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Comparisons of Digital Filter, Matched Filter and Wavelet Transform in PD Detection

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SUMMARY

Analysis of Partial Discharge (PD) measurement is often hampered by electrical noise. To remove this noise it is necessary to apply sophisticated digital signal processing techniques. In the past, various digital filtering techniques based on the Fast Fourier Transform (FFT) were applied. However, their results have not been up to expectation. More recently, the recent application of the matched filters and the Wavelet Transform (WT) have shown great promise, in terms of the effectiveness of denoising and enhancing the SNR (signal-noise ratio).

This paper presents the authors' experience in applying three different types of techniques, i.e. matched filter, wavelet transform and the traditional digital filter, to PD data denoising in laboratory and industrial PD testing. The paper starts with an introduction to the background of the three methods. The second section of the paper presents the results of the application to, and the effects of the three methods on analysis of, PD data from laboratory experiments, practical PD testing on a 400/275kV power transformer using IEC60270 detection systems and PD testing on utility cables using high frequency current transformers (HFCTs). Finally the conclusions are presented with comparisons of the three methods in terms of effectiveness, computation time and their advantages and disadvantages.

The results revealed that both the matched filter and WT techniques are superior to the traditional digital filters in PD detection and analysis, in terms of SNR and the number of PD pulses that can be discriminated from noise. The matched filter is the most effective when the waveform of the signal to be detected is perfectly known and when the only interference present is white noise. The more flexible and robust technique of WT can be applied to on-site testing, where severe and more complex noise interference is present. Another important advantage of the WT over the matched filter is that WT allows unambiguous reconstruction of the original pulse, which is extremely useful given that the distinctive shapes of PD pulses may be used to identify signal sources, for diagnosis or validation purpose.

KEYWORDS

Partial Discharge, Denoising, Digital Filter, Wavelet Transform, Matched Filter.

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1. INTRODUCTION

Failure of high voltage plant is generally preceded by a degradation phase which may last several years. It is widely recognised that the degradation phase, irrespective of the causative mechanism, results in small sparks being generated at the site(s) of degradation. These electric sparks are generally referred to as partial discharges (PD). The detection and characterisation of PD can provide information on the location, nature, form and extent of degradation.

Unfortunately, and crucially, the data collection process can be severely compromised in practical, on-site testing. As the PD pulse signals from degradation sites can be extremely small, the detection strategy and equipment utilised must be capable of very sensitive measurements. In the field, this makes signal detection prone to the influence of external interference or 'noise' from the surrounding environment. At best, this generally results in data corruption, compromising the efficacy of the assessment of plant integrity. At worst, where the 'noise' plane is greater than the signal level from partial discharge activity, it generates a mistaken belief that no discharge activity exists.

Noise encountered in PD measurement includes radio frequency noise from communication systems, pulse-shaped noise from thyristor firing and stochastic noise generated by corona and ambient noise [1]. In an increasing number of situations it is expected that regular noise signals will also come from the electronics in inverter and motor exciter circuitry. To solve the problem of noise, a number of methods, in either frequency-domain or time-domain [2-5], have been used. Each of these screening and filtering techniques, i.e. analogue band-pass filtering, polarity discrimination circuitry, time-windowed methods and digital filters, is, however, applicable to only certain types of noise. Implementation of those methods also requires a knowledge and thorough understanding of the noise present, to ensure that the correct technique is applied. Determination of the noise structure inherent in the measurement can be extremely difficult, especially for on-line monitoring of PD activity, and requires expert intervention.

One of the main reasons for the ineffectiveness of the traditional methods is that all the methods in frequency domain, e.g. the digital filter techniques, employ the Fourier Transform (FT) which analyses signals in an infinite interval. It decomposes a signal in plane waves (trigonometric functions) which oscillate infinitely with the same period and have no local character. As PD pulses are of a transient, irregular and non-periodic nature, the FT fails to reveal a number of important pieces of information carried by the pulse, e.g. time of arrival and pulse duration.

In terms of the effectiveness of denoising, the recent application of matched filters [6] and the Wavelet Transform(WT) [7] have shown great promise. Mathematically the matched filter can be proven as the most powerful tool in maximising the signal-to-noise-ratio (SNR) of the filter output signal provided that the signal waveform is known. On the other hand, WT can overcome the difficulties encountered when applying the traditional methods in either time or frequency domain by providing a unique way of analysing data in that it presents the data in a time-scale (frequency) view. In other words, WT allows the PD data to be presented in the time-domain with segments of different frequency range of the data.

Over the last 5 years the present authors have carried out investigations into the use of WT in PD detection and analysis in laboratory experiments with different setups and on-site PD testing on transformers. They have also acquired large amounts of PD testing data on utility cables using HFCT. This paper presents the research work the present authors carried out over the last 5 years in applying the three different types of techniques, i.e., matched filter technique, wavelet transform and the traditional digital filter, to PD data denoising in lab and industrial PD testing and compares the methods in terms of effectiveness, computation time and their advantages and disadvantages.

2. WAVELET TRANSFORM Vs TRADITIONAL FILTER (FT) AND MATCHED FILTER TECHNIQUES.

The digital filter technique first transforms a signal from time domain to frequency domain and applies knowledge of the useful signal bandwidth of interest to remove noise. In the frequency spectrum, noise is subtracted from the corrupted signal based on the knowledge of frequency distribution of PD signal and dominant noise. Most earlier applications were based on this technique. The technique is easy to implement and is relatively less demanding than the other techniques in terms of processing power as it involves only a simple convolution process. However it does not distinguish a transient signal and a continuous one so long as they sit in the same frequency band.

The matched filter is designed to extract a known waveform from noisy data by calculating the cross correlation between the noisy data with the time-inversed filter impulse response of the known waveform[6]. If a waveform of identical shape exists in the data to be processed, the filter output signal equals the autocorrelation function of the waveform. Hence, the output reaches its maximum. The output of any other filter with the same energy as the matched filter has a lower peak value. Since the noise power at the filter output is the same for all filters of equal energy, the matched filter output has the highest SNR, and outperforms any other filter when it comes to noise reduction [6]. As a perfect match between the desired pulse shape and the matched filter is required in order for the method to produce maximum effect, a matched filter bank is required when incoming pulses possess different shapes. The variation in the PD pulse shapes may be due to the different geometry or mechanism of their source of origin or due to the attenuation the travelling pulses suffer on their way to detection systems.

The WT is a mathematical tool born in the mid-1980s [7]. Having evolved from the Fourier Transform, it is particularly designed to analyse transient, irregular and non-periodic signals in a phase-space (time-scale or time-frequency) domain. The WT provides a unique way of analysing data. It presents the data in a time-scale (frequency) view, allowing the PD data to be presented in the time-domain with segments of different frequency range of the data. From the proven power of the widely adopted discrete form of WT, i.e. Discrete Wavelet Transform (DWT), to denoise signals in areas where signals are transient, irregular and non-periodic in nature, e.g. the seismic, audio and video industries, this approach clearly has the potential to provide the fundamental breakthrough required to extract PD signals from noise. Ideally, if a wavelet can be automatically selected to match the PD pulse shape, the PD pulse could be extracted from data in any harsh environment, irrespective of the presence of any kind of noise.

Though the DWT generates more information than the FT, it is inherently more complex to apply than the basic FT and the FT-based filter approaches and involves procedures which are dependent on the shape of the signals to be extracted from noisy data, the record length and the sampling rate. The level of success of applying the technique sometimes depends on the experience and expertise of the users. The procedure of applying the DWT technique used in this paper is given in [4].

3. APPLICATION OF THE THREE METHODS TO LABORATORY EXPERIMENTS

To evaluate the effectiveness of the above-described three methods in denoising data from practical PD test, experiments were carried out in the HV lab using an experimental system as shown in Figure 1 and complying with the standard IEC 60270.

Each sample in the experiements simulates a single void-in-solid defect, which can be found in many solid insulation structures. The solid material is a two-part epoxy resin. The void is produced with great care. As a result, its surface is natural and the overall shape is spherical. In addition, the void is located in the middle of the resin slab, which is 2mm thick. The size of voids can not be accurately controlled but can be measured with optical microscopes.

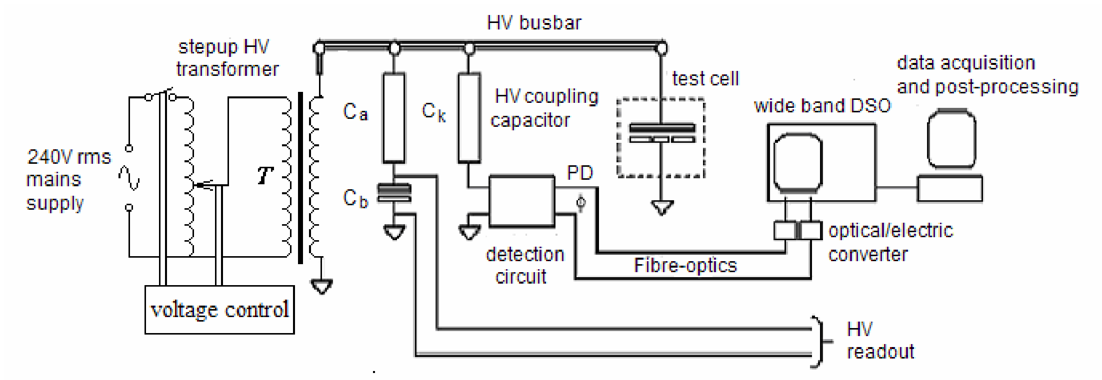
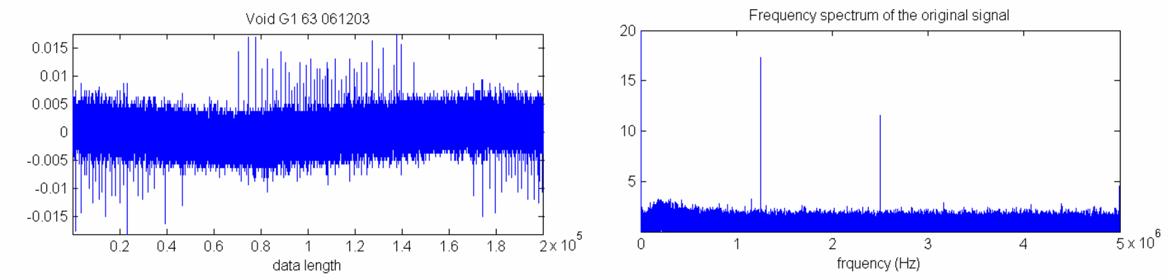


Figure 1 Experimental system showing both HV and detection circuits.

Figure 2 shows a typical set of data as obtained from the experiments. The sampling rate is set at 10MHz. During a full cycle of the 50Hz power frequency (20ms) a set of 200,000 sampling points is collected, a typical data waveform is shown in Figure 2. Calibration of the system has determined the sensitivity to be 1.6pC/mV.

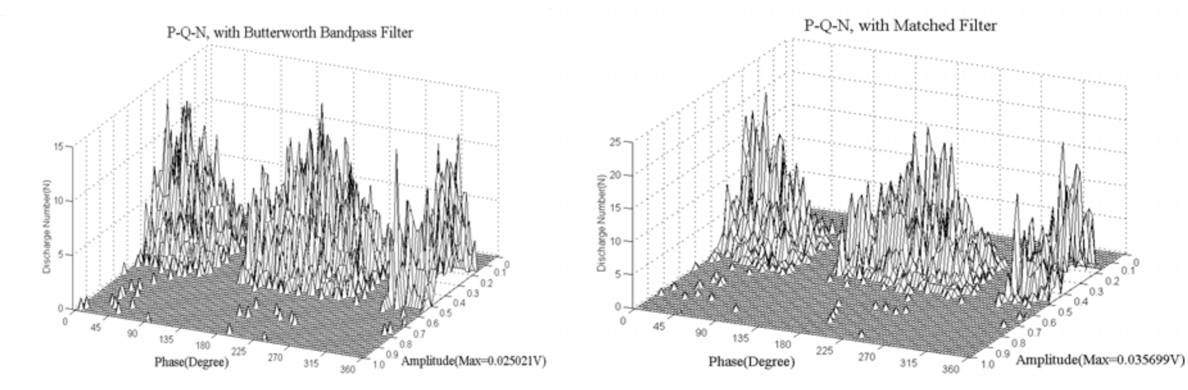


(a) (b)

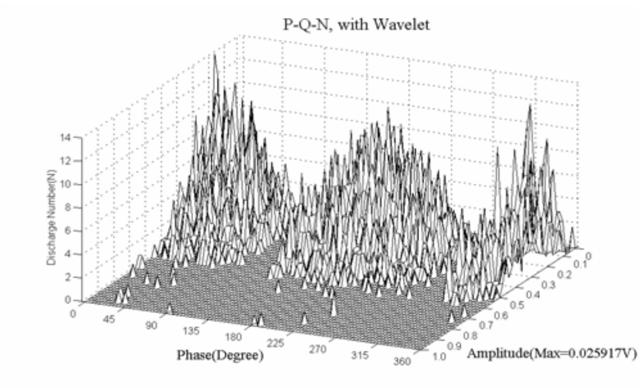
Figure 2 (a) Time-domain data acquired in the lab test using IEC60270 system from a resin sample with a 1.6mm void. (b) Signal in frequency domain.

The three algorithms, described previously, are then applied to the data and the resulting φ-q-n plots are displayed in Figure 3. The diagrams, showing the number of discharge pulses after denoising in relation to the phase angle and apparent charge, are produced using 20 identical records. Repeated experiments with point-point, point-air configuration have all led to the following conclusions:

- As the detection system response is known, the pulse shape is perfectly identified.
- Matched filter identified more PD pulses (about 20 compared with 15 from the other two methods).
- WT is the most effective at denoising after analysis of the frequency spectrums.



(a) (b)

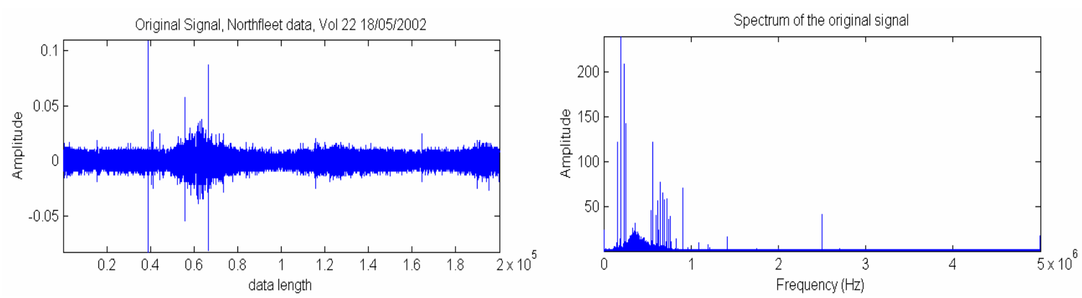


(c)

Figure 3 The φ-q-n plot of the PD activities after the application of (a) traditional filtering, (b) matched filter, and (c) wavelet technique developed by the authors.

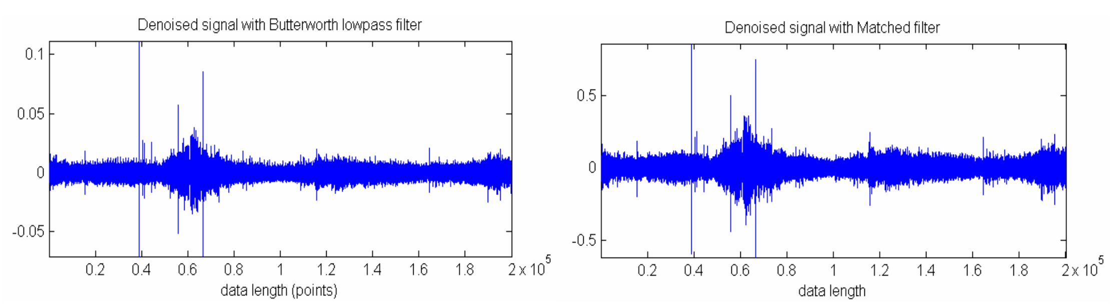
4. THE APPLICATION OF THE THREE METHODS TO PD TESTING ON A PRACTICAL TRANSFORMER

The same three methods have also been applied to signals collected during a practical test on a 400kV/275kV transformer at Northfleet substation [5]. The PD measurements were made simultaneously on each of the three phases on the 275kV side of the transformer using the same IEC60270 detection systems as that used in the laboratory experiments, shown in Figure 1. The IEC60270 response pulse was adjusted so that it has frequency components much lower than 5MHz. The sampling rate was set at 10MS/s. Figure 4 shows, in a similar manner to Figure 2, a typical PD data capture across a triggered 20ms power cycle for the C phase of the transformer. Figure 5 gives the denoised data in time domain using the three denoising techniques.

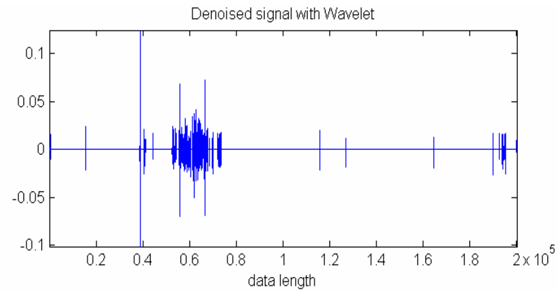


(a) (b)

Figure 4 Typical PD measurements across one power cycle on a 400kV transformer. (a) Original data in time domain, (b) The frequency spectrum of the original data.



(a) (b)



(c)

Figure 5 Denoised data following the application of: (a) traditional filtering, (b) matched filter, and (c) wavelet technique developed by the authors.

In this case, the output pulse shape from the detection circuit is supposed to be identical to those measured under lab test conditions. However the pulses were badly corrupted by strong RF noise as found following visual inspections on the original data. The application of the three methods for denoising revealed that the WT is the most effective as it removes most noise among the three methods and WT identified twice the amount of pulses than the other two methods. The reason that the matched filter technique loses its effectiveness is due to the distortion of the output pulse by the presence of strong RF signals near the central frequency of the detection system.

5. APPLICATION OF THE WT TO A CABLE PD DETECTION SYSTEM USING HFCT

The three methods are also applied to denoise data measured from a cable on-line PD measurement system. The setup of the condition monitoring system is illustrated in Figure 6 and a set of typical results is shown in Figure 7 where ths sampling rate is 100MS/s and the frequency bandwidth of the HFCT, which is attached to the earth strap of an 11kV feeder, is 13kHz-15MHz.

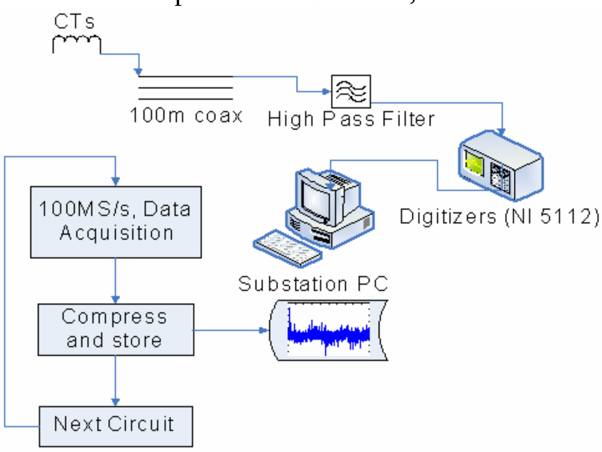
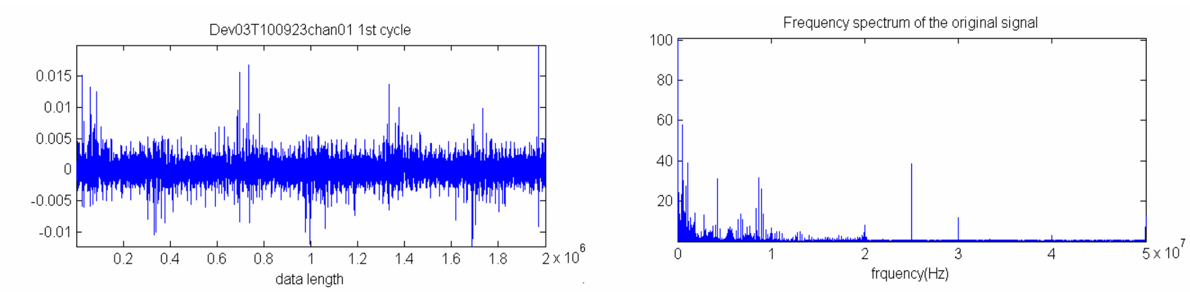


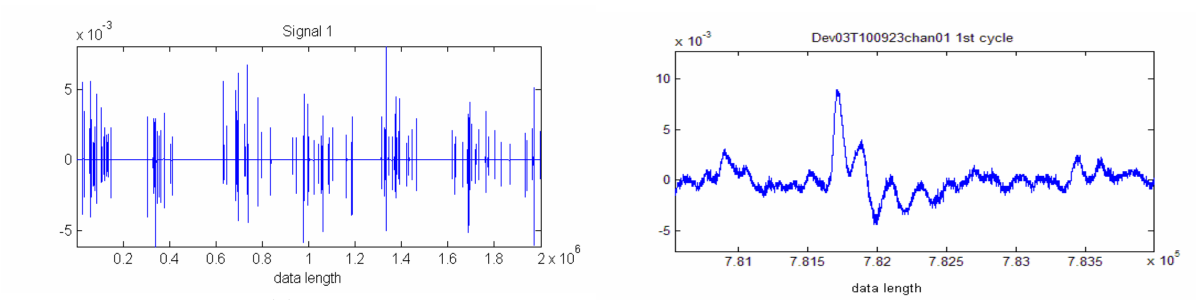
Figure 6 The setup of condition monitoring system in EDF Energy.



(a) (b)

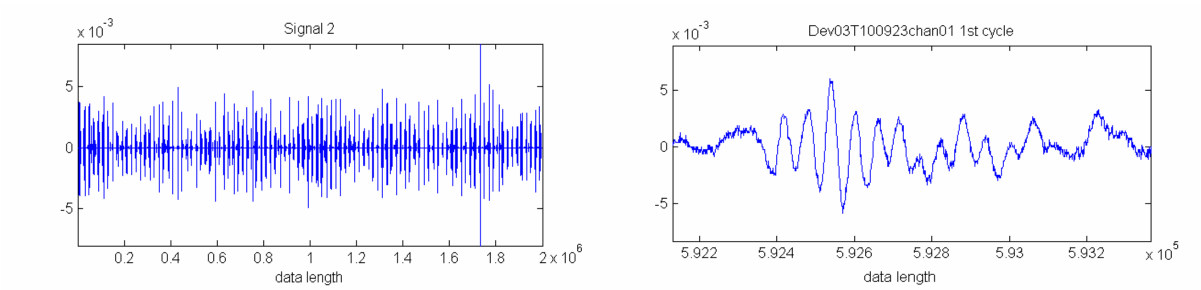
Figure 7 The PD measurement data from a 11kV feeder using HFCT in (a) time domain and (b) frequency domain.

The data clearly contains a significant amount of noise. The results of the analysis revealed that the data appears little changed after the application of the traditional filter technique. The matched filter simply does not work as the data contains different pulse shapes and some of them contain so many data points that the application of matched filter technique crashes computer due to the amount of computation required. Wavelet analysis is the only method which can not only remove noise, but also allows identification and classification of different types of signals as demonstrated in Figures 8 to 10. These figures show 4 types of transient signals which have been identified and reconstructed from the original signal, as given in Figure 7.



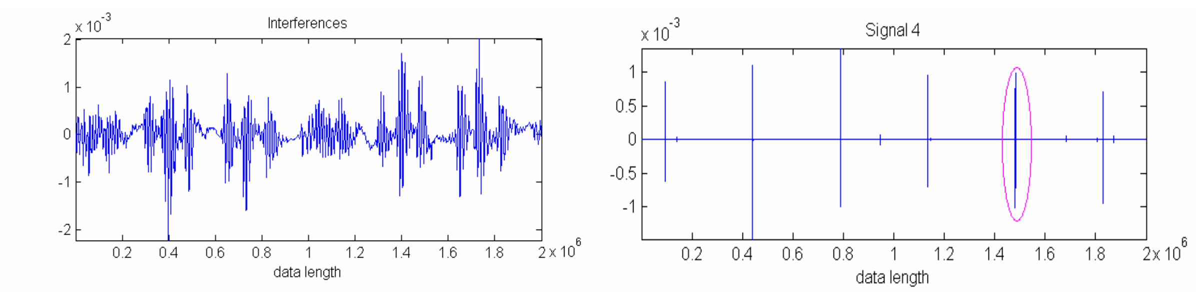
(a) (b)

Figure 8 The type-1 pulse identifed from Figure 7. (a) distribution over a cycle and (b) the shape of an individual pulse, the frequency bandwidth is just below 0-1MHz.



(a) (b)

Figure 9 The type-2 pulse identified from Figure 7. (a) the distribution over a cycle and (b) the shape of an individual pulse, the signal has a bandwidth of around 1.5-2MHz.



(a) (b)

Figure 10 (a) The type 3 pulse identified from Figure 7. The signal contains low-frequency ossicilations at around 0-300kHz. (b) The type-4 pulse identified from Figure 7. The signal contains 6 high frequency(around 20MHz) and high magnitude pulses.

As the signals in Figures 8 to10 are situated in different frequency ranges, they all appear at different levels, each of which provides a view of the original data in a specific frequency range[4], following the DWT, thus allowing denoising and reconstruction of the pulse shapes separately. The results represent a breakthrough in PD measurement denoising. The availability of such algorithms would be extremely valuable to PD measurement-based condition monitoring for power plant. First, after elimination of noise, smaller PD can be identified, PDs further away from detection points can be monitored. Secondly, with classification of pulse shapes, better diagnostics and localisation results can be expected. For example, the type-1 pulses above may be cable PDs whilst the type-2 pulse are due to local switchgear events. The type-3 pulse, identical to the data measured at another channel except for phase shift, and the type-4 pulse where the 6 pulses are symmetrical in phase are clearly the result of electronic activities. Furthermore the use of these kinds of denoising algorithms can reduce hardware deloyment, such as noise gate.

6. CONCLUSIONS AND DISCUSSIONS

The results of this investigation revealed that both the matched filter and WT techniques are superior to the traditional digital filters in PD detection and analysis in terms of SNR and the number of PDs that can be identified. The matched filter is the most effective when the waveform of the signal to be detected is perfectly known and where only white noise is present, whilst the WT can be more flexible and more robust for on-site testing in presence of severe noise interference. The matched filter loses its effectiveness quickly when the acquired pulse shape is distorted by noise or due to propagation from its site of origin to the detection point. Furthermore the processing time required by the WT increases linearly with the data length of the wavelet in contrast to that the time required using the matched filter increases exponentially with the date length of the matched filter. Another important advantage of the WT over the matched filter is that WT allows unambiguous reconstruction of the original pulse, which is extremely useful when PD activities of distinct shape need to be identified for diagnosis or validation purpose.

In conclusion, the use of WT for denoising PD measurement data will better help utility companies gain more robust data for plant condition monitoring. By effectively removing noise interference smaller PDs can be identified. PDs further away from detection points can be monitored. Successful categorisition or identification of different pulse shapes will enable diagnosis and localisation of defect site and lead to better diagnosis results.The utilities will enjoy a reduced risk of plant failure through more effective assessment of their plant integrity. This will have significant economic and health/safety implications to an ageing plant population.

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