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Application of Wavelet-Based De-noising to Online Measurement of Partial Discharges

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Abstract: For online detection of partial discharge (PD) activity within power cables and cable accessories, one of the non-conventional PD detection techniques, VHF capacitive coupling has been proved to be suitable. However, the existence of excessive interference will significantly influence the measurement sensitivity and reliability. This paper investigates the application of wavelet transforms for de-noising signals obtained using capacitive couplers. The experimental work has been carried out on a 132kV cable loop with a known defect within the cable joint. Obtained results indicate that the wavelet analysis technique can effectively discriminate internal PD pulses among corona discharges and pulse-like interference. Further, removal of interference has been achieved by applying level dependent threshold values.

INTRODUCTION

Online partial discharge (PD) detection using non-conventional PD techniques such as capacitive couplers, inductive couplers and acoustic emission methods, has recently become popular. However, the big challenge of onsite PD tests is to cope with excessive noise and interference.

A wide range of noise and interference can be experienced during onsite PD measurements, according to their characteristics they can be classified using the following [1]

- Discrete Spectral Interference (DSI) from radio transmissions and power line carrier communication systems
- Periodic pulse-shaped interferences from power electronics and other periodic switching etc.
- Stochastic pulse-shaped interferences due to the discharges from other power equipment
- Random noise similar to the white noise from amplifiers

Various methods for post-processing of PD signals have been reported with the advancement in digital signal processing techniques during the last two decades. These methods include designing of suitable filters (FIR and IIR), Fast Fourier Transform (FFT) based approaches, moving averages, adaptive filtering as well as wavelet analysis. Among them wavelet analysis has recently been found to be an extremely efficient tool in partial discharge detection as it can provide both time and frequency domain information [1-4]. However most published work is concerned with the processing of signals acquired by conventional PD detection method. For online PD detection, signal post-processing techniques have only been applied to a few non-conventional PD detection sensors so far such as Rogowski coils and current transducers (CT)[5]. It is necessary to investigate the de-noising of signals obtained using capacitive couplers.

WAVELET BASICS AND DENOISING

Basics

A wavelet is a small waveform with limited duration and a zero mean value. Similar to the Fourier Transform, which breaks up a signal into sine waves of various frequencies, the wavelet transform breaks up a signal into shifted and scaled versions of the original (or mother) wavelet. A continuous wavelet transform is defined as the sum over all time of the signal s(t) multiplied by a scaled and shifted version of the wavelet function ψ [6]

$$C(a,\ b) = |a|^{-\frac{1}{2}} \int s(t)\,\psi\left(\frac{t-b}{a}\right)dt \qquad (1)$$

Where, ψ is the mother wavelet, b is the shift operator and a is the scaling function. The result is a two-dimensional coefficient array of scale a (related to frequency) and position b (related to time) of the time domain signal s(t). The continuous wavelet transform is computationally intensive and generates a lot of redundant data. Therefore the discrete wavelet transform (DWT) is usually employed at $a = 2^j$ and $b = k2^j$ (j, k are positive integers) for speed and convenience.

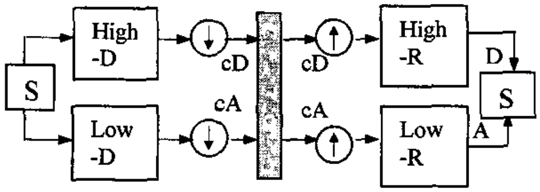

Figure 1. One stage decomposition and reconstruction

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Single level signal discrete wavelet decomposition produces a series of approximation coefficients (cA) and detail coefficients (cD) through a low-pass filter (low-D) and a high-pass (High-D) filter respectively as illustrated in Figure 1. The approximation (A) and detail (D) of a signal can be reconstructed using reconstruction filters (High-R, Low-R) based on these coefficients, which correspond to the low frequency and high frequency components of the signal(s). Multi-resolution Signal Decomposition (MSD) up to level j produces series of approximation and detail coefficients corresponding to multi frequency sub-bands of the signal [6].

De-noising Procedures

The principle of de-noising based on MSD wavelet analysis is simple; first the original signal is decomposed into approximation and detail components up to desired number of levels. This is done by first choosing a suitable mother wavelet according to the signal and noise characteristics. Then those components corresponding to PD signals, interference and random noise are identified at each level by visual inspection and knowledge of frequency characteristics. Finally those coefficients corresponding to interference and random noise are discarded while retaining those coefficients corresponding to PD signals by setting threshold values accordingly. The reconstruction of the signal based on the modified coefficients gives an interference-free signal.

CHARACTERISTICS OF SIGNALS DETECTED BY CAPACITIVE COUPLERS AND ISSUES IN APPLICATION OF WAVELET METHOD

Signal Characteristics Compared to Conventional PD Detection

Compared to the conventional narrow-band PD detection method, capacitive couplers are very sensitive and broadband. Figure 2 shows a PD pulse captured by a capacitive coupler and a conventional PD detector (Robinson 700). The zoomed PD pulse and its frequency distribution are given in Figure 3.

The PD activity itself inside a void is very fast and usually lasts only a few nanoseconds or less. The detected pulse depends on the coupling and measuring system. As can be seen from time domain the PD pulse captured by CC lasts less than 50ns, while the same activity captured by conventional PD detector lasts much longer (30 microseconds) due to its quasi-integral procedure in the measurement. In the frequency domain a conventional PD detector usually works below 1MHz, while the frequency band of the CC is very wide up to several hundreds of MHz. In general, signals detected by CCs are quite different in both time domain and frequency domain with conventional PD detectors, therefore special considerations should be given in the post-processing of these signals using wavelet analysis.

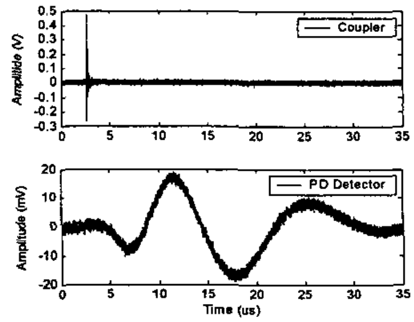

Figure 2 Same PD pulse captured by a CC and a PD Detector

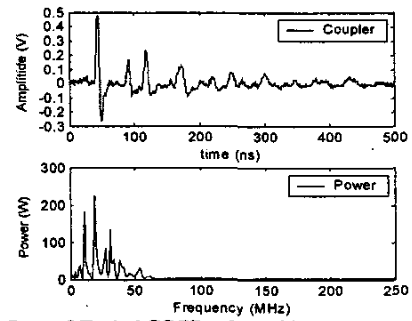

Figure 3 Typical CC PD pulse and its power spectrum

Selection of Mother Wavelet

The selection of the suitable mother wavelet function is essential in using the wavelet analysis. Best wavelets are those that can represent the signal of interest as effective as possible. This can be difficult to implement in practice. In most cases, a trial and error method is used. Ma et al. [3,4] discussed optimal wavelet selection based on calculation of the cross-correlation coefficients between PD pulses and wavelet shapes regarding signals obtained using conventional PD detectors; db2 and db8 are thought to be the best wavelet for analysing an exponential PD pulse and a damped resonant PD pulse respectively. From the frequency point of view, the main consideration in choosing the wavelet is the central frequency of the wavelet compared to the signal of interest. In this application, db1 was chosen as it has the highest central frequency in Daubeches family. Some other wavelets with sharp waveform such as lower order biorthogonal wavelets bior1.1 and reverse biorthogonal wavelets rbio1.1 and rbio1.3 can also give good results.

Number of Decomposition Levels

The determination of the number of decomposition levels depends on the lowest interference frequency bands to be eliminated from the signal. The goal is to have sufficient resolution in the low frequency range in order to suppress the interference completely. 10 levels were chosen and found to be sufficient for this application.

Threshold

The de-noising procedure involves thresholding of those coefficients corresponding to signals and interference as mentioned above. The determination of threshold values is based on the identification and evaluation of these coefficients corresponding to the signal and interference. In this application threshold values are manually determined as no automatic threshold rules are available for pulse-shaped interference. Hard-threshold method was adopted as it can maintain the PD pulse magnitude better than the soft-threshold method.

TEST ARRANGEMENT

The HV test was carried out on a 132kV cable loop system as illustrated in Figure 4. Two sections of cable are connected through a prefabricated cable joint with a known defect (conducting paint). Both ends of the cable are terminated with oil-filled cable terminations. A capacitive coupler (CC) is installed near the defect side of the cable in order to detect the internal PD activities caused by the conducting paint inside the joint. A surge protector (sgp) with maximum operating frequency up to 1GHz and response time less then 10ns is connected to the output of the coupler to protect the measuring system from possible over-voltage. The measuring system consists of a digital oscilloscope (LC684DXL) and a personal computer. A 20dB broadband amplifier (up to 1GHz) is used to amplify the signal before it is fed to the digital oscilloscope. The personal computer is connected to the oscilloscope via a GPIB board to collect the data for post-processing.

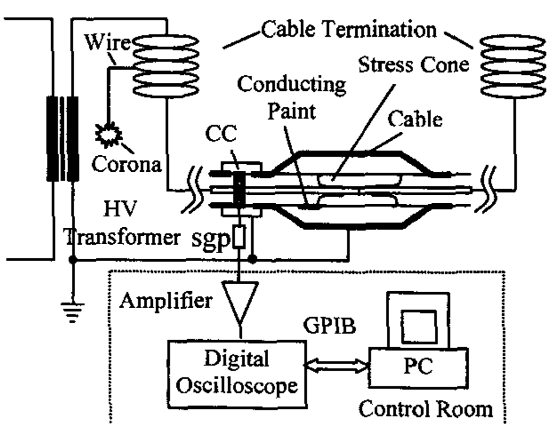

Figure 4 Experiment arrangement

Based on the frequency components shown in Figure 3, in which sampling rate of 1GHz was used to ensure the sampling complies with Shannon's sampling theorem. As can be seen from it, the power frequency components of the PD pulse detected by CC is below 100MHz. So a lower sampling rate of 250MHz was used to ensure manageable amounts of data are collected over a power cycle.

Corona discharges are the most common interference during online PD measurements. In this case corona discharges were produced using a metal wire connected to the HV side (Figure 4).

RESULTS

PD Activities Without Corona Interference

The test was first carried out without introducing corona interference. Figure 5 shows the obtained PD activities over one power cycle (20ms) and their persistence plot under high voltage of 35kV. Two fixed phase interference pulses located approximately at 10ms and 20ms have been detected as can be seen from the persistence plot. The pulses in the first and third quadrants are internal PD pulses.

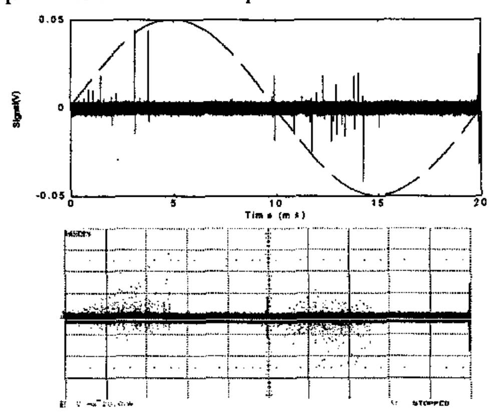

Figure 5 PD activities without corona interference and their persistence plot at 35kV

Wavelet De-noising of PD with Corona Interference

Corona discharges were introduced into the system as external interference. Figure 6a and Figure 7 show the result and its persistence plot over one power cycle at an applied high voltage of 30kV. The persistence plot clearly shows corona discharge pulses around the negative peak and two other pulse-shaped interference pulses. However from the original signal shown in Figure 6a, internal PD pulses and external corona discharge pulses are mixed together and it is difficult to discriminate between them just by visual inspection.

The original signal has then been decomposed into details and approximations up to 10 levels using the db1 wavelet (Figure 8). The detail level 1 D1 clearly shows all of the internal PD pulses, while the corona pulses are mostly concentrated in detail level 3 D3. The two pulse-shaped interference pulses located at 10ms and 20ms cannot be seen in D1 and D2 at all. They are distributed among several levels from D3 to D9. This indicates that their frequency components are much lower than that of corona pulses and internal PD pulses. This kind of pulse interference always occurs at specific phase angles and is very common in PD tests. Köpf et al. [7] have reported similar interference pulses. They are caused by facilities that are operating synchronously with the mains such as rotating machines with commutators, rectifiers as well as other power electronic devices.

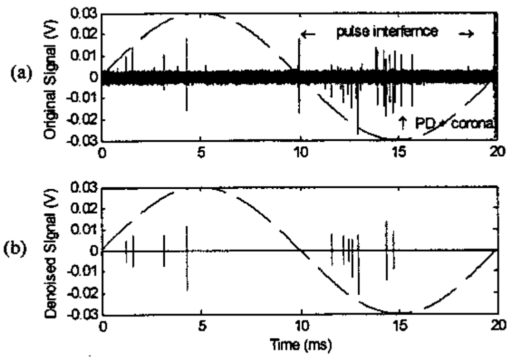

Figure 6 (a) original and (b) de-noised signals for 1 power cycle

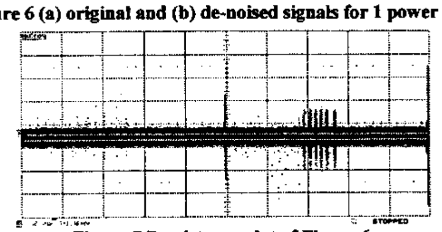

Figure 7 Persistence plot of Figure 6a

The above wavelet decomposition has effectively discriminated internal PD pulses among external corona discharges and two synchronous interference pulses. The final procedure is de-noising by setting threshold values at each level. This has been done manually in this case with the following threshold values from level 1 to level 10 ([0.006, 0.01, 0.017,0.038, 0.088, 0.166, 0.063, 0.026, 0.018, 0.019]). All pulse-shaped interference and random noise have been effectively removed as can be seen from Figure 6b.

CONCLUSIONS

Regarding the characteristics of the capacitive coupler, wavelet analysis has been applied to the signals obtained using capacitive couplers. Results shows that it can effectively discriminate internal PD pulses among pulse-shaped interference such as corona discharge and synchronous pulse interference as well as random noise through carefully selection of the mother wavelet function and decomposition levels. Further removal of interference has been accomplished by setting threshold values for each level. Signal to noise ratio has been significantly increased with minimum loss of pulse magnitude and distortion of the pulse shape. This is significant considering online PD measurements and further quantification of measured results.

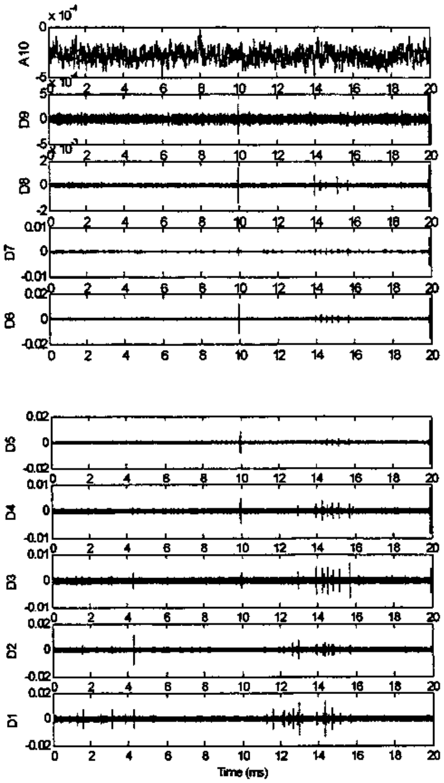

Figure 8 Decomposition results of the original signal in Figure 6a

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