.

[7] E. Howells, and E.T. Norton, "Parameters affecting the velocity of sound in oil", IEEE Trans. Power Apparatus Syst., Vol.103, May 1984, pp. 1111-1115.