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Denoising of UHF Signals based on RBPF and the Localization of PD Sources using FDTD Method in Power Transformer

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SUMMARY

In this study, to localize partial discharge sources, a time-difference look-up table method which compares the time-difference of simulated signals using finite-difference-time-domain (FDTD) with that of measurement data denoised by Rao-Blackwellised particle filter (RBPF) is proposed. The proposed method is a technique for estimating the position using direct comparison between the measured time-difference and the simulated time-difference database. Since the time-difference of signals which are arrived at UHF sensors located on different positions reflects the time-delay by the inside complex structures of a transformer, a time-difference look-up table method would be a more accurate approach to localize the partial discharges (PDs). In addition to the localization method, to improve the arrival time estimation, the raw signal is denoised by the RBPF. RBPF is capable of treating any type of probability distribution, nonlinear and non-stationary, and clean the broadband noise signal by directly modelling the statistical characteristics of the random noise. The accuracy of the proposed method with denoised measurement signal is verified through comparison with experiment results and compared with triangulation method. The average error using the proposed method has been estimated to be 371 *mm* while that of the triangulation method was 617 *mm*. Since PD activity is a random process and the signals emitted by a PD source cannot be specified with well-defined signals, the time-difference is the only information for PD source localization. Therefore, from this point of view, the time-difference look-up table method can be a very efficient method of the condition monitoring system for power transformers.

KEYWORDS

Denoising, Partial Discharges, Power Transformers, FDTD, Localization, UHF sensor

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1. Introduction

Accurate partial discharge (PD) localization is very important for both power grid management companies and transformer manufacturers. Recently, the localization of PD in power transformers by measurement of ultra-high frequency (UHF) electro-magnetic (EM) waves from a PD source is receiving increasing attention. Also, recognizing when PD occurs through UHF signals is very important since the PD phenomenon indicates the failure and fault of the insulation system in power transformers [1]. The UHF method has numerous advantages compared to traditional PD detection methods such as the IEC 60270 method. Since the UHF method detects signals of UHF band (0.3 GHz ~ 3.0 GHz) and UHF sensors are installed on tank walls which act as faraday cages, it is robust against external noise over the traditional electric PD detection method [2].

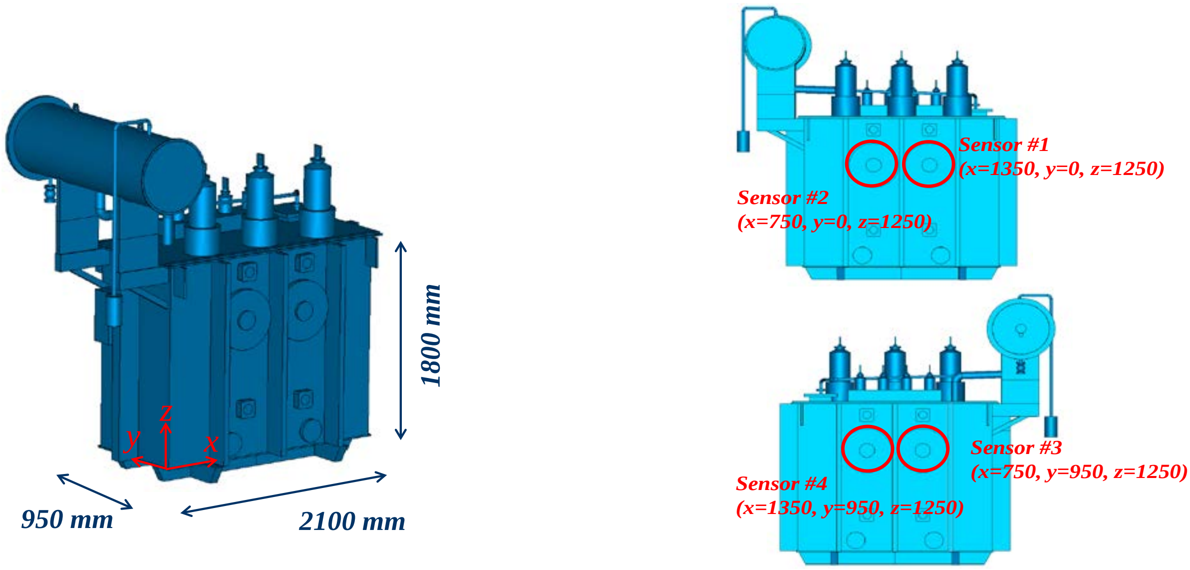
In the UHF localization method, internal UHF sensors are used to detect EM waves emitted by the PD phenomenon and the difference between the delay times of the EM waves reaching the antennas within the transformer are used to find the source of the PD. The signals measured by the UHF sensors are recorded with appropriate measurement instruments. If multiple internal UHF sensors are used, it would enable the localization of where the PD sources occur. However, one must take into account the effects of the physical size and position of the active part of the transformer in the EM wave propagation. Due to the different characteristics of the various materials used in the transformer, such as the dielectric constant and losses, EM waves will arrive at the antenna with different time delays and attenuation while propagating through these materials. PD localization is only determined from the time-difference of arrival (TDOA) of the signals. With accurate TDOA and appropriate localization algorithm, the PD location can be determined.

For accurate TDOA estimate, to eliminate the random noise of measurement data is important process. To remove the statistical random noise with nonlinear and non-Gaussian-distribution and improve the accuracy of the arrival time estimation, the Rao-Blackwellised particle filter (RBPF) was used [3]. RBPF is a way to efficiently represent non-Gaussian distribution and is a recursive Bayesian method for dynamic system state estimation. Also, RBPF is capable of treating any type of probability distribution, nonlinear and non-stationary, and clean the broadband noise signal by directly modelling the statistical characteristics of the random noise.

In this study, as a PD localization method, a time-difference look-up table method which compares the time-difference of the simulated signals using finite-difference-time-domain (FDTD) with that of measurement data was firstly presented. The accuracy of the proposed method was shown by comparison with experiment results. Since the time-difference arriving at the UHF sensors located on different positions reflects the time-delay by the inside structures of the transformer, it would be a more accurate approach to localizing the PDs.

2. Modeling and Simulation

To simulate TDOA, the CST MWS Studio software was used on a three-phase 3MVA power transformer with a 2100 *mm* × 950 *mm* × 1800 *mm* tank. Figure 1 shows the simulation model and sensing location to calculate the TDOA. As shown in Fig. 1, since the installation locations of the UHF sensors are restricted, the sensors were forced into a close arrangement. Although optimization of the sensor arrangement is important, the close arrangement was sufficient to studying and verifying the proposed localization method. As a PD source, a dipole antenna with a standardized voltage source (IEC 60270) was placed in pre-defined coordinates. The spacing between the PD sources was set to 150 *mm*. At each source position, simulation was performed, and after finishing, the time-difference among the sensors and source coordinates were stored. The stored data was utilized as a reference time-difference look-up table (see Table. 1) to localize the PD source position. Mesh lines for N_x, N_y, and N_z were 227, 117, and 142, respectively, and the total number of mesh cells was 3,600,858.



(a) (b)

Figure 1: Analysis model of power transformer - (a) the size of model and (b) sensor locations to detect the EM waves.

In Fig. 2, the flow chart of the time-difference look-up table method to localize the PD sources was summarized. Firstly, the simulated EM waves were recorded at four sensor locations as shown in Fig. 1(b). From the recorded data, the difference in arrival time with a reference sensor (sensor 4) was calculated. With the reference time-difference table, experiment data was compared using the root-mean-square-error (RMSE) method.

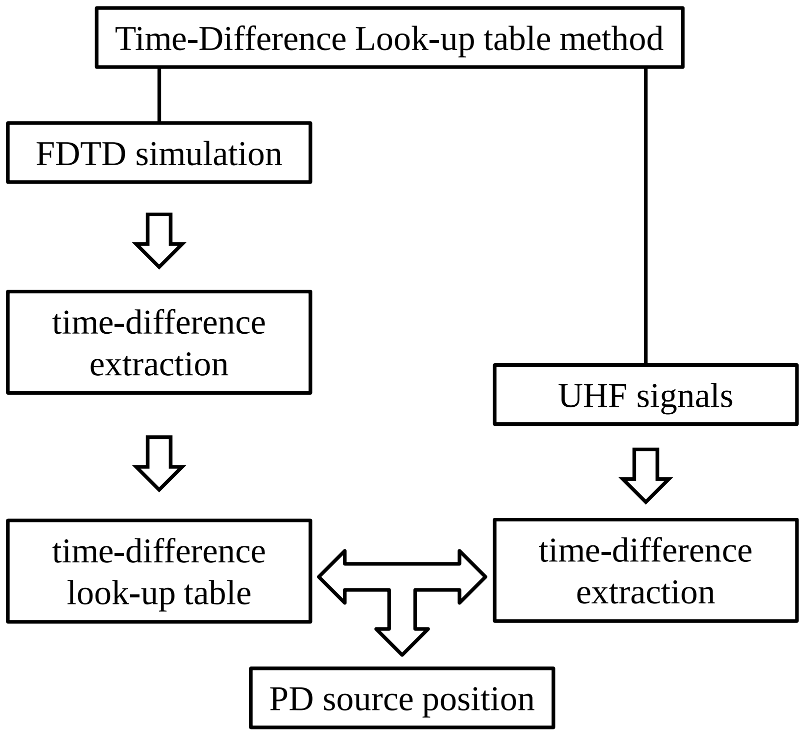
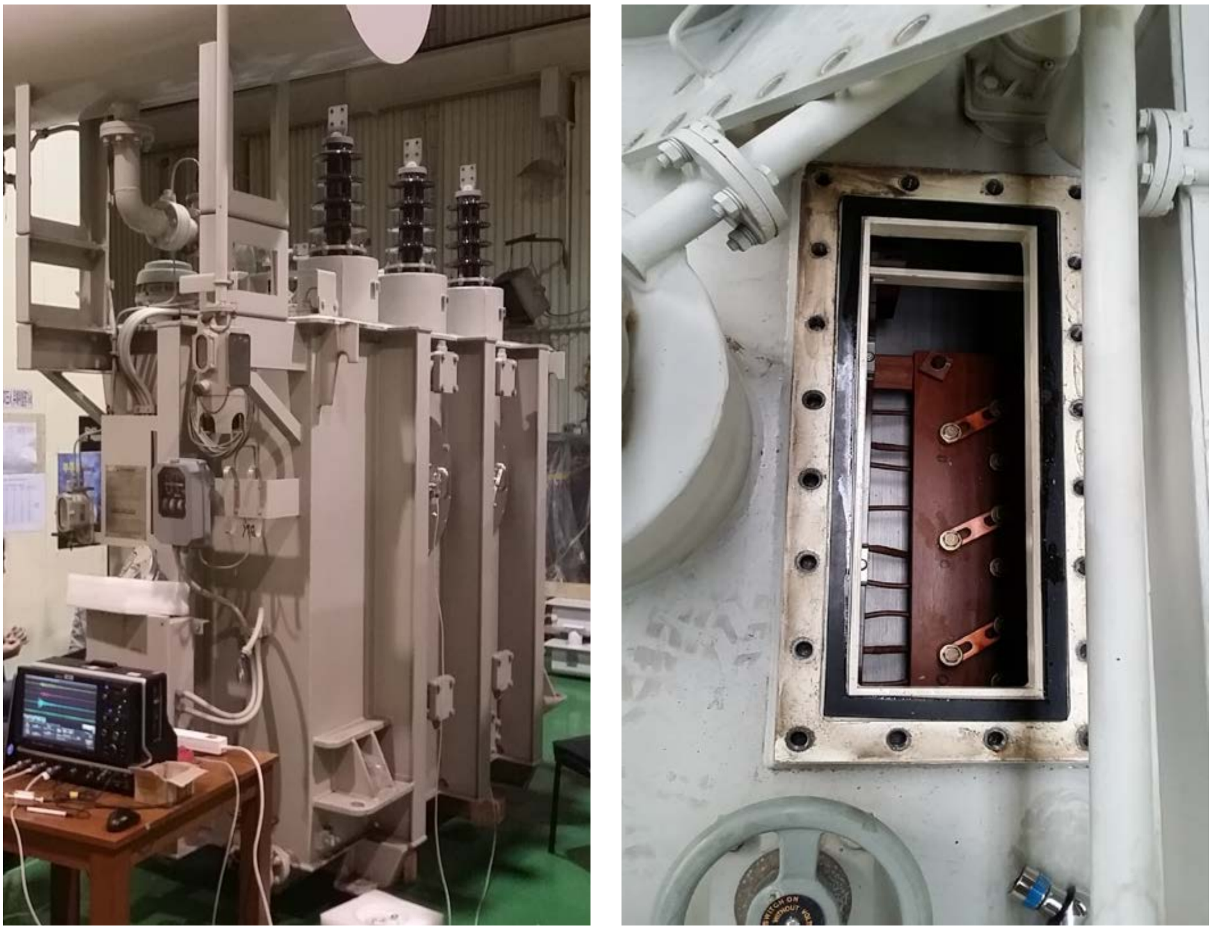


Figure 2: Flow chart of partial discharge localization algorithm

3. Experiments

To prove the proposed localization method, test on a three phase 3MVA power transformer was performed (Fig. 3(a)). To simulate the PD signals, a sleeve antenna of UHF band was used employing a pulse input with 0.2 ns rise time. Antennas were located on pre-defined coordinates as shown in Table 1. Since the accessibility is limited near the hand-hole, the test position was confined to the proximity of the lead support (Fig. 3(b)).

To detect the radiated EM waves, after draining the mineral oil, Hanbit EDS UHF sensors were installed on the hand-hole as shown in Fig. 1(b). The measurement data was recorded using LeCroy WaveRunner 610Zi 1 *GHz* Oscilloscope.



(a) **(b)**

Figure 3: (a) Test on a 3MVA-power transformer, (b) opened hand-hole to simulate PD signal.

4. Results and Discussion

A. Extraction of arrival time

Determining the arrival time of the recorded EM signals is very important for source localization in the UHF method. That is, the accuracy of the extracted arrival time affects the accuracy of the source localization.

Since the received signals from the UHF sensors will have a lot of multi-path components, estimating methods such as cross-correlation cannot be used. Instead of that, in this study, the arrival time was calculated using the energy of the received signals. To calculate the arrival time, H. R. Mirzaei, *et. al*. [4] used three different estimating methods including the cumulative energy method, the energy criterion method, and the average time window threshold method. Although these methods give similar results and are appropriate for automation, the cumulative energy method and the average time window threshold method need to be used with caution in order to set a proper threshold level. Therefore, in this study, the energy criterion method, which takes the minimum point of the processed signals, was used to eliminate such an arbitrary determination.

The energy criterion method uses the following equation to relate the time point and starting point of a signal:

$$\eta(n) = \sum_{j=1}^{n} s_j^2 - n\gamma \tag{1}$$

$$\gamma = \frac{\sum_{j=1}^{N} s_j^2}{N} \tag{2}$$

where s_j is the received signal and N is the total number of samples. When *eqs*. (1) and (2) is applied to the received signals, the minimum point of *eq*. (1) corresponds to the starting point of signal.

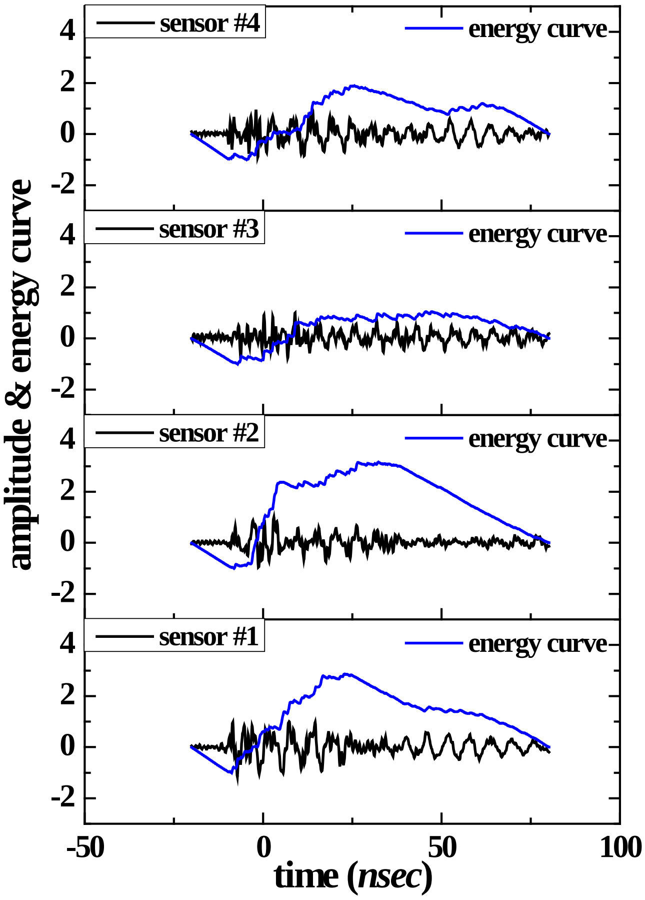


Figure 4: The estimation of arrival time using energy criterion method.

Figure 4 shows the energy curve with raw signals and estimated arrival time. As shown in Fig. 4, the criterion for the starting point can be estimated without an arbitrary determination. However, there is still error in the starting point estimation due to noise signals. As expressed in *eq.* (1), when the strength of the received signal near the starting point becomes large, the minimum point of the energy curve becomes clear to distinguish. However, in real environments, the EM waves radiated from a source go through multiple-reflections, and then the reflected signals arrive behind the signal transmitted by the shortest path. Moreover, various noise components, such as mobile devices and white noises, make it more difficult to determine the starting point. Thus, if possible, it is necessary to remove such unwanted components from the received signals as much as possible.

B. Denoising

Although the UHF method is a very sensitive method and is able to detect the radiated EM waves from a source, the captured signals cannot be always clear. Due to the nature of the structure inside a transformer, multi-path reflections and diffractions are unavoidable phenomena. These phenomena lead to attenuation of the signal. In addition to this, the noise component makes it more difficult to determine the arrival time of the signal. Thus, if possible, it is necessary to remove noise components, then, the accuracy of the estimated arrival time can be improved.

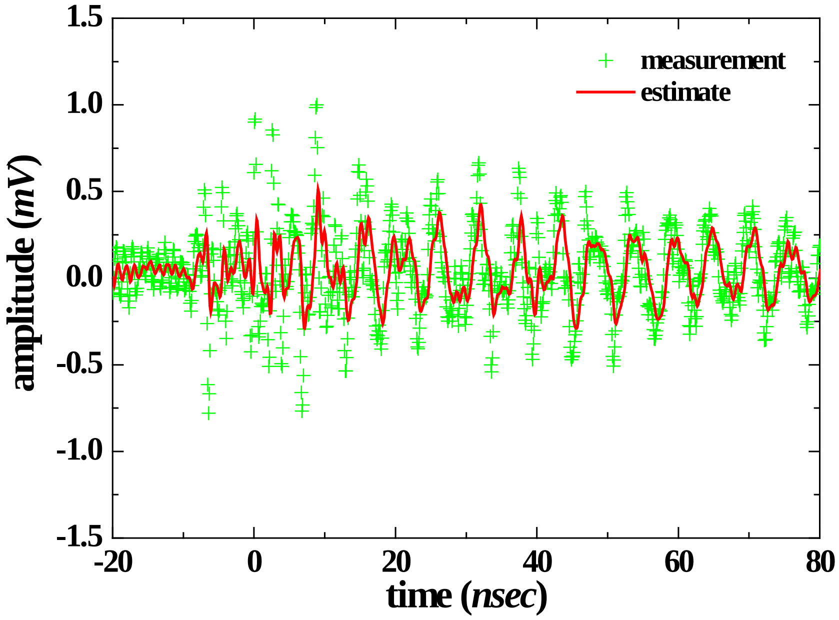


Figure 5: The comparison between raw signal and smoothed signal using particle filter.

Figure 5 shows the comparison of the raw and smoothed signals. When RBPF was applied to the raw signal, the starting point became more obvious, as shown in Fig. 5, which then the arrival time could be estimated more obviously. Fig. 6 shows the energy curve with filtered signals and the estimated arrival time. When the energy curve of the smoothed signal with particle filter (PF) is compared with that of the raw signal, it can be seen that the accuracy of the estimated arrival time is improved.

Table 1 shows the time-difference look-up table and the estimated arrival time of the experiment data. For the case of reference sensor 4, the time-difference between sensor *i* and 4 is calculated as follows:

$$T_{i4} = T_i - T_4,\ \boldsymbol{i = 1,2,3} \tag{3}$$

Each time-difference from the experiment data was directly compared with the time-difference look-up table.

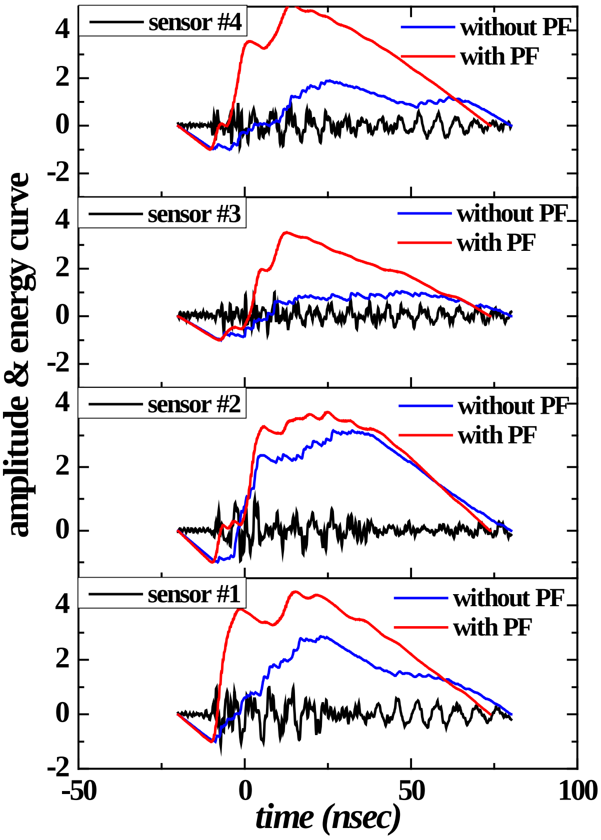


Figure 6: The comparison between raw signal and smoothed signal using particle filter.

Table 1: The time-difference look-up table and estimated arrival time of experiment data

Time-Difference Look-Up Table (FDTD simulation)				Measurement data: time table for raw signal				Measurement data: time table for filtered signal			
Reference Index	TD14	TD24	TD34	Measurement Index	TD14	TD24	TD34	Measurement Index	TD14	TD24	TD34
#1	-0.63	-2.42	-1.44	#1	-2.10	-3.10	-2.10	#1	0.40	0.30	0.80
#2	-0.71	-2.39	-1.29	#2	-2.00	-3.00	-2.00	#2	0.40	0.30	0.80
#3	-0.78	-2.28	-1.11	#3	1.30	0.30	1.30	#3	0.40	-0.10	0.80
#4	-0.89	-2.24	-0.89	#4	-2.50	-2.80	-3.30	#4	-3.60	-4.10	-4.50
#5	-1.00	-2.02	-0.62	#5	-2.90	-3.10	-3.60	#5	-3.30	-3.20	-4.50
#6	-1.09	-1.67	-0.32	#6	-2.90	-3.20	-3.70	#6	-3.30	-3.20	-4.50
#7	-1.19	-1.17	0.01	#7	-1.80	0.70	-3.30	#7	-0.20	1.50	-1.90
#8	-1.36	-0.77	0.32	#8	-1.80	0.60	-3.40	#8	-0.20	-1.40	-2.00
#9	-1.39	-0.36	0.63	#9	-1.80	-1.90	-3.80	#9	-0.20	-1.90	-2.00
#10	-1.35	0.01	0.89	#10	-4.10	-2.30	-1.50	#10	-2.00	-0.30	0.20
#11	-1.18	0.33	1.11	#11	-3.60	-2.00	-1.10	#11	-1.60	0.20	0.60
#12	-1.09	0.59	1.30	#12	-3.60	-2.00	-1.10	#12	-1.60	0.20	0.60
#13	-0.96	0.82	1.45	#13	2.00	2.10	0.10	#13	1.60	1.60	0.40
#14	0.64	-0.80	-1.79	#14	2.50	2.20	0.40	#14	2.50	1.70	0.90
#15	0.72	-0.58	-1.69	#15	2.40	2.60	0.40	#15	2.00	1.70	0.40
#16	0.80	-0.31	-1.50	#16	1.50	1.40	1.00	#16	0.40	0.70	0.10
⋮		⋮		#17	1.60	1.10	0.10	#17	0.40	0.80	0.20
				#18	1.50	1.50	0.00	#18	0.40	0.80	0.20
#102	-0.38	0.94	1.19	#19	-0.90	-1.80	0.10	#19	-2.90	-1.40	-0.40
#103	-0.33	1.14	1.37	#20	-0.90	-2.50	0.10	#20	-2.40	-1.40	-0.30
#104	-0.31	1.30	1.52	#21	-0.90	-2.50	0.10	#21	-2.80	-1.40	-0.30

In real environments, various noise components exist in the UHF range, such as telecommunication signals, thermal noise in a detection system and from a transformer, and periodic pulses from switching operations, and so on. Although noise components that may appear in the experimental conditions in this study are different from the actual environment, the introduced signal processing method may be useful in real tests to estimate the arrival time of PD signals.

C. Localization

EM waves radiated by an antenna will propagate in the transformer through the structure and arrive at four different sensors with different time instants. Since sensors are installed on different locations from the source, each sensor will receive signals at different times. Thus, the received signals among the sensors will have a finite time delay.

When the EM wave is emitted by the antenna, it will be reflected and scattered by the structures. It means that the arrival time is delayed by the structure than the time to reach over a straight-line path. That is, the arrival time measured by each sensor is the information including the time delay caused by such structures. Therefore, if the measured time-difference can be used for position estimation without any process, such as solving nonlinear simultaneous equations, it would be more efficient and will have high accuracy. The proposed method in this study is a method for estimating the position using direct comparison between the measured time-difference and the simulated time-difference database. As explained in the previous section, Fig. 2 shows the procedure of the time-difference look-up table method. A measurement data is compared with all the reference data using RMSE, and then the minimum value of RMSE is found. A coordinate at that point indicates the source position.

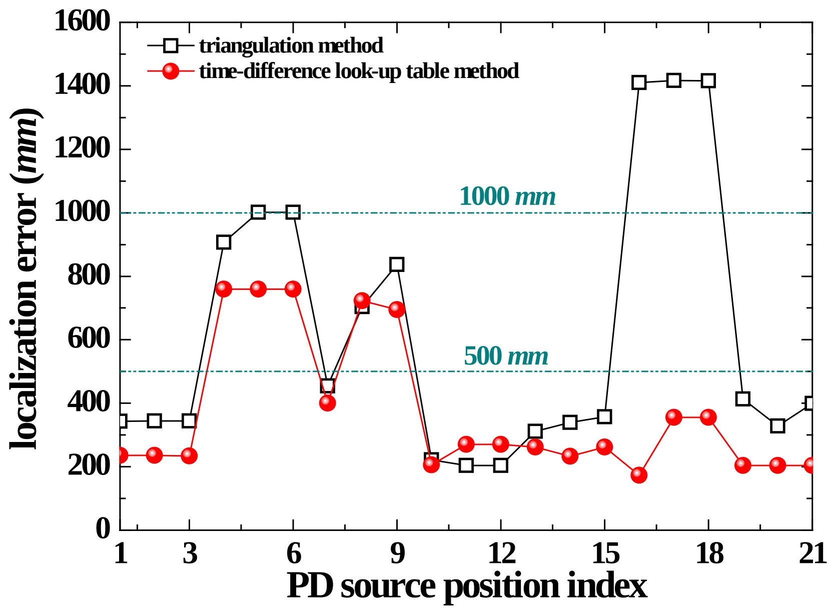


Figure 7: The localization error of time-difference look-up table method and triangulation method.

Figure 7 shows the calculated error in distance using the time-difference look-up table method. To compare its accuracy, the error in distance using the triangulation method was shown together. As shown in Fig. 7, the average error using the proposed method was 371 *mm*, while that of the triangulation method was 617 *mm*. Although the proposed method could reduce the error in distance by about 40%, there are still high errors for some points. However, the proposed method still has the possibility of further improvements by more accurately estimating the starting times of the measured signals, measuring more clear signals with well-controlled environment, and optimizing the location of the UHF sensors. Since PD activity is a random process and the signals emitted by a PD source cannot be specified with well-defined signals, the time-difference is the only information for localizing the PD source. Therefore, from this point of view, the time-difference look-up table method could be a very efficient method of a condition monitoring system for power transformers.

5. Conclusion

The proposed time-difference look-up table method was presented and verified through experimentation. In addition to the localization method, to obtain more accurate arrival times, the received raw signals were smoothed using the Rao-Blackwellised particle filter (RBPF). The average error using the proposed method was 371 *mm*, while that of the triangulation method was 617 *mm*. The proposed method could reduce the error in distance by about 40 *%*. Although there are still high errors for some points, the proposed method has the possibility of improvement by more accurately estimating the starting times of the measured signals, measuring more clear signals with well-controlled environment, and optimizing the location of the UHF sensors. When the random process characteristics of PD activity is considered, the time-difference look-up table method could be a very efficient method of a condition monitoring system for power transformers.

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