Paper

Location of Multiple PD Sources on Distribution Lines by Measuring Emitted Pulse-Train Electromagnetic Waves

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This paper presents a new system designed for locating multiple sources of partial discharge. The system employs a sequential triggering method which can detect many pulses or pulse-train electromagnetic waves emitted from partial discharge in one measurement. We utilize four VHF wideband antennas as electromagnetic sensors and calculate the time delay of arrival between them in order to locate PD sources in 3-D. With this technique, we can locate multiple sources based on the assumption that there is only one electromagnetic pulse contained in the detected time window of 2 μs or each time window indicates a signal from one source. The smoothed coherence transform is applied to improve the time delay estimation and compared with the standard cross correlation. The proposed system also enhances the reliability of the method because many pulses are analyzed. A field experiment was performed to evaluate the proposed system.

Keywords: partial discharge location, multiple sources, pulse-train electromagnetic waves, time delay of arrival (TDOA), smooth coherence transform, power distribution lines.

1. Introduction

So far, the partial discharge (PD) measuring technique has been used to detect defects in insulation materials of HV equipment of power systems (1). In case of power distribution lines, the partial discharge emits the electromagnetic waves which may interfere the communication systems as noises on television, radio broadcast, and radio telecommunication (2). For obtaining higher reliability on power systems and better electromagnetic environment, it is very important to know the position of partial discharge source as soon as possible so that an appropriate action can be taken in order to remove this cause(2-9).

The possibility to locate partial discharge by using multiple antennas to detect the emitted electromagnetic waves has been investigated. M. Kawada et al. (7) utilized time delay of arrival between antennas to locate partial discharge from outdoor GIS tank in two dimensions. Concerning the power distribution lines, Y. Suzuki et al. (8) proposed the superimposed positioning optimization method to locate the partial discharge source in three dimensions as volume by moving the antenna set at least two times. However, the concerned papers pay attention to only the detection of single PD source. In practice, there are sometimes more than one PD source simultaneously occurring in power systems and apparatus. The suitable technique to locate multiple sources is still not evaluated and required to be developed. For preliminary study, the characteristics of PD pulses in VHF range from single and multiple sources have been investigated (10) (11). It was found that the width of PD pulse is normally less than 0.5 μs and the time window of 2 μs is sufficient to cover the PD pulse data. The PD pulse interval depends on various factors such as a level of applied voltage, a kind of discharge. In case of power distribution lines, it was investigated that the average pulse interval is around 1∼3 ms (11). Considering the 2-μs time window of proposed system, there is a very low possibility that each time window includes more than one pulse from different sources. Moreover, based on the fact from experimental data (11), there is only one PD pulse in the time window of 2 μs while simultaneously generating three separate PD sources. From this result, it was concluded that each time window indicates only one PD source.

In this paper, a new location system for multiple PD sources is presented. The system employs a sequential triggering method to detect many pulses or pulse-train electromagnetic waves emitted from partial discharge in one measurement. We utilize four VHF wideband antennas as electromagnetic sensors and calculate the time delay of arrival between them in order to locate PD sources in three dimensions (3-D). With this technique, we can detect and locate multiple PD sources based on the time delay data sets from the detected pulses. The smoothed coherence transform (SCOT) (12) (13) is applied to improve the time delay estimation and compared with the standard cross correlation (SCC). A field experiment was performed to evaluate the proposed system. Some time delay estimation and location results are shown and discussed.

2. PD Location

2.1 Basic Concept for 3-D Location

To locate the PD in 3-D, we require at least four sensors for determining three independent values of time delay of arrival between received signals. Fig. 1 shows the idea of PD location in 3-D. The position of PD source is assumed as the unknown variables (X,Y,Z). Four antennas are labeled as (0),..,(3) and their co-ordinates are (X_0,Y_0,h),..,(X_3,Y_3,h), respectively. The antenna (0) is referred as a center for computation. The relations between the co-ordinate of antennas and the time delay of arrival are expressed as

$$\begin{aligned}\sqrt{X^2+Y^2+(Z-h)^2}-\sqrt{(X-X_1)^2+(Y-Y_1)^2+(Z-h)^2}&=cT_1\\ \sqrt{X^2+Y^2+(Z-h)^2}-\sqrt{(X-X_2)^2+(Y-Y_2)^2+(Z-h)^2}&=cT_2\\ \sqrt{X^2+Y^2+(Z-h)^2}-\sqrt{(X-X_3)^2+(Y-Y_3)^2+(Z-h)^2}&=cT_3 \qquad (1)\end{aligned}$$

where, T_i = time delay between antennas (i) and (0), c = the velocity of light (=3×10^8 m/s), h = a height of antenna (=1.5 m). From these equations, we can determine the position of partial discharge P(X,Y,Z) if time delay values (T_1,T_2,T_3) are obtained.

2.2 Time Delay Estimation A signal received at two spatially separated sensors can be mathematically modeled as

$$\begin{aligned}x_1(t)&=s(t)+n_1(t)\\ x_2(t)&=\alpha s(t-D)+n_2(t) \quad \cdots\cdots\cdots\cdots\cdots\cdots (2)\end{aligned}$$

where s(t) is the source signal, $n_1(t)$ and $n_2(t)$ are uncorrelated and zero-mean noises, α is an attenuation factor, and D is time delay. Generally, the standard cross correlation method is utilized to estimate time delay by detecting the time that maximizes its function. The cross correlation between signal $x_1(t)$ and $x_2(t)$ is related to the cross power spectral density function $G_{x_1x_2}(f)$, which is a function used to estimate the frequency content in a correlated signal, by the well-known Fourier transform relationship.

$$R_{x_1x_2}(\tau)=\int_{-\infty}^{\infty} G_{x_1x_2}(f)e^{j2\pi f\tau}df \quad \cdots\cdots\cdots\cdots (3)$$

In practice, only a function $G^E_{x_1x_2}(f)$, which is an estimate of $G_{x_1x_2}(f)$, can be obtained from finite observation of $x_1(t)$ and $x_2(t)$. To compensate the effects of noises and attenuation, the weighting function $\psi_g(f)$ is applied. Consequently, the generalized correlation

$$R^E_{x_1x_2}(\tau)=\int_{-\infty}^{\infty} \psi_g(f)G^E_{x_1x_2}(f)e^{j2\pi f\tau}df \quad \cdots (4)$$

is evaluated and used for estimating time delay. In order to reduce the error in the time delay estimation, various kinds of weighting functions have been introduced(12). The suitable weighting function accentuates the signal passed to the correlator at those frequencies at which the signal-to-noise (S/N) ratio is highest. In this paper, the smoothed coherence transform (SCOT) is used to estimate the time delay comparing to the standard cross correlation (SCC) and their weighting functions are concluded in Table 1.

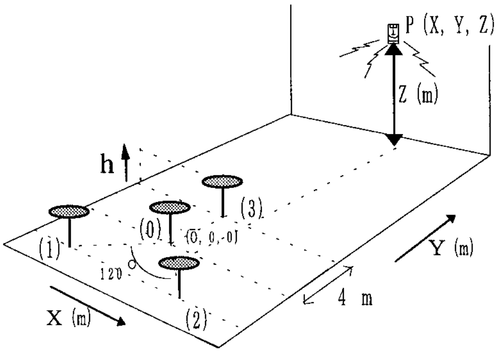


Fig. 1. The idea of PD location in 3-D.

Table 1. Correlation methods and weighting functions.

Correlation method	Weighting function
1. SCC	1
2. SCOT	$1/\sqrt{G_{x_1x_1}G_{x_2x_2}}$

2.3 Algorithm for Locating Multiple PD Sources Fig. 2 indicates a flow chart diagram of a main algorithm for locating multiple PD sources used in this paper. The processing of the location algorithm is performed as follows: (1) a fast Fourier transform is applied to extract the spectra of signals received at two antennas; (2) a cross power spectral density function is calculated by convoluting the results from (1); (3) an appropriate weighting function(12) is multiplied to reduce the influence from noise interference and signal attenuation; (4) time delay is estimated by detecting the peak of a generalized cross correlation function; (5) based on a sequential triggering technique, many sets of PD pulses are detected in each measurement and one set of PD pulses provides one time delay data set. The time delay (T_1,T_2,T_3) groups are built and sorted based on their numbers of pulse data sets; (6) PD location is performed by using Newton-Raphson method because of the nonlinear and complicated relations of Eqs. (1).

3. Field Experiment

3.1 Experimental Method In experiment, we employed four sets of VHF wideband plate antennas as the electromagnetic wave sensors. The antenna configuration was set as shown in Fig. 1. The antenna (0) was aligned with angle 120 degrees and distance 4 meters to the others. Three PD sources, which are PD1 (-9.7 m, -10.5 m, 1.9 m), PD2 (7.8 m, -13.0 m, 1.9 m), and PD3 (5.6 m, 12.7 m, 1.9 m), were generated from the corona discharge generators by applying ac high voltage around 3.81 kV on them (regarding the 6.6 kV system, the phase voltage is 3.81 kV). A discharge was generated from needle-plane electrode with the resistance 2 GΩ on both ends of electrode. This discharge has a magnitude around 2000 pC and can be simulated as the discharge on small air gap occurring in power distribution systems(8).

3.2 Measurement Setup Fig. 3 shows a proposed measurement system. Four wideband antennas were connected to digital storage oscilloscope (DSO:

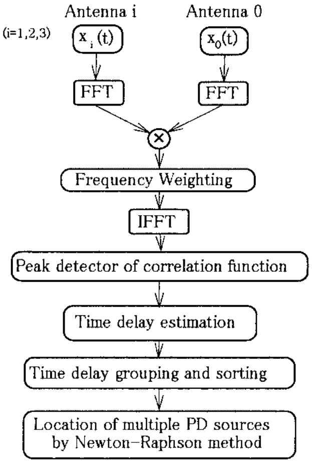


Fig. 2. Main algorithm for locating multiple PD sources.

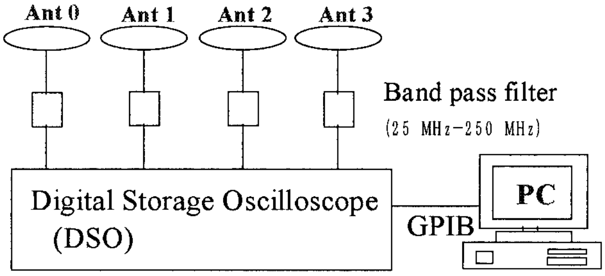


Fig. 3. Measurement system.

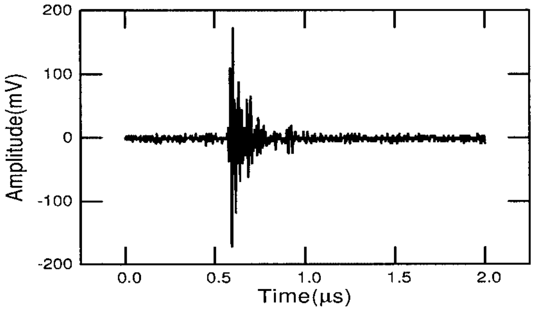


Fig. 4. An example of electromagnetic waves emitted from PD.

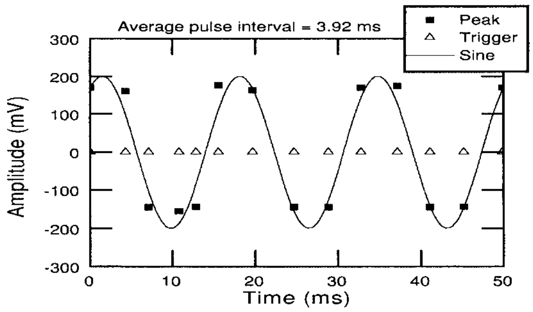


Fig. 5. An example of the relation between triggered time and peak values of the electromagnetic pulses when single source was generated.

Lecroy 9374L) by coaxial cables (type: 5D-2V, connector: BNC, length: 30 m) and band-pass filters (25-250 MHz). The electromagnetic waves were digitized at a sampling rate 500 MHz by using a DSO controlled by a personal computer (PC) through GPIB board. To detect pulse-train electromagnetic waves, we applied a sequential triggering technique for each electromagnetic pulse. We divided the whole memory of DSO into 1000 segments, and each segment can record one wideband electromagnetic pulse for time window of 2 μs. Once the electromagnetic pulse from PD is detected and its amplitude exceeds a threshold value (triggered level), a triggering circuit is turned on to record a waveform and saves it as one segment with resolution 8 bits then the system returns back to wait for triggering the next signal. With this technique, we can record maximum 1000 wideband electromagnetic pulses in each measurement. Note that the minimum time between two consecutive electromagnetic pulses is about 70 μs due to instrumentally dead time.

4. Results and Discussions

4.1 Characteristics of electromagnetic waves

Fig. 4 shows an typical example of electromagnetic waves emitted from partial discharge generated by corona discharge generator. The pre-triggered time was set at 30 [%] so the PD signal appears around t=0.6 μs in the time window of 2 μs. The signals from each PD source were measured by adjusting an appropriate scale of DSO (mV/div parameter) and a triggered level set at antenna (0). The 1000 electromagnetic pulses were observed and the timing of them was recorded. When single source was generated, the average pulse intervals of PD1, PD2 and PD3 were 7.75 ms, 3.92 ms and 5.81 ms, respectively. For a typical example of the characteristic of pulse intervals, the relation between triggered time and peak values of pulses in the first 50 ms when PD2 was generated is shown in Fig. 5. The triangle mark plotted on x-axis shows the triggered time of each electromagnetic pulse. The rectangle mark shows the peak value of electromagnetic pulse on that trigger. The sinusoidal curve whose period 16 ms (=the period of applied ac voltage) is plotted in order to easily see the relation between triggered time and system frequency. It is shown that the polarity of the peak of emitted electromagnetic pulse depends on the phase of applied voltage. The pulse interval is not constant and has a tendency to periodically vary with system period. From this result, there is a possibility to construct the pattern of statistical PD characteristics, Φ-q-n *pattern* (Φ=the phase angle, q=PD charge, n=the number of PD pulses)(15), by this proposed system based on the relation between electric charge and electric field intensity of electromagnetic wave(16).

4.2 Time Delay Estimation

Table 2 indicates the ideal time delay of arrival between antennas of each PD source. In this subsection, the standard cross correlation method (SCC) and the smooth coherence transform (SCOT) are utilized and compared to estimate the time delay. For example, considering the time delay between antennas (1) and (0) when PD2 was gener-

Table 2. Ideal time delay between antennas of each PD source.

PD source	Ideal time delay (ns)		
	T_1	T_2	T_3
PD1	12.50	-4.58	-10.50
PD2	-1.95	11.12	-11.81
PD3	-11.30	-3.25	11.77

Table 3. Time delay estimation of all segments when PD2 was generated.

Method	Time delay estimation (ns)		
	T_1	T_2	T_3
SCC	12 (1000)	10(991),8(99)	-14(1000)
SCOT	-2(1000)	10(404),8(184),-2(147), 6(103), 4(99),-4(43), -4(7),-12(6),4(5),2(1), 12(1)	-12(833),-14(167)

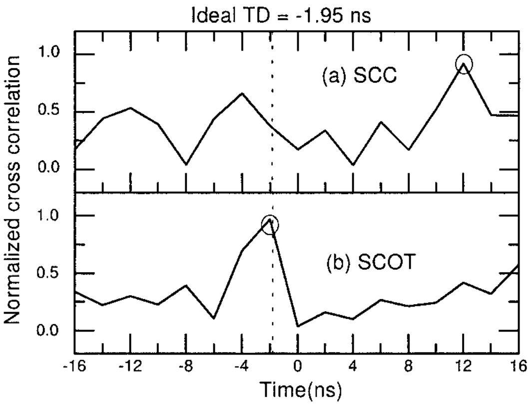


Fig. 6. Normalized cross correlation functions between signals received at Ants. (1) and (0) when PD2 was generated; (a) by SCC and (b) by SCOT.

Table 4. Time delay estimation and location results by Newton-Raphson method when single PD source was generated.

(a) PD1

TD group(ns)			Location result (m)			Number of segments
T_1	T_2	T_3	X	Y	Z	
12	-2	-12	-10.46	-16.41	1.73	298
10	-2	-12	-5.01	-9.34	4.03	130
10	-2	-14	-3.65	-7.79	1.37	76
12	-2	-14	-6.83	-11.99	1.93	64
12	-4	-14	-4.35	-6.85	1.65	29
10	-4	-14	-3.01	-5.43	1.42	24

(b) PD2

TD group(ns)			Location result (m)			Number of segments
T_1	T_2	T_3	X	Y	Z	
-2	10	-12	5.01	-9.34	4.03	337
-2	10	-14	3.65	-7.79	1.37	152
-2	4	-12	1.37	-4.61	4.38	87
-2	8	-12	3.12	-6.89	4.55	83
-2	6	-12	2.08	-5.53	4.52	68
-2	8	-14	2.41	-6.15	1.53	30

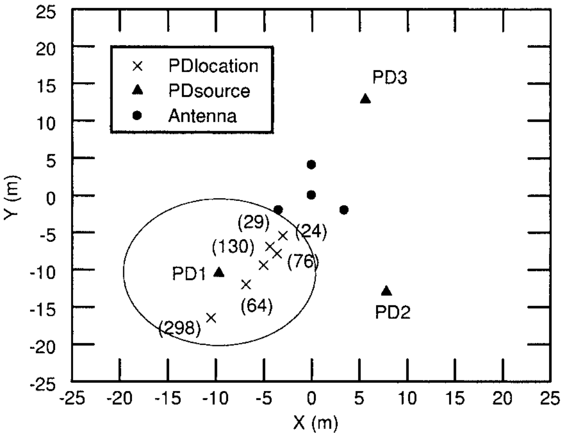
(c) PD3

TD group(ns)			Location result (m)			Number of segments
T_1	T_2	T_3	X	Y	Z	
-12	-4	12	3.91	8.50	1.52	441
-10	-4	12	5.93	19.08	7.61	428
-12	-10	12	0.88	12.28	4.09	55

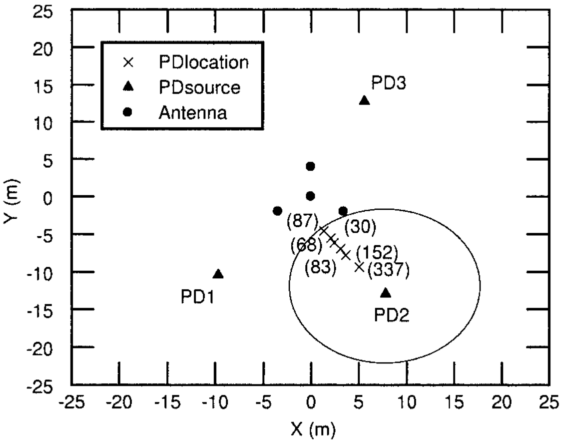
ated, the ideal time delay is -1.95 ns. Fig. 6 shows the normalized cross correlation functions obtained by SCC and SCOT of this case. The graph can be plotted with time interval 2 ns due to sampling time 2 ns from experiment. The time delay obtained by SCC is 12 ns which makes the estimation wrong. On the other hand, the time delay obtained by SCOT is -2 ns which is near the ideal time delay. As previously concerned, the proposed system can detect maximum 1000 pulses in one measurement, and the memory storage for one pulse data is called *a segment*. Table 3 shows the time delay estimation of all segments in this case. The number in the parenthesis shows the number of segments corresponding to the time delay. Although, the distribution of time delay results by SCOT is larger than that by SCC, the correct results can be obtained in majority. From these results, it is shown that SCOT is useful to get more correct time delay and will be used to perform PD location in this paper.

4.3 Location of Single PD Source Before performing multiple PD source location, the location of single PD source was investigated. In experiment, the electromagnetic waves were measured three times for each single PD source. The location results were determined. The results are nearly same, therefore only one of them is shown. Because some of the detected pulse groups do not provide the appropriate time delay for PD location, the suitable pre-processing procedure is needed. The time delay results, whose signs(±) are accordant with those of time delay obtained by peak-to-peak estimation, are considered as the good ones and selected. Tables 4 (a)-(c) show the time delay estimation and the location results by Newton-Raphson method for each single PD source. Due to the large distribution of time delay groups, only the time delay groups, whose numbers of segments are more than 20, are shown and used to perform the PD location. Fig. 7 shows the location results mapping on the X-Y plane when single PD source was generated. The number in the parenthesis shows the number of segments. The circles whose radii 10 m are plotted by using the PD sources as the centers and all location results are included in them. It means that the error of location on X-Y plane is within 10 m.

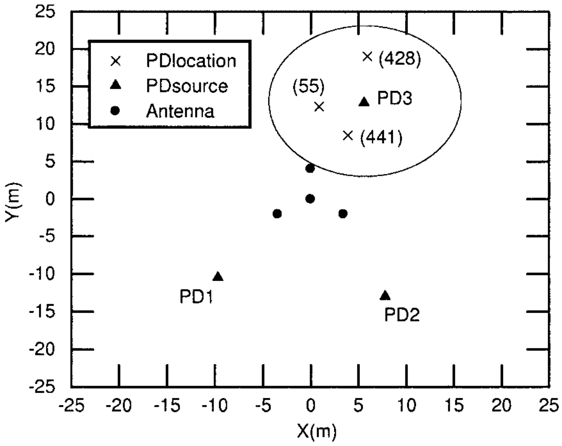
4.4 Location of Multiple PD Sources As described in subsection 4.1, the average pulse interval from single source is around 3∼8 ms. The width of PD pulse, which is less than 0.5 μs (as shown in Fig. 4), is very short comparing to the pulse interval. This result is accordant with the previous report(11). From this point of view, it is concluded that there is a very low possibility that there are more than one pulse from separate sources included in the time window of 2 μs. We can assume that one time window data is from only one source of PD. Table 5 shows the time delay estimation and location results when three sources (PD1, PD2, PD3) were simultaneously generated. The number of segments according to each PD source is different. It is discussed that the ratio between the numbers of electromagnetic pulses from PD sources depends on various factors such as the triggered level and the frequencies of PD occurrences themselves. Fig. 8 shows the location results on the X-Y plane. In the same way as Fig. 7,



(a) PD1



(b) PD2



(c) PD3

Fig. 7. Location results mapping on the X-Y plane when single PD source was generated; (a) PD1, (b) PD2 and (c) PD3.

Table 5. Time delay estimation and location results when three sources (PD1,PD2,PD3) were simultaneously generated.

TD group (ns)			Location result (m)			Number of segments	Expected source
T_1	T_2	T_3	X	Y	Z		
-2	12	-14	6.85	-11.99	1.93	87	PD2
-2	10	-12	5.01	-9.34	4.03	83	PD2
12	-4	-12	-5.42	-7.65	1.43	56	PD1
-2	12	-12	10.46	-16.41	1.73	45	PD2
12	-10	-12	-12.06	-8.06	1.54	45	PD1
-12	-4	12	3.91	8.5	1.52	32	PD3
12	-2	-12	-10.46	-16.41	1.73	29	PD1
-2	10	-14	3.65	-7.79	1.37	27	PD2
-12	-10	12	0.88	12.28	4.09	24	PD3
10	-2	-12	-5.01	-9.34	4.03	22	PD1

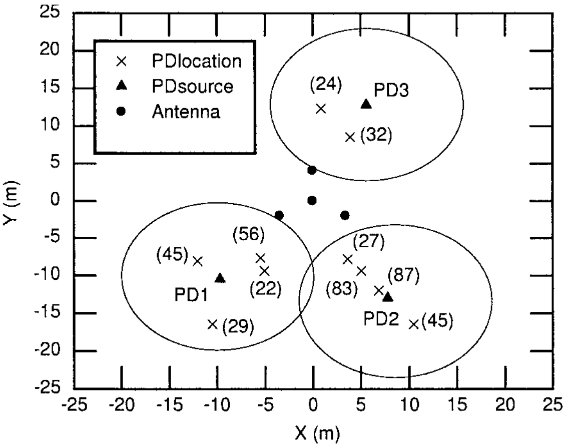


Fig. 8. Location results mapping on the X-Y plane when PD1, PD2 and PD3 were simultaneously generated.

the circles whose radii 10 m are plotted and all location results are included in them. It means that the error of location on X-Y plane is less than 10 m. Considering the minimum standard distance between electric poles which is 30 m, the error of proposed system is acceptable for practical use in power distribution systems.

4.5 Consideration for error of location In this experiment, the error of PD location of proposed system is around 4∼12 m (error in 3-D) which is sufficient to diagnose on which electric pole partial discharge occurs. It will be more useful if we can decrease the error in order to diagnose that which equipment on electric pole is faulted. In order to improve the location accuracy, the causes of error are discussed and summarized as follows.

4.5.1 The feature of PD pulse As can be seen from Fig. 4, the PD pulse possesses some periodical features. As for the theory of the correlation method, one of the signals is translated in time-axis and the time that maximizes the multiplication result between signals is considered as time delay. Therefore, the error may be high when analyzing signals whose features exhibit strong periodicity.

4.5.2 Detection of other electromagnetic pulses or noise interference During the measurement of many consecutive pulses, there may be other electromagnetic pulses which intermittently occur and have been triggered, resulting in obtaining wrong data in some segments.

4.5.3 Limited sampling rate Due to the sampling rate of measurement system, the error of time delay estimation is assumed to be ±1 ns. The error can be decreased by using the higher sampling rate DSO whose price becomes cheaper at present.

5. Conclusions

A new system for locating multiple sources of partial discharge has been designed, constructed and evaluated. The proposed system employs the sequential triggering method which can detect many pulses or pulse-train electromagnetic waves emitted from partial discharge in one measurement. The system can observe maximum 1000 electromagnetic pulses by using a time window of 2 μs with a sampling rate 500 MHz. An algorithm to locate multiple sources was constructed based on the fact from experimental data that there is only one partial discharge pulse included in the time window of 2 μs or each time window indicates only one source of partial discharge. In order to locate partial discharge, the standard cross correlation and smooth coherence transform were applied and compared to estimate time delay of arrival between antennas. It has been shown that the smooth coherence transform is useful to get more correct time delay estimation. The proposed system shows the effectiveness in the detection and location of multiple sources of partial discharge, enhances the reliability of method because many partial discharge pulses are analyzed. The error of location is acceptable for practical use in power distribution systems.

In future schedule, we plan to make the system compact and test it in the actual field. In order to get more accuracy in location result, the optimal method to estimate time delay should be investigated and the sampling rate should be increased. The characteristics of emitted electromagnetic waves will be studied in order to classify the partial discharge sources.

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