COMPARATIVE STUDY OF PARTIAL DISCHARGE LOCALIZATION BASED ON UHF DETECTION METHODS

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ABSTRACT

Partial discharge (PD) monitoring is essential for insulation diagnostic of high voltage power transformers. PD activities can generate electromagnetic waves in the ultra-high frequency (UHF) range. The signals captured from several antennas installed inside the transformer can be analyzed to determine their time of arrival (TOA) and time difference of arrival (TDOA). Then by solving non-linear triangulation equations, the position of the PD source can be found for corrective action. This paper examines the effect of the sensor position on the S-parameter regarding the UHF sensor performance for PD detection. A comparative study of the methods in terms of PD localization based on the UHF method is then carried out. Acoustic, UHF and HFCT sensors are applied in the experiment. The results show that the transformer tank boundary can affect the sensor performance in capturing the signal and the acoustic-UHF triggering method has the highest level of accuracy.

1. INTRODUCTION

The operating condition of power transformers is critical in electricity distribution networks. An effective condition monitoring system can protect these installations in case of unexpected electrical insulation failure. Partial discharge is a typical cause, resulting in insulation breakdown and may lead to a serious fault if not treated at an early stage. Thus, detection of PD occurrence in transformers is important. Recently, on-line condition monitoring systems provide an effective way to guide regular maintenance and take precautions against unexpected power outage.

Localization of PD sources helps to fast-track the maintenance process since repair can be carried out in a targeted way. For PD monitoring purpose, HF, UHF and acoustic methods have been proposed for online PD monitoring in power transformers. The first method uses high frequency current transformers (HFCT) to detect the magnetic field resulting from PD activities [1]. The UHF method uses antennas to detect electromagnetic waves radiated from the PD source. The acoustic method uses piezoelectric sensors to detect the pressure waves. The acoustic and UHF methods can be utilized for PD localization, and the steps for TOA/TDOA method are shown in Fig.1. Considering the sensors are placed at different positions, the PD-induced signal will arrive at the sensors at different time instants, which lead to several time differences of arrival. These parameters can be utilized to estimate the PD position through numerical localization algorithms.

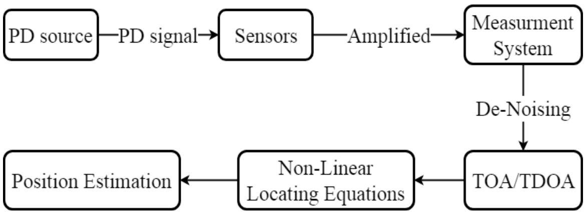


Fig.1 PD Localization Process

In previous research, [2], [3] have proposed the hybrid method for PD localization using both the acoustic method and the UHF method. To date, many contributions have focused on using these methods solely; few efforts have been devoted to comparison of these methods under identical experimental condition.

In this paper, laboratory experiments are carried out using a distribution transformer tank filled with oil but without internal active parts. The effect of the enclosing metal tank structure on the performance of an ultra-wide bandwidth UHF antenna is studied. Moreover, four localization mechanisms, namely the acoustic method, the UHF method and the acoustic method with UHF or HFCT triggering, are compared and evaluated based on the accuracy of position estimation.

2. PD LOCALISATION TECHNIQUES BASED ON TDOA AND TOA

The fundamental localization calculation is based on equation (1):

$$(x_s - x_k)^2 + (y_s - y_k)^2 + (z_s - z_k)^2 = (v_s \times \Delta T_k)^2 \qquad (1)$$

where (x_s, y_s, z_s) is the coordinate of the PD source; (x_k, y_k, z_k) is the position of the k-th sensor; ΔT_k is the time difference of sensing signal to reach the k-th sensor, and v_s is the propagation velocity of the sensing signal (acoustic or UHF signal) under experimental condition.

The schematics of localization using the TDOA and TOA are shown in Fig. 2. Fig. 2a illustrates the situation using four identical sensors: acoustic sensors or UHF sensors. In this regard, the signal from the PD source can be captured by these sensors, then three time-delays

(ΔT_{12}, ΔT_{13}, ΔT_{14}) between sensors S$_2$-S$_4$ and the reference sensor S$_1$ can be estimated. In such situation, the actual arrival time instant refers to the PD occurrence is not necessarily required, the position analysis is primarily based on the constant difference of the distance resulting from the TDOA, such as D$_3$-D$_1$ in Fig. 2c, which develops hyperbolas in two dimensions or hyperboloids in three dimensions for source positioning in the intersection area. Therefore, for the approach shown in Fig. 2a, equation (1) can be extended to equations (2-5):

$$(x-x_1)^2+(y-y_1)^2+(z-z_1)^2=(v_s\times\Delta T)^2 \quad (2)$$
$$(x-x_2)^2+(y-y_2)^2+(z-z_2)^2=[v_s\times(\Delta T+\Delta T_{12})]^2 \quad (3)$$
$$(x-x_3)^2+(y-y_3)^2+(z-z_3)^2=[v_s\times(\Delta T+\Delta T_{13})]^2 \quad (4)$$
$$(x-x_4)^2+(y-y_4)^2+(z-z_4)^2=[v_s\times(\Delta T+\Delta T_{14})]^2 \quad (5)$$

Another method for solving the locating problem is shown in Fig. 2b, which represents a hybrid approach to determine the position of the PD source. Here, the time instant when the signal is captured by a HFCT or UHF sensor is considered as the time origin when the PD occurs. Hence, the time differences between this triggering signal (HFCT or UHF sensor) and the acoustic sensors (T_2, T_3, T_4) is the absolute propagating time of the acoustic signal. To locating the source by TOA, equation (1) can be extended to (6-8) based on Fig. 2b:

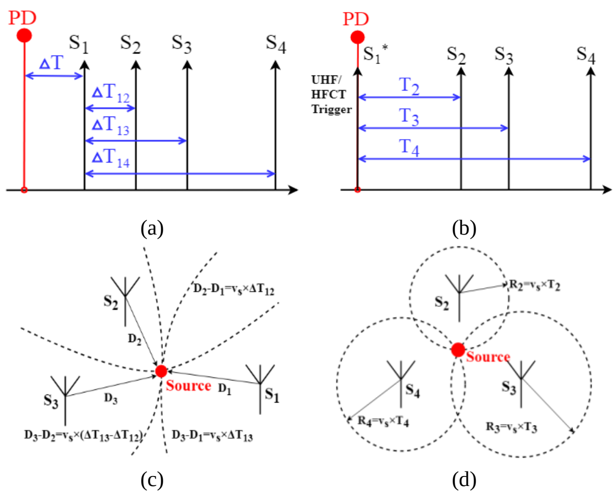
$$(x-x_2)^2+(y-y_2)^2+(z-z_2)^2=(v_s\times T_2)^2 \quad (6)$$
$$(x-x_3)^2+(y-y_3)^2+(z-z_3)^2=(v_s\times T_3)^2 \quad (7)$$
$$(x-x_4)^2+(y-y_4)^2+(z-z_4)^2=(v_s\times T_4)^2 \quad (8)$$

As shown in Fig. 2d, localization based on TOA is different from which derived by TDOA, the source is located in the intersection of the circular area in two dimensions or spherical area in three dimensions. To this end, note that four sensors should be applied to locate the PD source based on triangulation for both TOA and TDOA localization methods.

The coordinates of the PD source in three dimensions can be determined based on equation (9) [4]:

$$\begin{bmatrix}x\\y\\z\end{bmatrix}=-\begin{bmatrix}x_{12}&y_{12}&z_{12}\\x_{13}&y_{13}&z_{13}\\x_{14}&y_{14}&z_{14}\end{bmatrix}^{-1}\times\left\{\begin{bmatrix}r_{12}\\r_{13}\\r_{14}\end{bmatrix}\times r_1+\frac{1}{2}\begin{bmatrix}{r_{12}}^2-H_2+H_1\\{r_{13}}^2-H_3+H_1\\{r_{14}}^2-H_4+H_1\end{bmatrix}\right\} \quad (9)$$

where x_{1k}, y_{1k} and z_{1k} denotes the distance between the k-th (k=2,3,4) sensor and the reference sensor 1; r_{1k} is the time difference between sensor S$_1$ and sensor k times the speed of the signal propagation; r_1 is the distance between the reference sensor S$_1$ and the PD source; H_i is determined as $H_k=x_k^2+y_k^2+z_k^2$ (k=2,3,4), which is a constant when the sensor position is fixed.



(a) (b)

(c) (d)

Fig.2 Schematics of Time Delay Determination

3. EXPERIMENT SETUP AND PROCEDURE

To verify the effect of the transformer tank on the frequency response of the antenna, the experiment is conducted as shown in Fig. 3 using a vector network analyzer R&S® ZVL3 (frequency range up to 3 GHz). Before conducting the measurement, calibration is required to minimize the error caused by the connector and cable between the terminal and the test object (antenna). The calibration kit including the open-circuit terminal, short-circuit terminal and load terminal is used. Then, the antenna is connected to port 1 to get the S11 parameter, and the configuration of the surrounding grounded boundary condition (tank) can be altered by changing the position of the antenna from L$_1$ to L$_4$. The antenna used in this experiment is the UWB sensor proposed in [5] so that the result can assist the sensor installation in the subsequent localization setup.

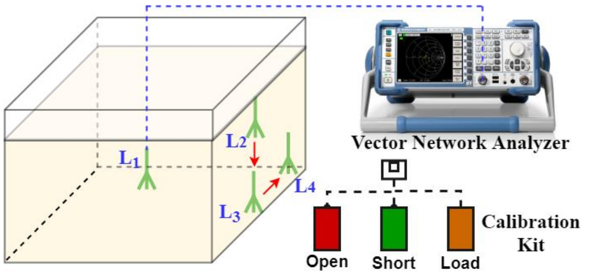


Fig.3 S11 parameter testing using VNA

In the next part, the experiment setup is developed as shown in Fig.4 in order to compare the accuracy of various localization methods. A needle-plate electrode arrangement is used as the PD source, immersed in a distribution transformer metal tank of dimension 1050mm × 580mm × 900mm filled with oil but the core and windings removed. The depth of the oil is 500mm. Four acoustic sensors are mounted at the tank wall outside the transformer, while four UHF sensors are submerged in the oil inside the tank. An HFCT is attached to the grounding line of the system.

For measurement, an Omicron's Mtronix MPD600 system which is IEC60270 compliant is used for monitoring PD occurrence. To record signals whose frequency range is lower than 200 MHz, i.e., acoustic and HFCT signals, a Keysight DSO1024A oscilloscope with

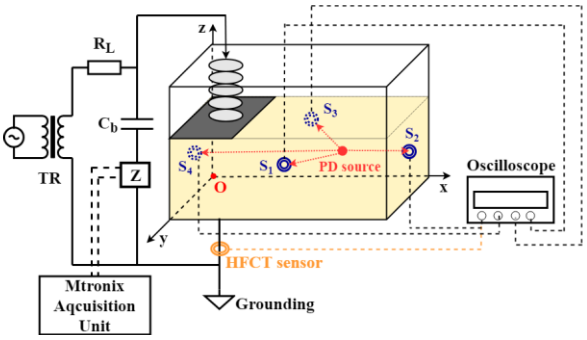


Fig.4 PD Localization Experiment Setup

four input channels is used and the sampling rate for this instrument is 2 GS/s. For UHF signals, a four-channel high sampling rate (40 GS/s) oscilloscope LeCroy WaveRunner 640Zi is employed.

As can be seen in Fig. 4, the three-dimension Cartesian coordinate system for reference is established and the coordinates of the sensors are fixed. The acoustic sensors S_{Ak} (k=1,2,3,4) and UHF sensors S_{Uk} (k=1,2,3,4) are placed externally and internally at the same horizontal and vertical position around the steel tank shown as S_k (k=1,2,3,4) in the figure; the position coordinates are considered as identical due to the small thickness of the tank wall. The sensor coordinates are listed in Table I. In the experiment, the location of the PD source is varied from Pos 1 to Pos 4 and the position information is also provided in Table I.

Considering there are four input channels on an oscilloscope, four measurement scenarios are carried out for comparison:

- Case 1: Four acoustic sensors (S_{A1}-S_{A4}) are used to capture the acoustic signals, and three TDOA values can be determined;
- Case 2: Four UHF sensors (S_{U1}-S_{U4}) are used to capture the EM signals, and three TDOA values can be determined;
- Case 3: One UHF sensor (S_{U1}) is used to pick up the triggering signal with three acoustic sensors (S_{A2}-S_{A4}) are used simultaneously, and three TOA values are determined;
- Case 4: One HFCT sensor is used as the triggering signal with three acoustic sensors (S_{A2}-S_{A4}) are used simultaneously, and three TOA values are determined.

TABLE I. SENSOR AND SOURCE COORDINATES FOR EXPERIMENT

Sensor Position	**Coordinate (mm)**
S_1	(610,580,320)
S_2	(1050,300,180)
S_3	(690,0,310)
S_4	(0,290,420)
Source Position	**Coordinate (mm)**
Pos 1	(720,300,130)
Pos 2	(620,350,130)
Pos 3	(820,250,130)
Pos 4	(720,250,130)

To achieve the four scenarios, AE sensors S_{A2}-S_{A4} are fixed to Channels 2-4 in Scenario 1, 3 and 4, while Channel 1 is altered by different reference signal (acoustic S_{A1}, UHF triggering and HFCT triggering). For Scenario 2, all channels are integrated with UHF antennas (S_{U1}-S_{U4}) and the connecting cables between the antenna and the measurement system have the same length in order to work out correctly the TDOA.

4. RESULTS AND DISCUSSION

Effect of the boundary condition

Regarding the UHF method for PD detection in power transformers, the sensors are usually inserted through the oil drain valve since there is no dedicated aperture for sensor installation, and the structure cannot be easily modified without power outage. When the sensors are installed in different positions in the transformer, the boundary condition is varied. This can affect the performance of the sensors because the grounding tank can influence the field distribution pattern around the antenna.

The S11 parameter, which represents the reflection loss of the antenna, is one of the significant parameters regarding the sensor performance. The loss decreases with the lower S11 value. The result of the S11 measured by the VNA can be seen in Fig. 5. The overall measurement frequency range is from 300 MHz to 3 GHz, while the S11 parameter will be mainly influenced by the physical surrounding over the range from 500 MHz to 1.5 GHz with a marked difference between various positions. This range is consistent with the frequency spectrum of the signal for PD activities immersed in the oil, which is between 300 MHz to around 1 GHz [6]. This contribution

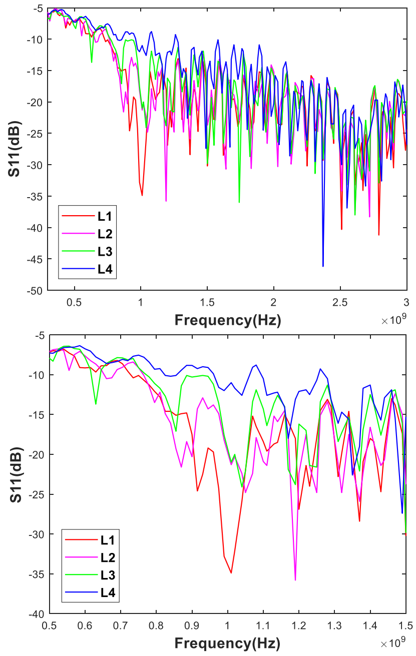


Fig. 5 S11 parameter at various positions L1-L4

is mainly based on [7], [8] which simulate the effect of the surrounding structure of the transformer tank on the antenna. The aim is to observe the appropriate position to place the UWB antenna in the transformer. The results indicate that L1 may be appropriate to install UHF sensors for lower reflection losses. However, it is not suitable for practical application in a real transformer with core and tank. L2 is considered in the localization evaluation experiment.

Locating performance evaluation

The basics of the localization techniques have been described in Section 2. The original signals captured by the oscilloscope are shown in Fig.6. To determine the TDOA and TOA values of each set of data, the first-peak method is employed which gives a higher accuracy compared to other methods such as correlation coefficient and cumulative energy [9]. The process of applying such method is described in Fig.7; the signal will be rectified after the unipolar process and non-linear scaling is applied to improve the determining of the time instant of arrival. A threshold value which is 20% of the normalized magnitude is chosen to mitigate the effect of the external interference.

Followed the TDOA and TOA calculations, the numerical elements in equation (9) are determined to work out the coordinates of the estimated positions. Apart from the distance between the fixed sensors, r_{1k} is dependent on the velocity of signal propagation. The propagation velocity of the acoustic wave in transformer oil can be affected by various factors including the oil type, the frequency range of the propagating signal, temperature, moisture content. Among these, temperature is a major factor for practical consideration [10]. The propagation velocity is approximately 1.4×10^5cm/s [10] for acoustic wave. As for the UHF signal, the velocity mainly relies on the permittivity of the medium. In this case, the velocity of the EM wave is 2.0×10^{10}cm/s in the oil insulation, which equals two thirds of the value in the air [9].

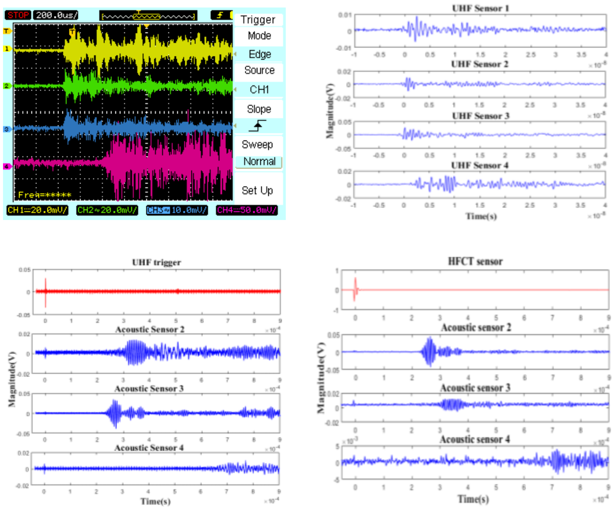


Fig.6 PD signals for localization

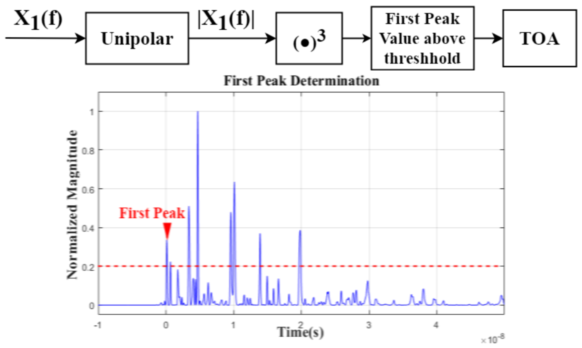


Fig. 7 TOA/TDOA determination by first peak

After solving the estimated position using equation (9), comparison of these four methods is conducted. In Fig. 8, the scatter plot shows the actual and estimated positions in the three-dimensional coordinates in terms of the four locating methods respectively. The degree of the scattering can be analyzed quantitatively by calculating the absolute distance between the actual and the estimated position, which is defined as the mean squared error (MSE) in equation (10):

$$MSE = \sqrt{(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2} \qquad (10)$$

where (x, y, z) is the estimated coordinate and (x_0, y_0, z_0) denotes the actual coordinate of the source position.

To evaluate the performance of the localization methods in statistics, the mean value and standard error of the MSE are calculated using equation (11) and (12) and compared in Fig. 9.

$$E(MSE) = \frac{\sum_1^n MSE_i}{n} \qquad (11)$$

$$Var(MSE) = E\left[\left(MSE - E(MSE)\right)^2\right] \qquad (12)$$

Pos	1	2	3	4
Actual	●	●	●	●
Estimated	•	•	•	•

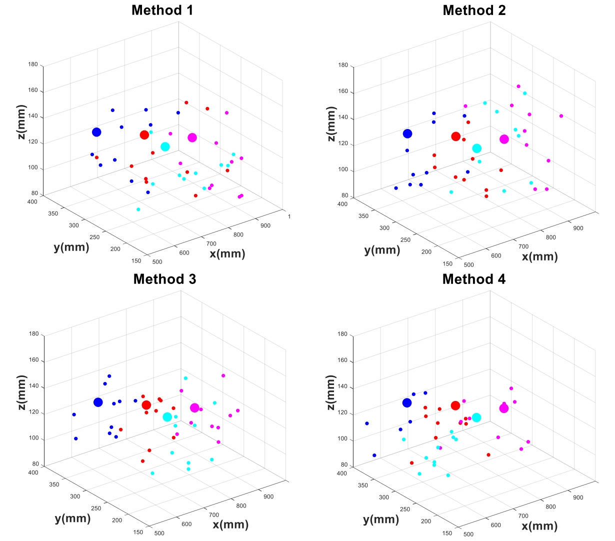


Fig. 8 Scatterplot of the localization results

By analyzing the results, UHF triggering has higher accuracy than the other methods. HFCT triggering has lower accuracy because the UHF sensor provides a faster response to the PD impulse, which is shown in Fig. 10.

The time delay ΔT_e can result in error between these two methods. Furthermore, the large error of the acoustic method may result from the signal propagating via the structure-borne path through the transformer tank rather than the direct path through the oil insulation. Also, the acoustic method is susceptible to external mechanical vibration, which can be another potential cause. On the other hand, for the UHF method, since the velocity of the EM wave propagation is very fast and the geometrical scale of the testing tank is small, the reflection and scattering of the signal can result in large errors.

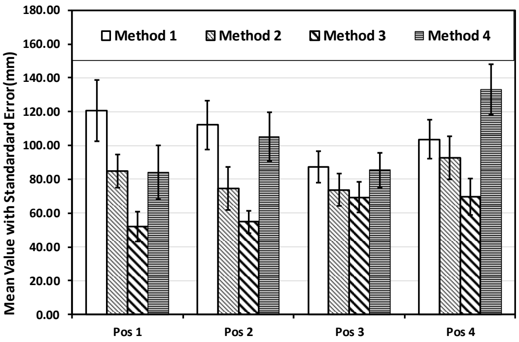


Fig. 9 Statistical comparison of the locating methods

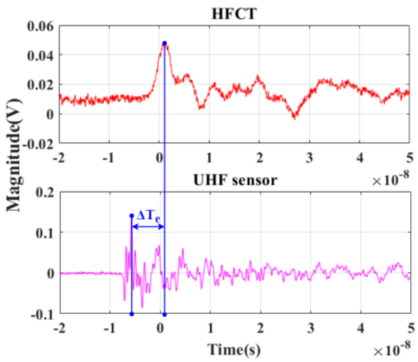


Fig. 10 Time delay between UHF sensor and HFCT

5. CONCLUSION

This paper examines the effect of the physical surrounding on the UHF sensor performance and evaluates the accuracy of PD localization in power transformer. The main results can be summarized as follows. Firstly, the transformer tank affects the reflection loss when receiving the induced EM signal. While the position in the center of the tank shows the lowest loss, the central area on the tank wall is more practical considering the real structure of the transformer with internal active parts. Secondly, among the four locating methods, the acoustic method with UHF triggering shows the lowest average error under the experimental condition.

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