A new technique for detecting partial discharges within an on-line power transformer subjected to interference

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Abstract

Increased demand on power transformers, due to the extension of equipment lifetimes and a trend to lower costs, has led to a need for condition based maintenance. However, there are currently no established techniques to accurately monitor and diagnose faults in real-time while the transformer is on-line. A major factor in the degradation of transformer insulation is partial discharging which, if left unattended, will eventually cause complete insulation failure. A partial discharge detection system (PDDS) is presented for electrically identifying partial discharge pulses and determining the number of partial discharge sources while the transformer is on-line and subjected to external interference. Current and voltage transducers are placed on the transformer bushings rendering it unnecessary for the transformer to be disconnected or opened. Partial discharge pulses are identified within narrowband and pulse interference using digital signal processing techniques which include an automated Fourier domain threshold filter and a continuous wavelet directional coupling filter. If multiple sources are active, the partial discharge pulses are grouped by a clustering neural network. Two 7.5kVA, 11kV transformers were used to conduct testing of the PDDS. High recognition rates of artificial partial discharge pulses were achieved in an off-line transformer, while a previously unknown natural partial discharge source was identified in the second energised transformer.

1 Introduction

Demands for electrical power and its distribution have been continuing to increase worldwide during the past decades. Naturally, this leads to the requirement for more power generation and for networks to transport it, which places a burden on the insulation of sometimes aging high voltage (HV) equipment. Power transformers are central and often critical components of any such power distribution network and their continued reliability is necessary for the integrity of that network. Under a system called condition based maintenance (CBM), repairing or replacing electrical equipment is done as required to prevent outages, rather than on an emergency or periodical basis. This allows operation of existing equipment to be optimised, working it harder and longer based on what it is truly capable of. Therefore, an accurate knowledge is needed of the current state of the electrical equipment, which includes the insulation of power transformers. This information should ideally be gathered in a timely fashion and while the transformer is operating on-line.

The insulation in power transformers slowly degrades over several decades, due to factors such as thermal, dielectric and mechanically related stress [1]. Various techniques have gradually been developed to provide information about transformer insulation degradation, including loading and temperature data, study of oil samples, dissolved gas analysis (DGA), total combustible gas (TCG), furanic compound analysis, degree of polymerisation (DP), dielectric response, low voltage impulse (LVI) testing, leakage inductance measurements, frequency response analysis (FRA) and partial discharge (PD) detection [1, 4, 13, 12, 2, 11, 9]. While combinations of techniques provide useful information, the issue of knowing the condition of a transformer and when a problem is going to occur is not yet solved, and high cost monitoring and diagnostic systems cannot be justified on economic terms.

The primary established techniques for electrical PD detection by measuring current or radio frequency (RF) pulses, as detailed in standards [3], are performed when the transformer is off-line and preferably within a shielded enclosure to eliminate electrical interference. Suppression of interference is one of the main challenges in detecting PDs, either while the transformer is off-line or on-line in a noisy environment. The off-line PD detection methods only provide snapshots in time of part of the transformer's condition. On the other hand, no standards have yet been developed for on-line electrical monitoring of PDs. In this case, the main sources of interference are narrowband signals, such as radio stations, and other pulse generators, such as external corona sources.

This paper presents the development of a partial discharge detection system (PDDS) that captures current and voltage signals at external taps of an on-line transformer. It is designed to be fitted to transformers already in use and does not require high voltage (HV) components that are typically expensive. New variations of signal processing techniques are used to identify PD pulses that may be buried in external narrowband and pulse interference. Two 7.5kVA, 11kV transformers were used to conduct testing of the PDDS. The first transformer (Tx1) was opened and modified so that internal PDs could be simulated by injecting artificial pulses. A second identically constructed transformer (Tx2) was energised and analysed for any natural PDs while external interference was present.

2 Overview of the partial discharge detection system

The main components of the partial discharge detection system are shown in Figure 1. Each segment is briefly described as follows:

- **Transducers:** A current transducer and a voltage transducer are attached to the base of each bushing of the transformer. The current transducer is in the form of a Rogowski coil, and the voltage transducer consists of two metal sheets forming a capacitive voltage divider. The bushing ceramic is used as the HV dielectric medium.

- **Analog filters:** A highpass filter for each current and voltage transducer prevents aliasing effects when signals are digitised. A lowpass filter attenuates power

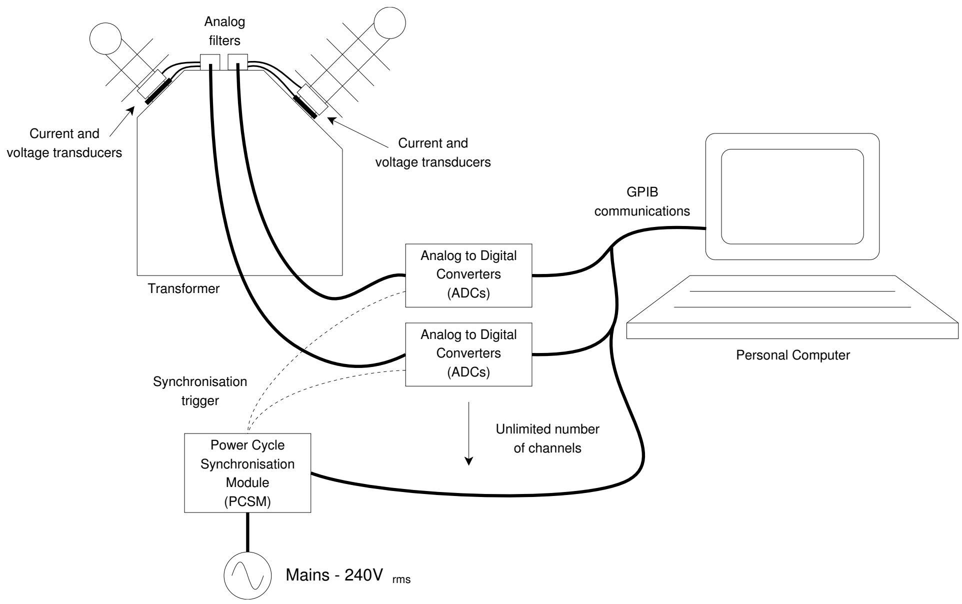


Figure 1: Simplified description of the partial discharge detection system.

frequency signals in order to improve the digital vertical resolution of captured signals.

- **Signal digitisation:** An analog to digital converter (ADC) for each channel captures the signals for use in a personal computer. For this prototype setup, HP54650A oscilloscopes were used. Each oscilloscope has a HP-IB Interface Module that provides a General Purpose Interface Bus (GPIB) port and is connected to a personal computer GPIB add-in card.

- **Power cycle synchronisation module (PCSM):** In order to reference PD pulses to the phase of the power cycle, the PCSM provides a trigger signal for ADC timing and synchronisation purposes.

- **Personal computer (PC):** Digitised signals are analysed by the PC through several sequential processing stages to identify any transformer PDs and the number of internal PD sources.

- **Software stages:**

  - **Fourier domain threshold filter (FDTF):** Each signal is transformed to the Fourier domain, where any significant narrowband signals are attenuated.
  - **Continuous wavelet directional coupling filter (CWDCF):** The current and voltage signals from a bushing are transformed using the continuous wavelet transform (CWT) and then combined to search for pulses travelling from the transformer. This is repeated for each bushing to confirm that a pulse has not originated from an external source and traversed the transformer winding.

– **Cluster neural network (CNN):** A neural network that does not require any prior knowledge is provided with the waveshapes of all identified internal PD pulses. The network groups the pulses to determine the number of PD sources and to provide information for phase resolved partial discharge analysis (PRPDA) plots for each source.

3 Hardware components

The PDDS can theoretically accept any number of input channels, allowing it to be used on three-phase transformers and other transformers with additional taps. To ensure that a PD pulse originates within the transformer, all external taps must be monitored. However, bushings and taps may be known to be free of external pulse interference and consequently do not require monitoring.

Two different types of transducers are used to acquire current and voltage signals from the transformer bushings for digitisation by the ADCs. The current transducer employed in the PDDS prototype is a Tektronix A6302 current probe connected to its matching Tektronix AM503 current probe amplifier. The current probe aperture is approximately 5mm, which is unsuitable for clipping around the bushing itself but can be clipped around a wire connected to a transformer bushing. However, there are current probes commercially available [8] that are suitable for the on-line environment.

The voltage transducer consists of a capacitive voltage-divider circuit, which uses the bushing of the transformer as a high voltage insulator, as shown in Figure 2(a). A resistor is placed across C_2 to form a highpass filter for power frequency voltage attenuation purposes and to increase the dynamic range of the ADCs. This design of the transducer also removes the need for an expensive high voltage measuring capacitor to be connected to the bushing. The voltage transducer is constructed of two layers of metal foil wrapped around the base of the bushing near the tank wall. The foil layers are each 14cm by 5cm in area and are separated by layers of paper. A cross section of the bushing and capacitors is shown in Figure 2(b). If available, a bushing tap could be used instead. It is not necessary to precisely know the various attenuation ratios because, once the capacitive voltage divider has been placed on the bushing of the transformer under test, calibration is performed.

Amplification and filtering are performed before digitisation both in order to remove unwanted frequency bands and to extend the effective dynamic range of the oscilloscope ADCs, which only provide 8 bit vertical resolution. PD pulses have been shown to contain transmitted frequencies of up to several tens of MHz at the bushing terminal. However, because of the cost of high speed ADCs and the increased computer processing time for the extra data gathered, a digitisation sample rate of 10MSa/s is chosen for the PDDS. This sample rate is not sufficient to observe subtle variations in waveshape contained in higher frequencies which can distinguish PD pulses coming from different sources. Therefore, a single high frequency (HF) channel is dedicated to recording pulses at a sample rate of 50MSa/s. In the PDDS, an analog filter cut-off frequency of approximately 2MHz is chosen. It is important that the frequency responses of the current and voltage transducer/filter combinations match, so that any pulse oscillations are synchronised in the time domain. This allows directional coupling to perform effectively. Highpass analog filtering is also performed in the PDDS in order to remove the power frequency and its

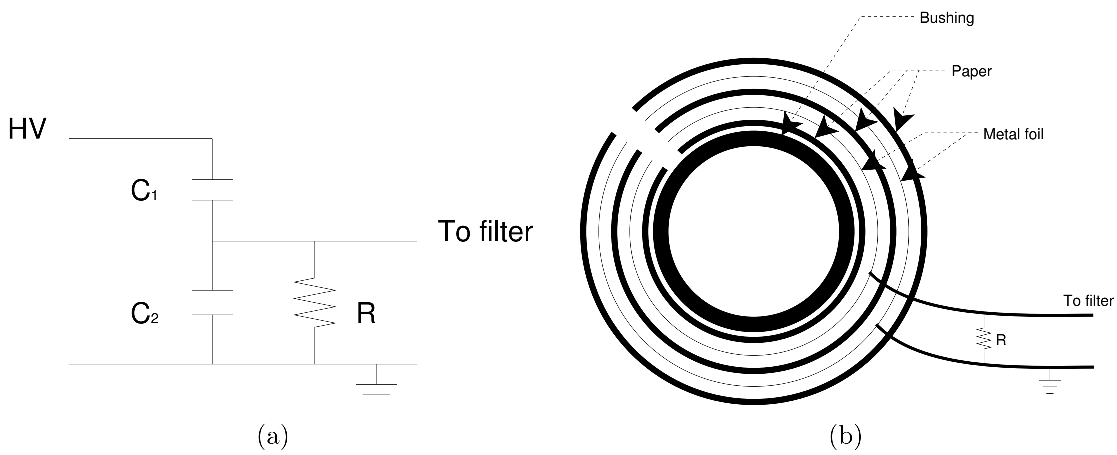


Figure 2: Voltage transducer: (a) capacitive voltage divider and (b) physical cross-section.

high magnitude harmonics, which improves the dynamic range of the ADCs.

In the case of the current transducer, a 5-pole Butterworth lowpass passive filter provides antialiasing for the ADCs with a high frequency -3dB cut-off at 2MHz. A 3-pole Butterworth highpass passive filter reduces power frequency magnitudes and has a low frequency -3dB cut-off at 30kHz. For the voltage transducer, an active filter provides high input impedance and amplification of the mV scale signals before digitisation. A second-order highpass filter follows an input buffer and precedes a fourth-order lowpass Butterworth filter. An op-amp provides amplification if necessary. The high sample rate channel is routed from the point before the lowpass filter. Additional anti-alias filtering built into the oscilloscopes provides lowpass filtering with a -3dB cut-off frequency of approximately 20MHz.

The frequency response of the voltage and current signal channels is a combination of the frequency responses of the transducers, filters and amplifiers. It was determined by injecting a variable frequency sinusoidal signal at the HV bushing terminal and is shown in Figure 3.

In order to be able to perform PRDPA, the timings of PD pulses have to be noted with respect to the power cycle phase. The PCSM provides a synchronisation trigger for all oscilloscopes at a consistent power cycle phase point, in this case, the voltage positive-going zero crossing. The PCSM trigger output on/off status is controllable from the PC, so that the recording of a new set of data is only initiated once the previous set has been analysed.

4 Signal processing

The objective of the digital signal processing stages in the PDDS is to identify and display any PDs that may be present within a transformer and to determine if multiple PD sources are simultaneously active. The signal processing is performed using Matlab, which provides features for communicating with external instruments and can thus control the oscilloscopes, the PCSM and the arbitrary waveform generators used for PDDS testing. It typically requires several seconds for transferring data from the oscilloscopes

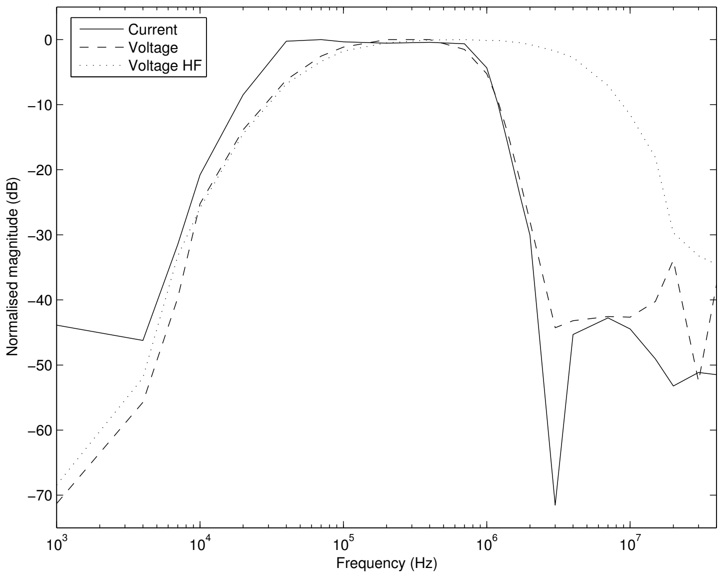


Figure 3: Frequency response of current, voltage and HF voltage transducers and analog filters on transformer Tx1.

to the PC and approximately 2 to 3 minutes for the PC to process the data. The speed of the digital signal processing in the PDDS is thus not fast enough for continuous real-time analysis. However, further optimisation of the signal processing algorithms could significantly decrease this time. Independently of this, only processing a small percentage of power cycles is still representative of the actual transformer PD condition, as PD sources will typically generate at least several pulses during every power cycle. In addition, a PD source normally changes its magnitude and phase timing characteristics over a much longer time frame than seconds or minutes.

The power transformer on-line environment typically involves interference that has been categorised into two types [10]. Continuous periodic interferences are sinusoidal, such as carrier communication, high frequency protection signals and radio broadcast. They appear as narrowband interference in the frequency domain. The other type of interference is pulse interference. It includes periodic pulse interference that occurs at fixed positions within the AC cycle, for instance, thyristor switching and non-periodic pulse interference where signals appear more or less at random, such as corona, external partial discharging and arcing between adjacent metallic components or from rotating machinery.

The temporal and frequency characteristics of narrowband interference and various types of interference pulses have little in common. The PDDS uses separate stages for removal of the different types of interference, as shown in Figure 4. The FDTF automatically removes narrowband signals of unknown frequency and magnitude. The corresponding algorithm is a form of multi-band rejection filter and consists of the following steps:

- The discrete time domain signal is transformed to the Fourier domain using the discrete Fourier transform (DFT).
- The Fourier domain sequence is divided into an arbitrary number of small, equal-

sized bins. The median of the absolute magnitude of the Fourier domain samples is calculated for each bin. Over the complete Fourier domain signal, these medians form a varying magnitude indicator that approximately matches the magnitude of the Fourier domain noise floor.

- A threshold level is calculated by multiplying the medians of each bin by 10.
- Any Fourier domain samples that have an absolute magnitude greater than the threshold are attenuated to the threshold, keeping phase information unchanged.
- The resulting thresholded signal is transformed back to the time domain using the inverse discrete Fourier transform (IDFT).

This method can handle signals in which the average magnitude of the noise floor varies with frequency. This may occur, for example, where a wide-band signal has dominant frequencies. Beat frequency effects caused by Fourier domain multiplications are countered by sampling extra data by the oscilloscopes at the start and the end of the time period of interest and which are discarded later.

Many real-world signals, such as PD pulses, consist of long duration, low frequency signals and short duration, high frequency signals. The continuous wavelet transform (CWT) can provide an excellent analysis of these signals, especially where a small and fast pulse appears at the same time as a larger and longer pulse. The CWT of a signal $f(t)$ and the inverse CWT (ICWT) are given by:

$$\mathrm{CWT}(s,\tau) = \int f(t)\Psi^*_{s,\tau}(t)dt \tag{1}$$

$$f(t) = \iint CWT(s,\tau)\Psi_{s,\tau}(t)d\tau ds \tag{2}$$

where * denotes complex conjugation [5]. The CWT is used instead of the discrete wavelet transform (DWT) because the CWT's extra data redundancy tends to reinforce subtle traits and generally makes information more visible, and because perfect reconstruction of signals is not required. As detailed in Figure 4, the CWTs of the current and voltage signals are multiplied in the CWDCF to result in a plot where positive values indicate internal signals and negative values indicate external signals, as shown in Figure 5. The positive CWT coefficients are used to select coefficients from the CWTs of the current and voltage waveforms for signal reconstruction purposes.

A CNN is used to differentiate PD pulses travelling from potentially multiple source locations within the transformer because it can separate inputs into logical groups without prior knowledge of the criteria for grouping [6].

As differences in the waveshape of pulses from different locations have been found to be most significant at higher frequencies [7], the single HF sub-channel (Ch1-V-HF) provides the input for the CNN of the PDDS. The CNN is trained with a sample of previously identified individual PD pulses, after which all PD pulses are presented to the CNN for group classification. Because the CNN starts with an excessive number of neurons or potential groupings, single groups of pulses from the same physical pulse location will be represented by multiple neurons. Comparison of neuron weight value differences allows the combination of results from similar neurons or groups.

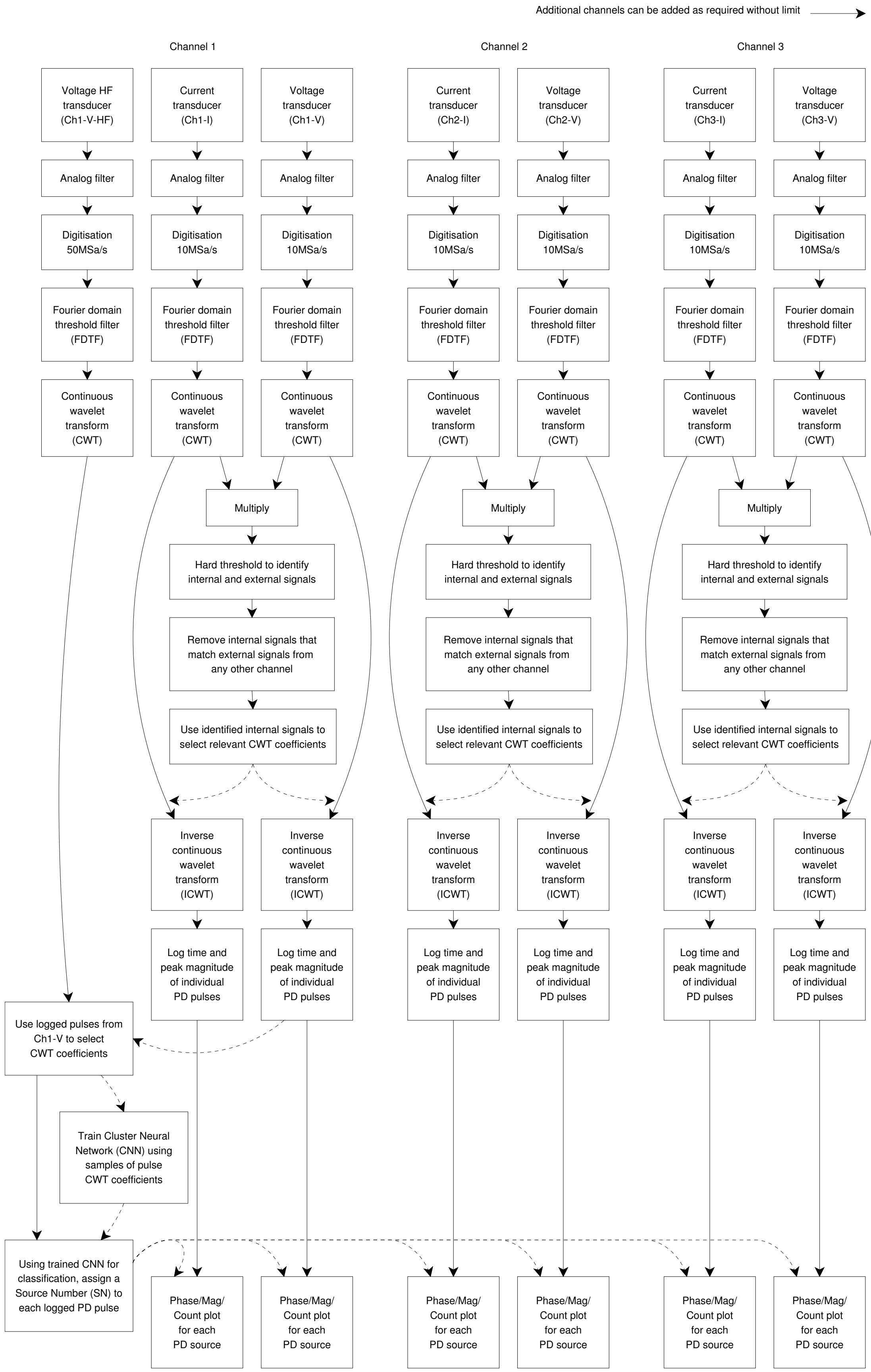
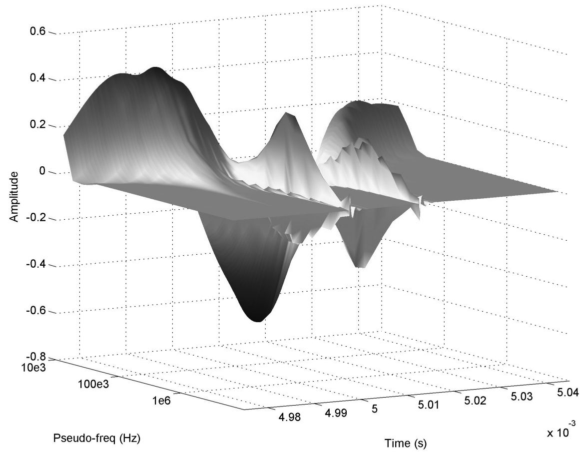
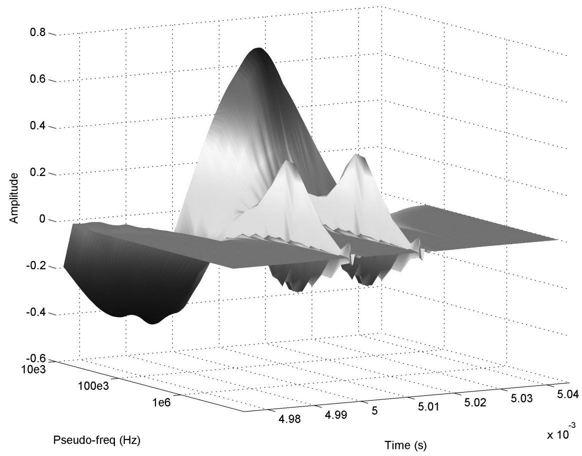


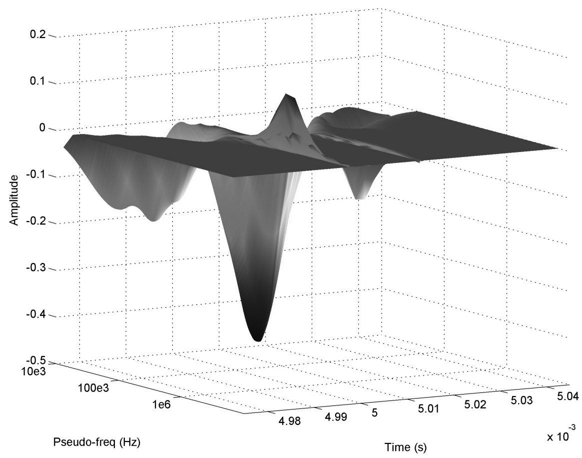
Figure 4: Overview of the structure of the signal processing stages in the PDDS.



(a)



(b)



(c)

Figure 5: Simulated internal pulse followed by an external pulse with an overlapping lower frequency external pulse: (a) CWT of current, (b) CWT of voltage and (c) multiplication of (a) and (b).

CNN analysis thus determines if the pulses are being generated by one, two or even more source locations, without requiring any prior knowledge of the internal construction or electrical response of the transformer. By identifying from which source each individual PD pulse came, further analysis of source characteristics can be performed, for example, by producing a plot that shows average pulse height, power cycle phase timing and total number of pulses for each source.

5 Results

Two tests were designed to determine the accuracy of the PDDS in detecting internal transformer PDs among external electrical interference. Two identically constructed 7.5kVA, 11kV transformers were used: Transformer Tx1 was used for off-line testing and has been internally modified by connecting wires to various points on the winding to allow artificial internal PD pulses to be injected. Transformer Tx2 was energised and subjected to external coronal interferences generated by spark gap instruments and other sources.

For the first test, programmable arbitrary waveform generators injected artificial PD pulses into three different locations within Tx1. Two generators created 2500 pulses/sec which ranged randomly from 400 pico-coulombs (pC) to 2000pC in magnitude and which had random timings within a specified power cycle phase range. The other generator created 1000 pulses/sec, ranging from 400pC to 1000pC in magnitude, also randomly. Two external pulse sources generated randomly timed pulses of up to 4000 pulses/sec at a maximum of 1000pC. Artificial sinusoidal interference was also added at 113kHz and 430kHz. Calibration of the PDDS involved injecting a pulse of known charge into the HV bushing and measuring the amplitude of the digitised result. Calibration pulses were generated using a step voltage generator connected to a capacitor of known value.

Figure 6 shows an example of the automated FDTF acting on Ch1-V. In the frequency domain, the noise floor was identified, a threshold fixed and excessive narrowband interference rejected. From the output of the CWDCF, internal PD pulses were identified, as the example in Figure 7 shows. Analysis from 100 power cycles of data provides the following statistics:

- 11679 artificial PD pulses were injected into the transformer. 10543 of these pulses were detected in the output of the CWDCF stage (90.3% success rate). Missed pulses came mostly from a more distant source and were typically small when injected. The CWDCF threshold was not low enough to detect these pulses. However, it is considered more important to lower false positives than to collect all internal PD pulses.

- 145 other pulses that did not represent internal artificial PDs were present in the output of the CWDCF stage. This equals a 1.36% error rate of incorrect pulses over all as internal detected pulses. These false positives were mostly small in amplitude, and the majority of them occurred where random noise had formed what appeared to be an internal pulse of low magnitude. These pulses would be filtered out if the CWDCF threshold was even higher, but at the same time less PD pulses would be detected.

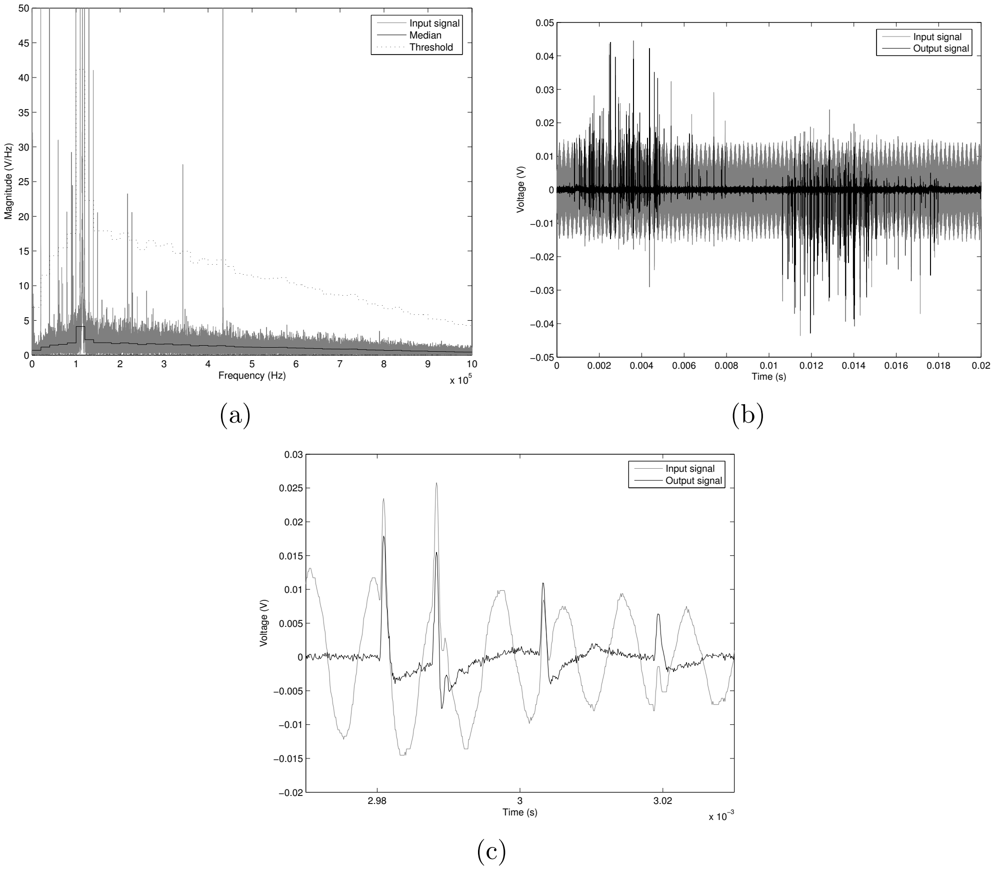


Figure 6: Test 1 - Effect of the FDTF for Ch1-V: (a) Frequency spectrum with bin medians and thresholds, (b) time domain input and output signals, and (c) selective zoom of (b).

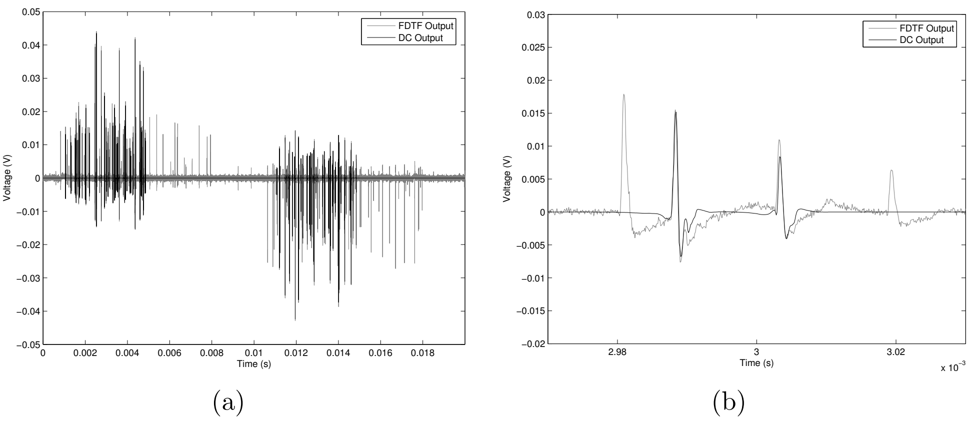


Figure 7: Test 1 - (a) Output from the CWDCF of Ch1-V and (b) selective zoom that shows two known internal pulses centred between two known external pulses.

Actual PD source	Group 1	Group 2	Group 3	No group
Internal pulse source 1	4567	69	137	163
Internal pulse source 2	0	3666	1	1285
Internal pulse source 3	1	31	1572	288
Other pulses	0	145	0	0

Table 1: Test 1 - Internal PD source group recognition.

For pulse location grouping purposes, 1020 pulses from the first 10 power cycles of data were used to train the CNN. The CNN then classified all pulses over 100 power cycles of data, which provides the statistics in Table 1. Recognition rates were very similar for the first 10 power cycles and the last 90 power cycles previously unseen by the trained CNN. From the correctly identified (by the CWDCF) internal PD pulses, 97.6% of pulses were correctly grouped together. An additional 145 pulses (1.4% of total) were incorrectly identified by the CWDCF as internal, and were grouped anyway. Pulses listed in the "No group" column include those that were not detected by the CWDCF and therefore not presented to the CNN for grouping. Many of these were small pulses generated by one internal PD pulse generator which were consequently not detected by the CWDCF. The timing of the rest of the pulses in the "No group" column occurred very close to another pulse, and the pulses were therefore obscured or not recognised as a separate pulse.

The success rate of correct internal PD pulse grouping in test 1 allows accurate PRPDA plots to be displayed. Incorrectly grouped pulses will show in the wrong plot and often appear as "outliers". Figure 8 show the internal transformer PD patterns over 100 power cycles in PRPDA format for Ch1-V. The three separate groups of PD pulses are merged beyond recognition when all the pulses are combined in Figure 8(a). The PDDS is able to present the 3 PD groups individually with a high degree of accuracy.

The insulation condition of the energised transformer Tx2 that was used in test 2 is unknown. The transformer was not opened and studied. Because the current probes were not capable of withstanding high voltages in wires passed through their apertures, they were mounted using Tektronix CT-5 High Current Transformers. To provide a source of external pulse interference, a spark gap generator referenced to earth was connected to each of the HV terminals. To simulate power transmission lines, a wire was connected to each HV terminal, each approximately 15m in length. This allowed high frequency pulses to radiate or capacitively couple with the surrounding earthed building environment. Calibration was performed in similar fashion to test 1.

From the CWDCF output, approximately 10 pulses per cycle were classified as internal to the transformer Tx2. These pulses were clearly visible in the current and voltage waveforms, and therefore strongly suggest that transformer Tx2 has a PD problem when energised. As the pulses only show in one pair of current and voltage transducers, this suggests that the sources are closer to these transducers than to the other transducers. Identified PD pulses were used to train a CNN and then classified by it. Three pulse sources were identified. One source was dismissed as it only consisted of a few pulses that appeared to be random noise. The other two sources have very similar neuron weights and may be the same source, or at least two physically very close sources.

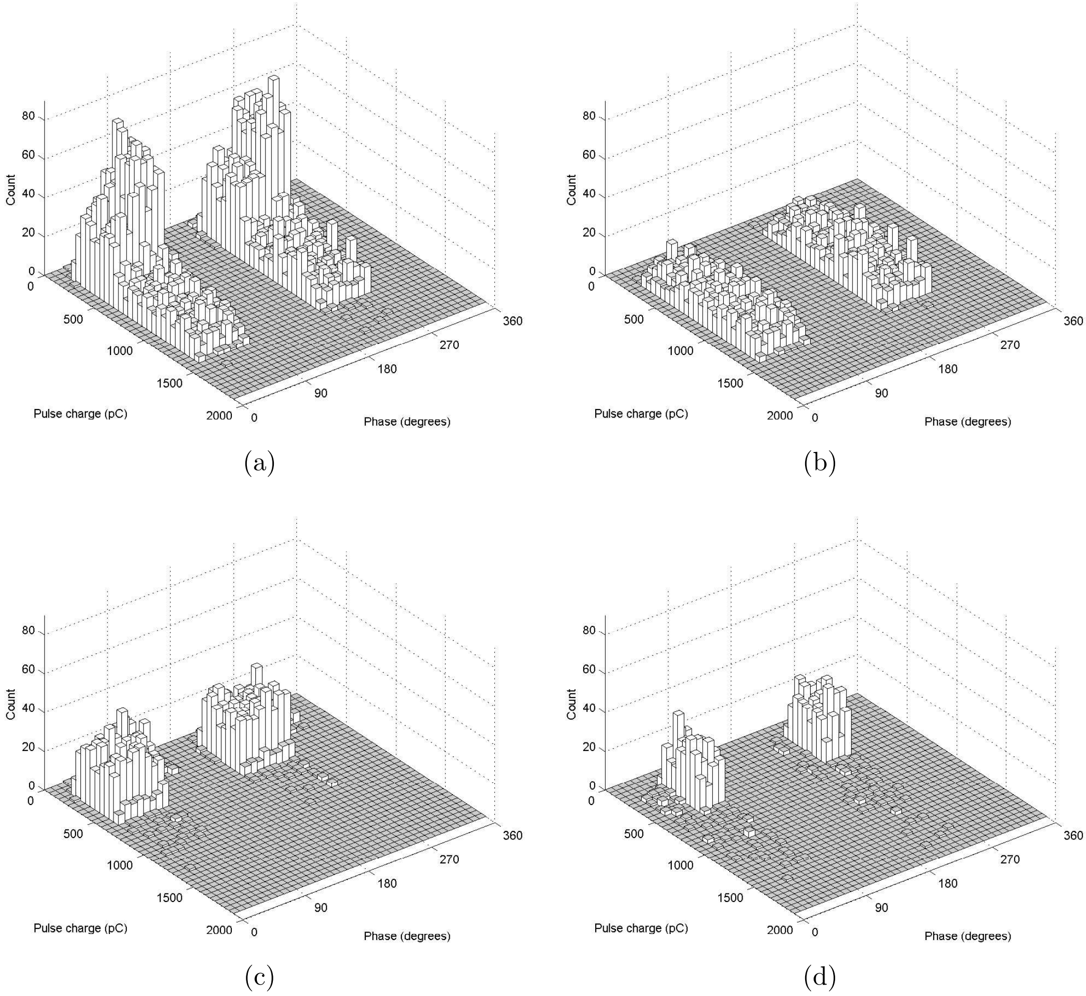


Figure 8: Test 1 - Internal PD pulse counts and apparent charges from Ch1-V relative to the phase of the power cycle: (a) all pulses, (b) group 1, (c) group 2 and (d) group 3.

6 Conclusions

A system that can detect PDs in a power transformer while it is on-line and subject to external interference has been developed. In addition, the PDDS can identify and separate multiple physical sources of PD generation, providing useful information for diagnosis. An off-line test has shown that the PDDS performs with a confirmed high success rate when known artificial PD pulses are injected into a test transformer. A test on a second energised transformer has identified at least one significant PD source in it.

The PDDS is comparitively inexpensive and can easily be retro-fitted to old transformers already in service. This is because the transducers have been designed to be attached to a transformer without the need to open or modify the transformer. Disconnection of the transmission cables is also unnecessary as the current and voltage transducers wrap around the bushings,

The PDDS does not give a definitive statement about the condition of a transformer, nor whether it should be disconnected, repaired or retired. In general, knowledge of PD patterns and world-wide collective experience of power transformer maintenance is required to interpret the PD results that the PDDS provides and to recommend a course of action. The PDDS contributes new unambiguous key information about PD pulses, which may not have been available before, in particular, for on-line transformers. It removes the need to make decisions about a transformer's condition and maintenance exclusively based on long-term statistical averages or other less regular or less precise monitoring systems. The results of the PDDS should be combined with existing techniques and possibly other new methods currently under research. Their combined information will provide a clearer and more complete picture about the state of a transformer than any one technique by itself could do.

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