A Study on the Algorithm for Detection of Partial Discharge in GIS Using the Wavelet Transform

J.S. Kang*, S.M. Yeo*, C.H. Kim* and R.K. Aggarwal**

Abstract - In view of the fact that gas insulated switchgear (GIS) is an important piece of equipment in a substation, it is highly desirable to continuously monitor the state of equipment by measuring the partial discharge (PD) activity in a GIS, as PD is a symptom of an insulation weakness/breakdown. However, since the PD signal is relatively weak and the external noise makes detection of the PD signal difficult, it therefore requires careful attention in its detection. In this paper, the algorithm for detection of PD in the GIS using the wavelet transform (WT) is proposed. The WT provides a direct quantitative measure of the spectral content and dynamic spectrum in the time-frequency domain. The most appropriate mother wavelet for this application is the Daubechies 4 (db4) ` wavelet. 'db4', the most commonly applied mother wavelet in the power quality analysis, is very well suited to detecting high frequency signals of very short duration, such as those associated with the PD phenomenon. The proposed algorithm is based on utilizing the absolute sum value of coefficients, which are a combination of D1 (Detail 1) and D2 (Detail 2) in multiresolution signal decomposition (MSD) based on WT after noise elimination and normalization.

Keywords: Partial Discharge, Wavelet Transform, Gas Insulated Switchgear, Mother Wavelet

1. Introduction

With increased industrialization worldwide, there is a demand for high quality power supply. This effectively entails a high reliability and efficient functioning of various equipment in a power systems network, including close monitoring of the condition of equipment. In this respect, the state of the GIS, which is becoming widespread throughout high voltage substations, is difficult to check with the naked eye because of its enclosed structure. It is thus necessary to develop technology that can monitor the condition of the various components within the enclosed body of a GIS [1]-[5]. Hitherto, the condition monitoring of the GIS based on PD detection has been achieved with limited success.

The WT has been extensively applied in solving many problems in applied science and engineering following its introduction in the early 1980's, and it continues to be used in many fields [6]. The WT analyzes a signal in a changeable frequency range by employing a moving window whereby a long time window is used to obtain low frequency information and a short time window is used to obtain high frequency information. Both of these can improve the analytic characteristics of PDs having a wide frequency range [7].

This paper is concerned with the development of a detection method for PDs that emanate from weakening of insulation leading to total breakdown. The distinction between PD and spurious noise is difficult to detect and this is more so by virtue of the fact that the magnitude of the PD signals are comparable to noise. It is thus necessary to eliminate noise and in this respect, the WT is ideally suited for de-noising the measured signal. This paper describes a study on the algorithm for detection of partial discharge in GIS; it is shown that the algorithm improves the performance of PD detection by employing the absolute sum value based on the WT. The detection process is performed through noise elimination, normalization, signal decomposition and thresholding of WT coefficients. Threshold value is determined by weighting the absolute sum value for one period in a moving window scheme and this forms the basis of sophisticated decision logic for the PD detection described herein.

2. Wavelet Transform

Analogous to the relationship between continuous FT (Fourier Transform) and DFT (Discrete Fourier Transform), the CWT (Continuous Wavelet Transform) has a digitally implementable counterpart called the DWT (Discrete Wavelet Transform), and is defined as:

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$$DWT(m,k)=\frac{1}{\sqrt{a_0^m}}\sum_n x(n)g\left(\frac{k-nb_0a_0^m}{a_0^m}\right) \quad (1)$$

where $g(n)$ is the mother wavelet, $x(n)$ is the input signal, and the scaling and translation parameters 'a' and 'b' are functions of integer parameter m. The result is geometric scaling i.e. 1, $1/a$, $1/a^2$, ----- and translation by 0, n, 2n, -----. This scaling gives the DWT a logarithmic frequency coverage and this is in marked contrast to the uniform frequency coverage of, for example, the STFT (short-time FT) [8].

By simple interchange of the variables n and k, rearrangement of the DWT Equation (1) gives:

$$DWT(m,n)=\frac{1}{\sqrt{a_0^m}}\sum_k x(k)g\left(a_0^{-m}n-b_0k\right) \quad (2)$$

Upon closer observation of this equation, it can be noticed that there is a remarkable similarity to the convolution equation for the Finite Impulse Response (FIR) digital filters, viz.:

$$y(n)=\frac{1}{c}\sum_k x(k)h(n-k) \quad (3)$$

where $h(n-k)$ is the impulse response of the FIR filter.

By comparing Equation (2) with Equation (3), it is evident that the impulse response of the filter in the DWT equation is:

$$g\left(a_0^{-m}n-b_0k\right) \quad (4)$$

By selecting $a_0=2$ or ($a_0^{-m}=1$, 1/2, 1/4, 1/8, ----) and $b_0=1$, the DWT can be implemented by using a multi-stage filter with the mother wavelet as the low-pass filter l(n) and its dual as the high-pass filter h(n). Also, down-sampling the output of the low-pass filter l(n) by a factor of 2 (↓2) effectively scales the wavelet by a factor of 2 for the next stage, thereby simplifying the process of dilation [8].

The approximations (A) are the low-frequency components of the signal and the details (D) are the high-frequency components. Thus, the decomposition process of the DWT resembles a filtering process using low-pass and high-pass filters. It is necessary to use the wavelet filter bank to progressively decompose the applied signal in order to decompose it into various components. Fig. 1 shows the structure of the filter bank [9]-[10].

3. Partial Discharge

As mentioned before, detection of PD is crucial in the maintenance of high quality power supply as it is indicative of weakening of insulation eventually leading to total breakdown. An early warning of insulation deterioration with appropriate corrective action taken can very often prevent a catastrophic failure within GIS and also importantly, a considerable saving in expenditure. However, again as mentioned before, PD signals are relatively weak, particularly in relation to spurious noise.

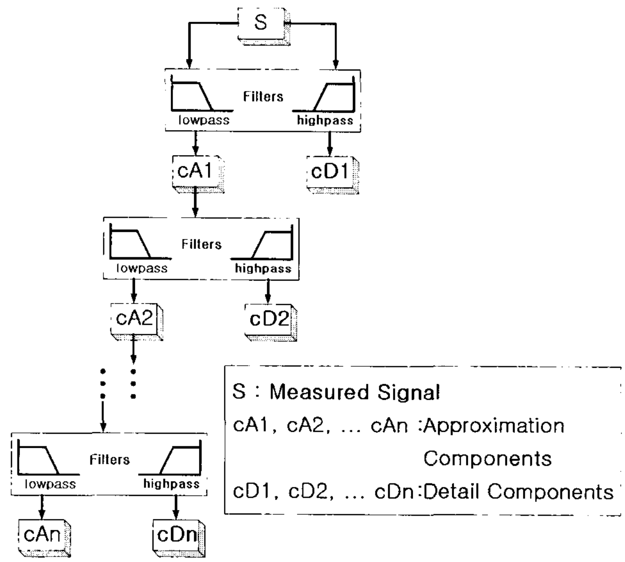


Fig. 1 Multi level decomposition

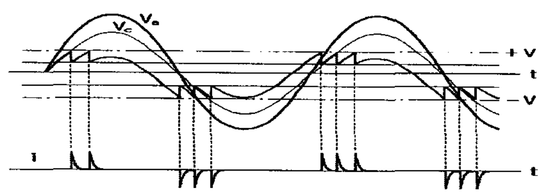


Fig. 2 Pattern of typical PD voltage and current

In GIS, the problem is compounded by the fact that a GIS is comprised of many different components resulting in PD activity emanating from a number of different sources within the GIS [11].

A characteristic feature of PD is that electromagnetic waves occur initially, followed by ultrasonic waves and finally acoustic waves occur when it progresses to the surface discharge. The pulse generated by a typical PD has the duration of a few nanoseconds, and the high frequencies contained in it excite the GIS chambers. Moreover, a measured PD signal can be characterized by its phase, charge and the number of pulses and each PD type will generate a different pattern, at a different phase angle. Therefore, the pattern and severity of a PD can be acquired through measurement of PD according to phase. This is called pattern recognition of the PD. PD pattern recognition is the ability to recognize and distinguish between different types of PD sources within the electrical insulating systems of power apparatus and cables and to differentiate them from extraneous interference phenomena. The area of PD pattern recognition constitutes an important and highly specialized subset in PD related studies. Fig. 2 typifies the pattern of typical PD voltage and current, which is void discharge. V and i signifies voltage and current, respectively. In this paper, we use 154kV practical data to verify the algorithm developed for detecting PDs; this data was measured for diagnosis of each GIS directly using the LEMKE data acquisition system at KEPCO and was associated with the GIS bus, circuit breaker (CB) and disconnecting switch (DS). The level of PD measured is diverse (the largest level is 800[pC]). Although PD is measured by nanosecond time ranges in LEMKE, LEMKE stretches high-frequency to low-frequency pulsive interference. Thus, PD of nanosecond time ranges converts to second time ranges. In this paper, we used data of this second time ranges. The LEMKE data acquisition system uses an inductive sensor and resonance frequency of 12.5MHz. The duration of each measurement was 40 sec.

4. Algorithm for Detection of Partial Discharge using Wavelet Transform

4.1 Selection of Mother Wavelet

Fig. 3 shows the 154kV Korean GIS diagram at Chodong substation, which is one of the examples of a number of substations considered in this paper. Here, square presents circuit breaker and circle presents disconnecting switch. The nominal power frequency is 60Hz. Fig. 4 typifies the actual PD, with noise eliminated after measuring the PD of circuit breaker (CB) 647 at Chodong substation, which is shown in Fig. 3.

To aid the detection of PD using WT, WT realization has been employed, which determines a coefficient of D1 (detail 1) using different mother wavelets from an actual PD. The mother wavelets considered are db (Daubechies) 4, bior (biorthogonal) 3.1, coif (coiflets) 4 and sym (symlets) 5. Fig. 5 depicts the coefficient of d1 for different mother wavelets with the WT realization. The behavior of the WT for actual PD waveforms is illustrated in Figs. 5a, 5b, 5c and 5d; as expected, all the coefficients of d1 increase with the occurrence of PD. These results lead us to the conclusion that the Daubechies 4(db4) ` wavelet is very well suited to the detection of PD. The PD detection technique described herein is thus based on this mother wavelet.

4.2 Detection Algorithm of Partial Discharge

Fig. 6 illustrates the 154kV GIS, the LEMKE system, the measured signal and the response of the developed PD detection algorithm. As clearly evident, the algorithm is extremely effective in de-noising the recorded PD signal and extracting the useful PD features from the original signal.

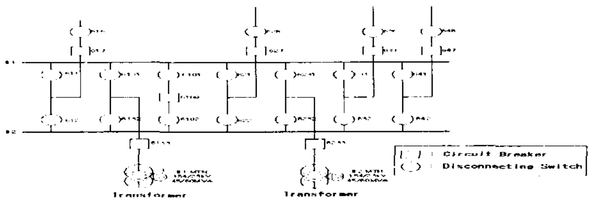


Fig. 3 The 154kV Korean GIS at Chodong substation

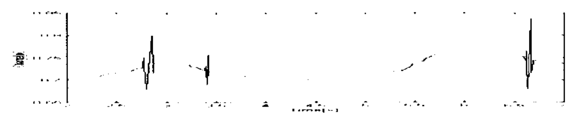
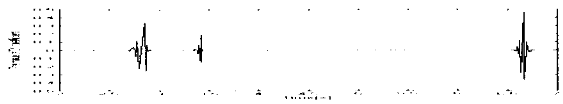
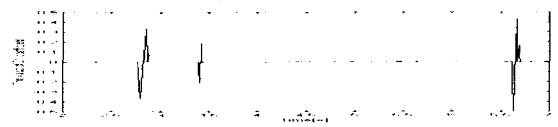


Fig. 4 A typical PD waveform measured at 647CB at Chodong substation

(a) db4 mother wavelet



(b) sym5 mother wavelet



(c) bior 3.1 mother wavelet

(d) coif4 mother wavelet

Fig. 5 The coefficient of D1

Fig. 7 typifies a measured signal with noise included. It is apparent that in its original form, it is virtually impossible to discern PD from noise. However, when the signal is de-noised using the WT, then the resultant signal depicted in Fig. 8 shows the PD activity very vividly. In all of the studies performed, the measured signals were decomposed into 8 levels to eliminate noise and this was achieved via the various functions of the wavelet toolbox supplied in Matlab. Based on experimentation, the PD was detected by using a fixed threshold, which was normalized for all data analyzed. The critical value of fixed threshold is calculated as:

$$\lambda = \sqrt{2 * \log(length(X))} \tag{5}$$

where X is measured signal with noise and $length(\ )$ is the number of samples.

Essentially, the details and approximations of the original signal are obtained by passing the normalized signal through a filter bank associated with the WT that consists of low and high-pass filters. Fig. 9 depicts detailed components of the de-noised signal (shown in Fig. 8) with realization from level 1 to level 8. For level 1 (Fig. 9(a)), ten PDs were detected and their maximum/minimum values range from +0.7 to -0.7; these occur at times 1, 3, 4, 17, 27 secs, etc. As would be expected, D2 was not detected at this level. Fig. 9(b) displays the corresponding PD activity at level 2, i.e. D2, and in this case, four PDs were detected at times 10, 12, 32 and 36 secs, with maximum and minimum values between +1 and -0.9. Here, there is an absence of the D1 components. Figs. 9(c) and 9(d) show complete absence of any PD activity. However, some PD activity is detected at 33 secs with maximum and minimum values between 0.2 and -0.4 in Fig. 9(e). Although there is a variation in signals occurring at the beginning and towards the end of levels 6-8 (Figs. 9(f) – 9(h)), this cannot be classed as PD activity by virtue of the fact that the signal components D6-D8 are not of short bursts but are of much lower frequency in nature.

It is thus apparent from the frequency realization that the only two levels that can be distinctly associated with PDs are D1 and D2, and these are shown in a more detailed form in Figs. 10 and 11. It should also be added that detection logic after summation of combined D1 and D2 components (SUM_D1&D2) is used to count the PD. In this respect, an extensive series of studies have revealed that once the measured signals have been de-noised and realized through the WT, the best approach to detect the PDs in a GIS is by combining components D1 and D2 emanating from levels 1 and 2.

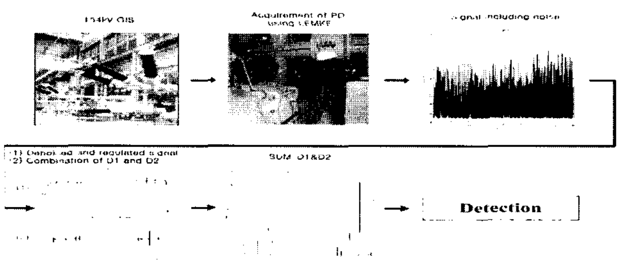


Fig. 6 Method for detection of partial discharge

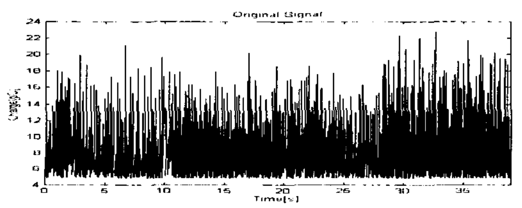


Fig. 7 Measured signal for a disconnecting switch

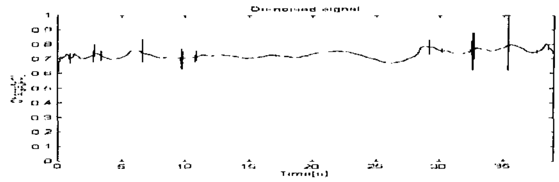


Fig. 8 Normalized and de-noised signal

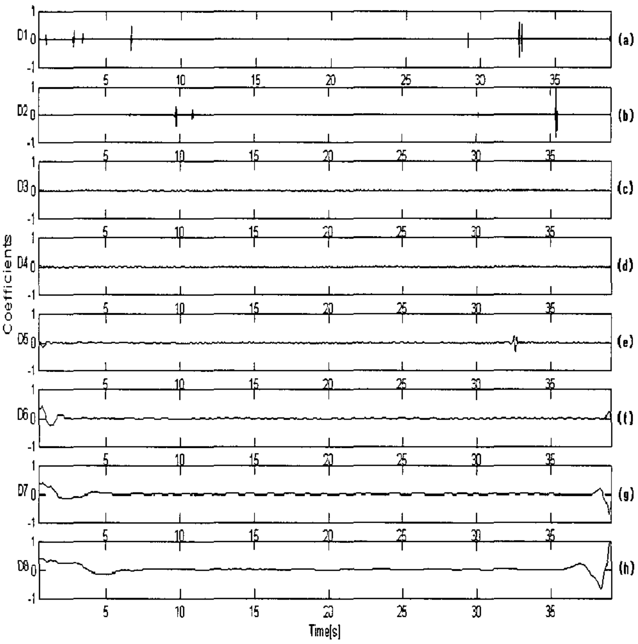


Fig. 9 Detail results of the wavelet transform
(a) highest level (level 1)
(h) lowest level (level 8)

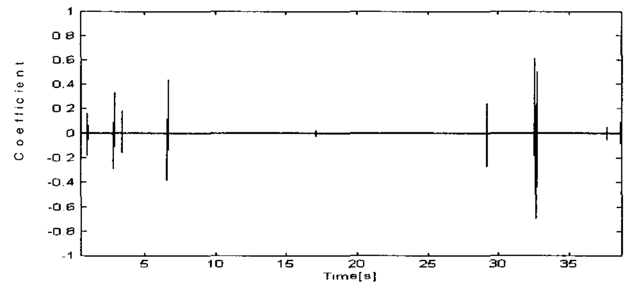


Fig. 10 Figure magnifying D1

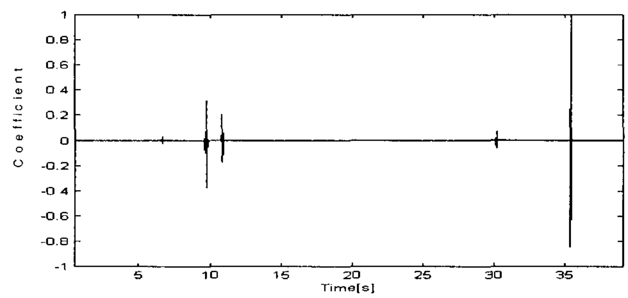


Fig. 11 Figure magnifying D2

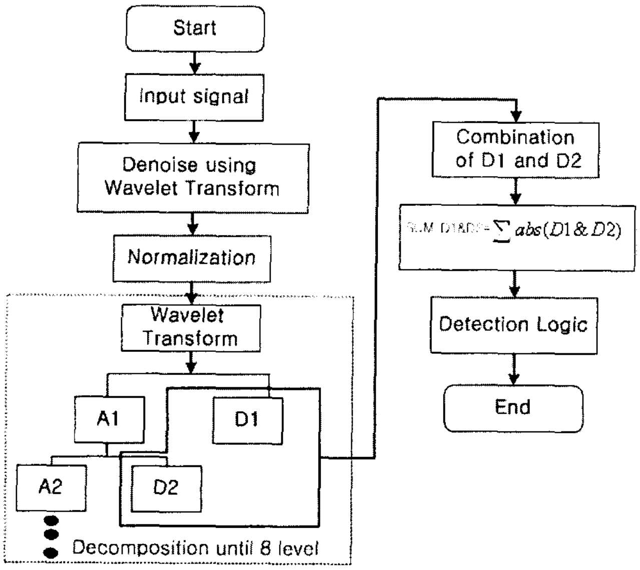


Fig. 12 Algorithm for detection of partial discharge using WT

Fig. 12 shows the algorithm developed for the detection of PDs. As mentioned before, the measured signals containing the PD activity contain a significant amount of spurious noise. The problem is compounded by the fact that much of this noise level is comparable to the magnitude of any PD components present. However, through the process of applying a threshold level and the WT, useful information in the form of short duration pulses can be extracted and normalized from the original measured signals and then a combination of D1 and D2 components emanating from levels 1 and 2 is conducted to detect the PDs in a GIS. Furthermore, detection logic after SUM_D1&D2 makes it possible to accurately detect the PD activity within the GIS.

SUM_D1&D2 is sum value of combined D1 and D2 for one cycle period and is represented as an absolute value. It should be mentioned that the summation process enhances the performance of the PD detection technique developed herein. Detection logic compares SUM_D1&D2 with threshold level, as the lower limit of SUM_D1&D2, which is used to detect the PD. Here, we define threshold level, which is less than the partial discharge and greater than the normal signal. The detection logic is conducted as follows. At PD occurrence, summation value temporarily increases to a point beyond the threshold level. Such variation has a single rising and falling edge. Thus, we detect PD at the rising edge of summation value, and count PD at the falling edge of summation value. As shown in Fig.12, the absolute sum value SUM_D1&D2 is based on summating the value of combined D1 and D2 components over a single cycle period. The whole process is based on a moving window approach whereby the 1 cycle window is moved continuously by 1 sample. The optimal setting for threshold level is 0.1.

5. Simulation Results

5.1 Uiryeong Substation

Fig. 13 shows the noise-ridden measured signal that is emanating from disconnecting switch 637DS at Uiryeong substation. Figs. 14 and 15 depict the de-noised signal and resultant PD spikes (combined D1 and D2 components); here the PD activity is prominent both in terms of frequency of occurrence and the actual magnitudes of the short bursts. Also, there is a clear indication of the presence of the PD phenomenon. Fig. 16 depicts the absolute sum value of combined D1 and D2 components using the db4 mother wavelet. It is apparent that PD occurs many times and this GIS is in fault state.

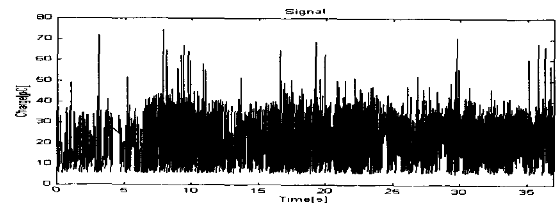


Fig. 13 Measured signal of 637 DS at Uiryeong substation

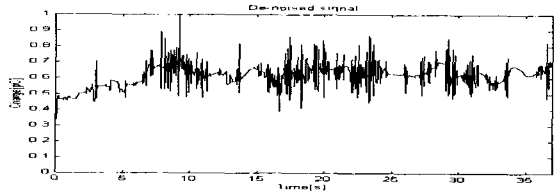


Fig. 14 Normalized and de-noised signal of 637 DS at Uiryeong substation

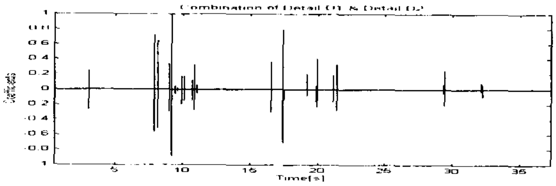


Fig. 15 Combination of D1 and D2 coefficients

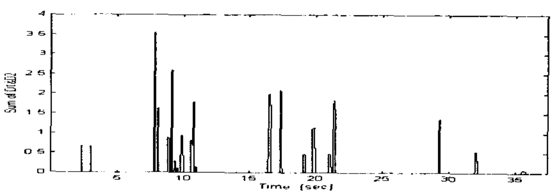


Fig. 16 Summation of combined D1 and D2 components

5.2 Hadong Substation

Figs. 17 to 20 typify the performance of the PD detection technique developed herein for the Hadong substation.

Fig. 20 shows the result of applying the algorithm to the noise-ridden measured signal shown in Fig. 17, which is for the measured signal emanating from a disconnecting switch. PD occurs with the highest magnitude as a whole; this corresponds to the waveform pattern observed in the de-noised signal illustrated in Fig. 18. Figs. 18 and 19 depict the de-noised signal and resultant PD spikes (combined D1 and D2 components). Fig. 20 shows the behavior of absolute sum value based on combined D1 and D2 components, as a function of time; the graphs also depict the moving window regime adopted. It is apparent that PD occurs many times and this GIS is in fault state.

5.2 Singosung Substation

Finally, Fig. 21 displays the measured signal of 6100CB at Singosung substation and Fig. 22 illustrates the normalized and de-noised signal attained at Singosung substation.

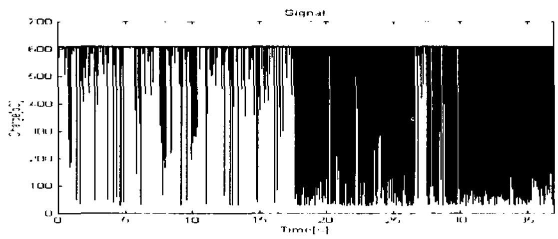


Fig. 17 Measured signal of 611 DS at Hadong substation

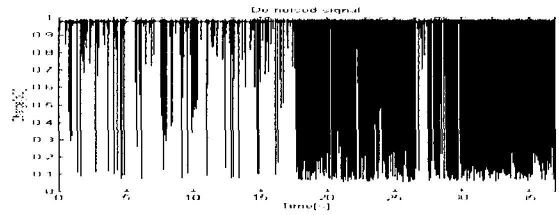


Fig. 18 Normalized and de-noised signal of 611 DS at Hadong substation

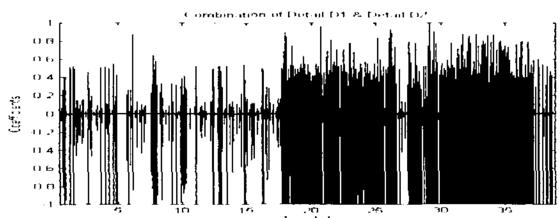


Fig. 19 Combination of D1 and D2 coefficients

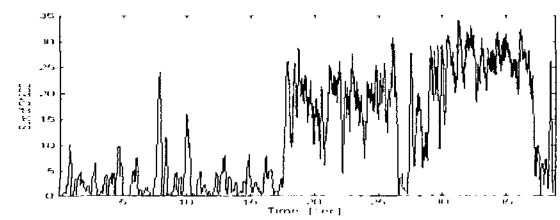


Fig. 20 Summation of combined D1 and D2 components

The former manifests itself into a significant PD activity as evident from the combined signal components of D1 and D2, very clearly indicated in Fig. 23. Fig. 24 typifies the variation in the absolute sum values of combined D1 and D2 components. When considering the dynamic behavior of the absolute sum value SUM_D1&D2 as a function of time, it is apparent that PD occurs many times and this GIS is in fault state.

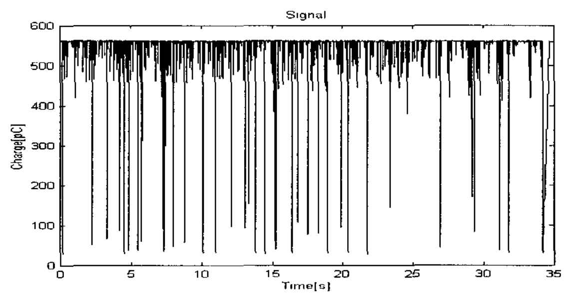


Fig. 21 Measured signal of 6100 CB at Singosung substation

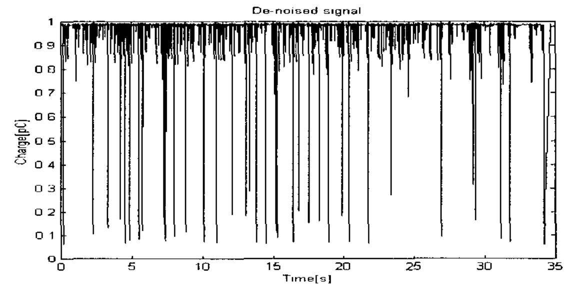


Fig. 22 Normalized and de-noised signal of 6100 CB at Singosung substation

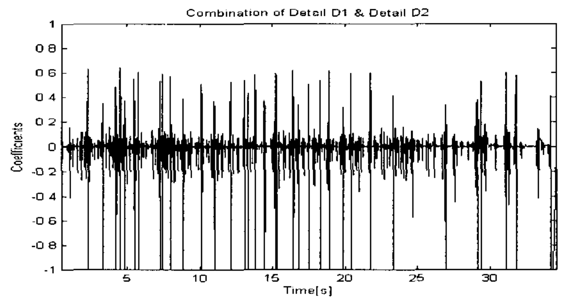


Fig. 23 Combination of D1 and D2 coefficients

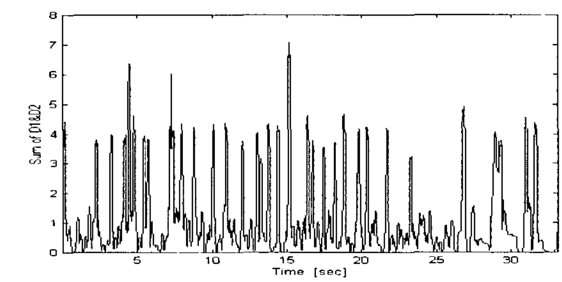
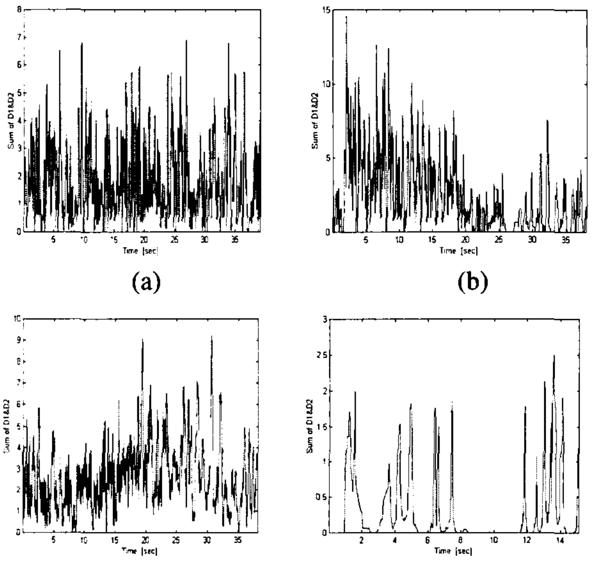


Fig. 24 Summation of combined D1 and D2 components

5.1 Summary

The performance of PD detection algorithm outlined herein was extensively tested for a set of measured signals emanating from a number of different substations viz., Chodong, Wanam, Shinkimhe, Sinwal and Machon. Fig. 25 typifies detection results of the practical measured at Sinwal 6131DS (fig. 25(a)), Uiryeong BUS (fig. 25(b)), Uiryeong 6100CB (fig. 25(c)) and Jindong 611DS (fig. 25(d)). Table 1 summarizes the performance of the PD detection technique described herein. It should be mentioned that these results accurately correspond to the findings of KEPCO, the Korean supply authority, which conducted the measurement tests using the previously mentioned LEMKE system.



(a) (b) (c) (d)

Fig. 25 Detection results of raw data

Table 1 Wavelet Transform of Practical Data

GIS Location (Substation)	Count of PD	SUM_D1&D2
Chodong 647CB	16 times	16 times
Gosung 626DS	5 times	5 times
Gosung 622DS	3 times	3 times
Gosung 6100BUS	17 times	17 times
Jindong 616DSB	8 times	8 times
Jindong 617CB	3 times	3 times
Jindong 626DS	8 times	8 times
Machon 6331DS	2 times	2 times
Shinkimhe 6344CB	1 time	1 time
Sinwal 6131DS	1 time	1 time
Sinwal 6301DS	6 times	6 times
Wanam 6232DS	1 time	1 time
Wanam 632DS	3 times	3 times

6. Conclusions

Accurate detection of PDs in all primary plants including GIS is increasingly becoming important by virtue of the fact that an early warning of any potential problems within a GIS would invoke a close examination of the plant and the corrective action to be initiated. This in turn would assist to enhance the reliability of electrical power supply to the consumers. In this paper, a PD technique based on the wavelet analysis technology is described. The db4 mother wavelet is chosen because of its asymmetrical characteristic and this makes it ideally suited for realizing the noise-ridden measurement signals thereby accurately extracting the PD signal. Also, detection logic is used to precisely detect PD after SUM_D1&D2 and combination of D1 and D2 coefficients. All the data employed are actual measured signals from a number of GISs on the Korean 154kV transmission system, which have definite recognized problems. The performance of the detection technique developed closely corresponds to the findings of KEPCO, thereby verifying the effectiveness of the technique and hence enhancing confidence in the developed technique.

Even though a conclusion may review the main results or contributions of the paper, the abstract or the introduction must not be duplicated. For a conclusion, elaboration might be placed on the importance of the work or on suggesting the potential applications and extensions.

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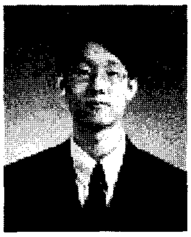

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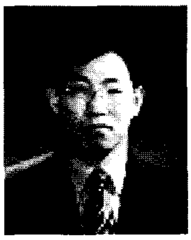

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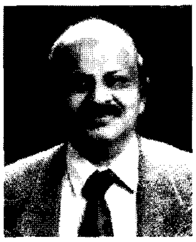

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