Using optical couplers to monitor the condition of electricity infrastructure

S.G. Swingler, L. Hao, P.L. Lewin and D.J. Swaffield

The Tony Davies High Voltage Laboratory, University of Southampton, Southampton

Abstract

Increases in renewable and distributed generation will change the operational characteristics of our ageing power networks. To cope with these changes improved monitoring of the performance of network infrastructure is needed.

Defects developing in electrical plant give rise to partial discharge (PD) activity. This paper describes an on-line PD monitoring system based on electro-optic modulators. This technique does not require a power supply at the site of the sensors and the optical transmission of signal data is a significant advantage in electrically noisy environments.

Laboratory based experiments and field trials are described, which show that this approach is feasible for HV transformers and underground cable.

Intelligent filtering techniques have been developed to improve the sensitivity of detection and identify PD signals without assuming any knowledge of their characteristics.

1 Introduction

Increasing renewable and distributed generation is changing the loading characteristics and current flows on our ageing power networks. The need to load particular parts of the system to maximise renewable output will also change the logistics of maintenance outages. To cope with these changes improved monitoring of the performance and degradation of network infrastructure is needed.

Electrical insulation ages as a result of thermal, mechanical and electrical stresses. Defects develop and may lead to catastrophic failure. Partial discharge (PD) activity is a prominent indicator of insulation defects. Continuous on-line PD monitoring provides information about progressive degradation under operational stress, thus reducing the likelihood of breakdown.

This paper describes the development and testing of a monitoring system based on an optical sensing technique using electro-optic (EO) modulators. This system does not require a power supply at the site of the sensors and the optical transmission of signal data is a significant advantage in electrically noisy environments such as HV substations. Laboratory based experiments and field trials have shown that this approach is feasible.

The monitoring system has been evaluated for use with underground cable circuits (using capacitative couplers on the cable joints) and HV transformers (via a broadband current transducer connected between the bushing tap point and earth).

Intelligent filtering techniques based on a support vector machine have been developed to identify PD signals without assuming any knowledge of their characteristics. In theory it has a greater capability of generalization than traditional neural network approaches. Its application to PD signal processing is described.

2 The Electro-Optic Modulation Technique

The PD monitoring technique is based on the use of a lithium niobate ($LiNbO_3$) electro-optic modulator. The basic principle of the technique is shown in figure 1. PD is detected using a conventional sensor, such as a capacitative coupler [1,2] and the measured PD signal is fed to an optical fibre coupled $LiNbO_3$ waveguide modulator. This modulates the intensity of any transmitted laser light as an approximately linear function of the voltage applied across it, turning the electrical PD signal into light beam of varying intensity. The optical network supplies polarized laser light via optical fibre to the modulator input, and monitors the optical output from the modulator using an optical receiver. The electro-optic modulator has the advantages of being compact and passive requiring no local power to operate.

The laser source, which is controlled by a temperature and current laser diode controller, has a wavelength of 1550 nm and maximum power of 10 mW. A polarization tuner was used to ensure that the input light for the modulator was linearly polarized. The optical receiver has a bandwidth of 1 GHz.

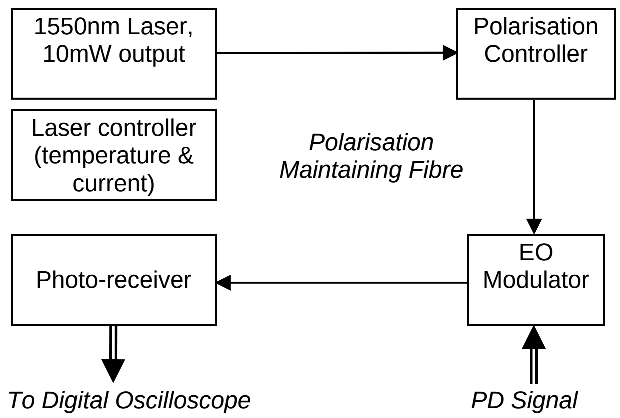

Figure 1 EO modulator-based capture of PD signals

3 Model tests on a transformer bushing

One of the laboratory models used to evaluate the EO modulator is based on a simple transformer bushing-tap system. The connection between the low voltage side of a transformer bushing and earth is monitored using a radio frequency current transformer (RFCT) connected to the EO modulator system (figure 2). The practical measurement bandwidth of the RFCT is 200 MHz. By using three turns on the primary side the measurement gain of the sensor is improved across the whole range of its bandwidth. For these tests the detection sensitivity of the EO modulator was enhanced by including a battery powered wideband amplifier (20 dB gain with a bandwidth of 1 GHz). A digital oscilloscope, LeCroy LC684DXL with a bandwidth of 1.5GHz, was used to display, store and analyse the signals from the RFCT/photodiode.

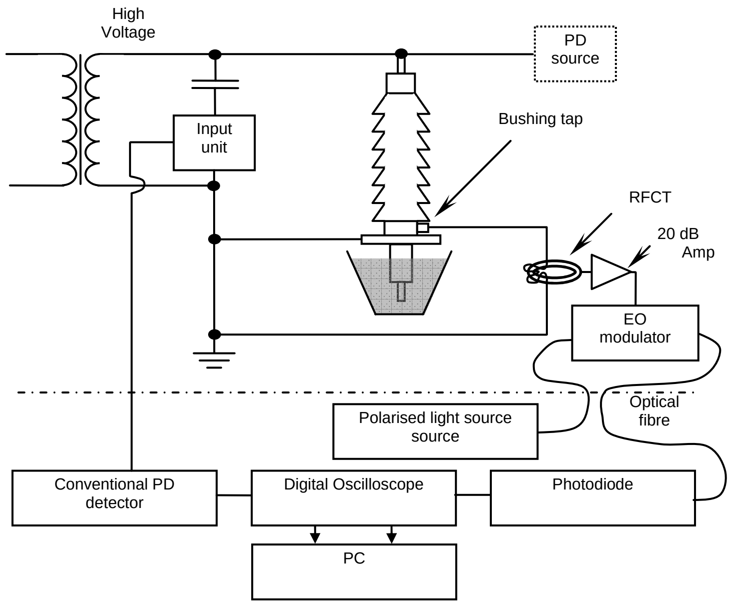

Fig. 2: Schematic of the experiment

For comparison, a conventional PD detector (Robinson Model 700 with 40kHz-80kHz band-pass frequency) was used alongside the EO modulator system. This allowed conventional measurement of the magnitude (apparent charge) of any PD observed. The data were also displayed and saved in a computer via an oscilloscope and a GPIB card.

PD signals were generated using two types of artificial PD source: These simulated a typical PD source external to a transformer under test and PD signals representative of internal PD in the transformer. External PD (corona in air) was generated by connecting a rod to the high voltage supply. Internal PD was simulated by covering a plane earth electrode with a 5mm thick Perspex sheet on which was placed a coil of tinned copper wire. A plane high voltage electrode was suspended over the Perspex leaving an oil gap of 10mm. Applying high voltage to the bushing producing PD from the ‘floating’ wire.

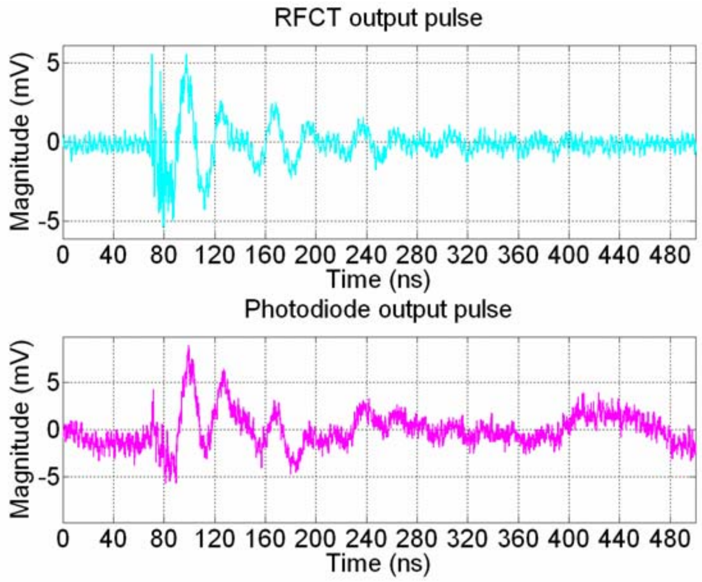

Fig. 3: Output from a corona pulse

Fig. 3 compares the same corona discharge signal recorded at the amplified RFCT with the output of the photodiode. Although the photodiode signal is noisier, the discharge signal is clearly identifiable. From comparison with data from the Robinson detector the electro-optic modulator circuit can reliably detect discharge events above 40 pC.

Corona discharge characteristically occurs around the negative peak of the voltage cycle and has a fairly consistent magnitude (around 50pC in this case). ‘Internal’ discharges from the floating wire occur across the voltage cycle and are more variable in magnitude. Fig. 4 shows the phase, amplitude and number (φ-q-n pattern) for floating discharge during 500 continuous power cycles. The average discharge magnitude was 100pC and the peak magnitude 380pC. For the floating discharge source it was again possible to detect discharge events greater than 40pC.

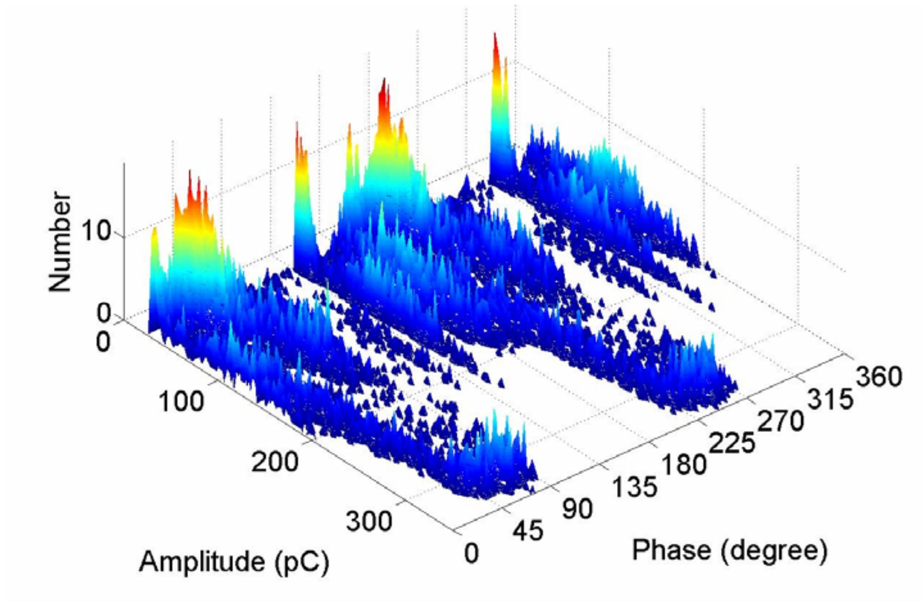

Fig. 4: φ-q-n patterns for floating discharges

4 Tests on full size 400 kV Cable joints

In addition to tests carried out on model cable and a 132 kV cable joint at Southampton [1], practical PD measurements have been carried out on full-size 400 kV cable joints at the Südkabel GmbH factory in Mannheim, Germany.

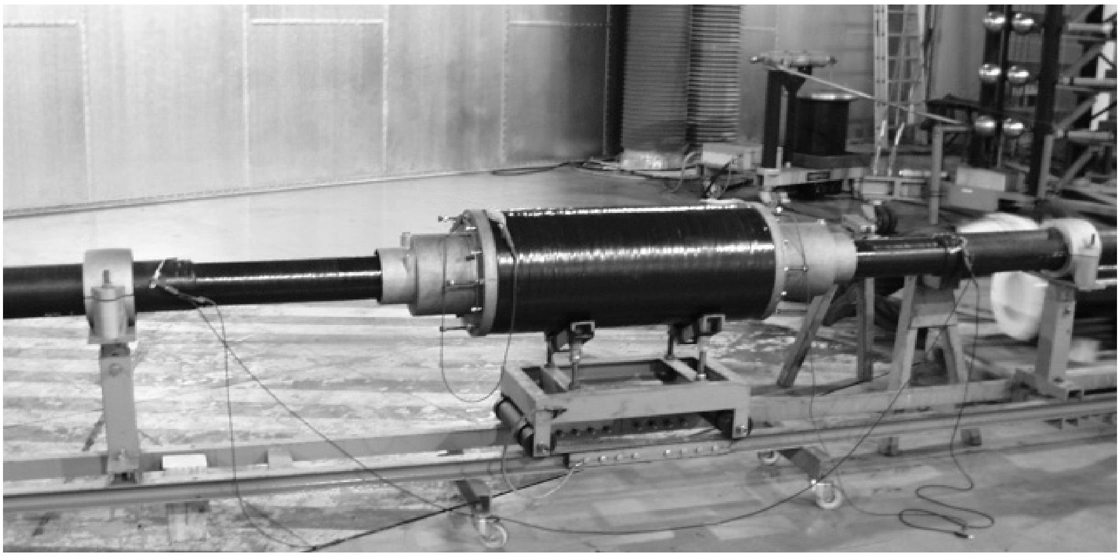

Figure 5: The 400 kV prefabricated cable joint

A short length of 400 kV cable containing a prefabricated joint (figure 5) was energised with alternating voltage using a series resonant supply. The earth screen of the pre-moulded joint was isolated from that of the XLPE cable screen to permit PD measurement across the screen interruption. PD was monitored using both the EO modulator and a conventional PD detector (a Robinson® Model 5).

Artificial defects were introduced into a joint, which had been shown to be PD up to an applied voltage of 250 kV. The locations of the defects are shown in figure 6. Firstly four metal wires were placed on the surface of the stress cone near to the HV copper stress shield (position A) and the joint reassembled and electrically tested. The wires were then removed and replaced by copper filings about halfway along the stress cone as can be seen at position B.

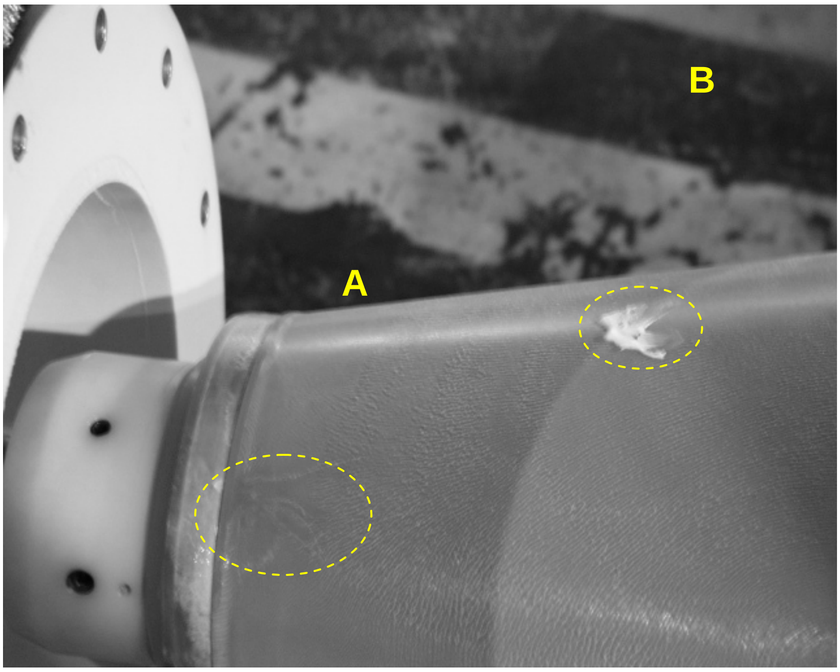

Figure 6: Location of the artificial defects: (A) the metal wires and (B) the copper filings on the stress relief cone within the cable joint

With the copper wires the joint began to discharge (PD inception) at 13 kV. The voltage was further increased and measurement was carried out at 70 kV. A typical PD signal is shown in Figure 7. The conventional PD detector indicated a PD level was 20 – 30 pC.

With copper filings on the stress cone the PD inception voltage was found to be 180 kV. At 480 kV discharges of magnitude 10-12 pC were observed (see figure 8).

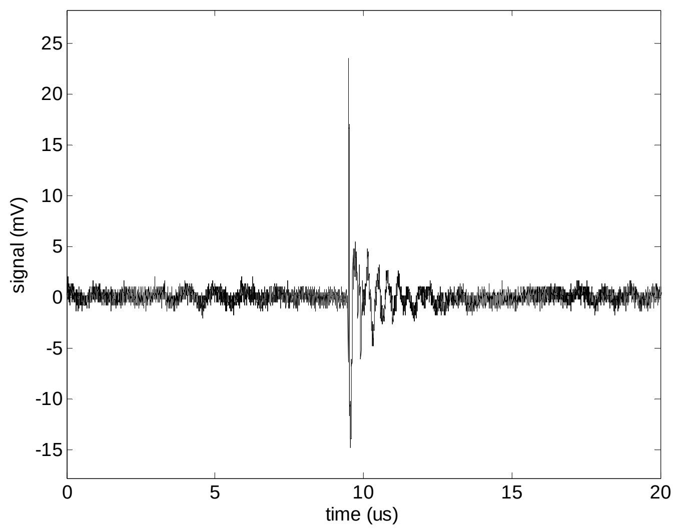

Figure 7: PD signal due to metal wires within the cable joint

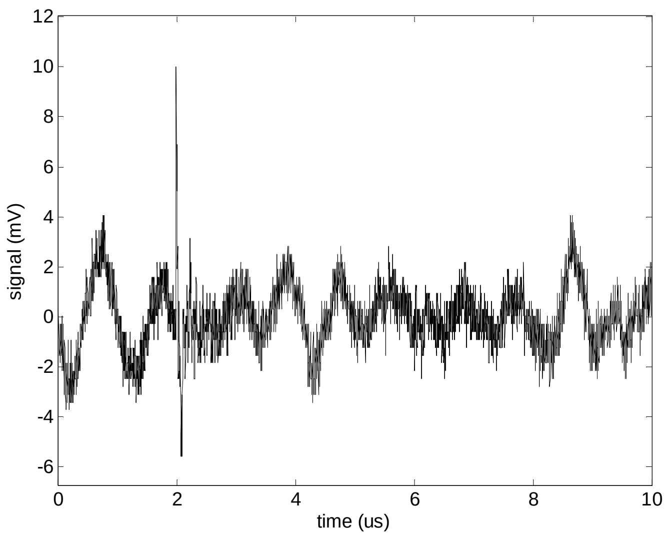

Figure 8: PD signal due to copper filings within the cable joint

During the test programme one joint without artificially introduced defects showed a PD inception voltage of 41 kV. The voltage was increased to 186 kV and PD of 30 pC was observed. Subsequent inspection revealed that the PD activity was due to a manufacturing defect (void) between the stress shield and the epoxy resin within the joint.

During these tests various optical and electronic configurations were examined to optimize the performance of the system and consideration was given to the trade-off between performance and cost [3].

5 Improving detection sensitivity

The performance of the PD detection system can be enhanced by improving both the hardware and the data analysis techniques.

Analysis of the measurement data revealed that much of the background noise is caused by the optical system itself having a resonant frequency of about to 1 MHz. Inserting a band-stop filter (stop band: 540 kHz – 1.6 MHz) will therefore increase measurement sensitivity.

The sensitivity of PD measurements made on-site is often impaired by high levels of background interference (electromagnetic noise), particularly where many items of plant are co-located in substations.

The use of multi-resolution wavelet transforms to improve the discrimination of PD signals has been investigated at Southampton [1, 4]. Results indicate that with the appropriate selection of wavelet family and number of decomposition levels, the wavelet analysis technique is effective at distinguishing real PD pulses from corona discharge, narrow-band radio interference and random noise. Further removal of interference has been achieved by applying level dependent threshold values.

This use of wavelet packets [5] to remove measurement noise/interference from PD data acquired in the field has also assessed. Results from cables in normal operation indicate that wavelet packet de-noising was capable of filtering signals heavily corrupted by noise without assuming a priori knowledge of the PD signal characteristics.

Extending this concept of developing intelligent filtering techniques to identify PD signals without assuming any knowledge of their characteristics has lead to the application of a pattern recognition tool, namely the support vector machine (SVM) in order to extract PD signals from EO modulator based measurements [6]. The approach combines wavelet filtering with a SVM which is based on statistical learning theory and principles of structural risk minimisation. Wavelets have the advantage of combining time domain and frequency domain information, thus providing more useful information to analyze than using a single domain. In theory, the SVM possesses a greater capability for generalization than traditional neural network methods. It is particularly useful in situations involving sparse data sets. Initial trials indicated that the SVM could distinguish between PD emanating from different sources [7].

Wavelet decomposition effectively applies a pair of high-pass and low-pass filters, which decompose the original signal into a series of detail coefficients (high pass) and approximation coefficients (low pass). The decomposition process is iterative. Hence if a signal is decomposed into detail coefficients (D1) and approximation coefficients (A1) the resulting approximation coefficients can themselves be broken down into detail coefficients (D2) and approximation coefficients (A2), and so on. The coefficients of each level have half the bandwidth and half the length of the level above.

The technique was investigated further using data generated with the transformer bushing rig (figure 2). PD signals were simulated using a UHF calibrator injecting calibration pulses directly into the bushing core bar. Conventional PD measurements were also taken using a Robinson detector.

The background noise and the simulated PD signals were decomposed using the Daubechies family order 7 as the mother wavelet, since research to date indicates this gives promising results [8]. Figure 10 shows the decomposition coefficients at seven different levels for the noise and 160pC PD data. (160pC is the minimum detectable PD level without filtering).

The detail coefficients at level 3 (D3) clearly discriminate between noise and the 160 pC PD signal. Therefore the D3 coefficients were selected as the feature for SVM discrimination.

Two sets of noise data were recorded and eight sets of PD data (at magnitudes of 30pC, 40pC, 50pC, 70pC, 90pC, 110pC, 130pC and 160pC). The SVM was trained with one set of noise data and the 160pC PD data. . Subsequently the SVM was tested with the rest of the data sets. In all cases 2800 signals were analysed for each level of discharge. The number of signals correctly identified as PD is shown in Table 1. It is seen that the SVM can reliably identify discharge activity to 50 pC and only failed to recognise 1 in 200 events at 30 pC. Similar tests using the frequency spectrum of the PD signal as the input feature for the SVM correctly identified only 14% of 30pC discharges[9]. Thus the combination of wavelet analysis and the SVM can achieve substantial improvement in the detection and measurement of PD in noisy environments.

Data sets	WDEC3
Noise2	100% (2800/2800)
30pC	99.4643% (2785/2800)
40pC	99.8214% (2795/2800)
50pC	100% (2800/2800)
70pC	100% (2800/2800)
90pC	100% (2800/2800)
110pC	100% (2800/2800)
130pC	100% (2800/2800)

Table 1 Identification rates achieved using the D3 feature.

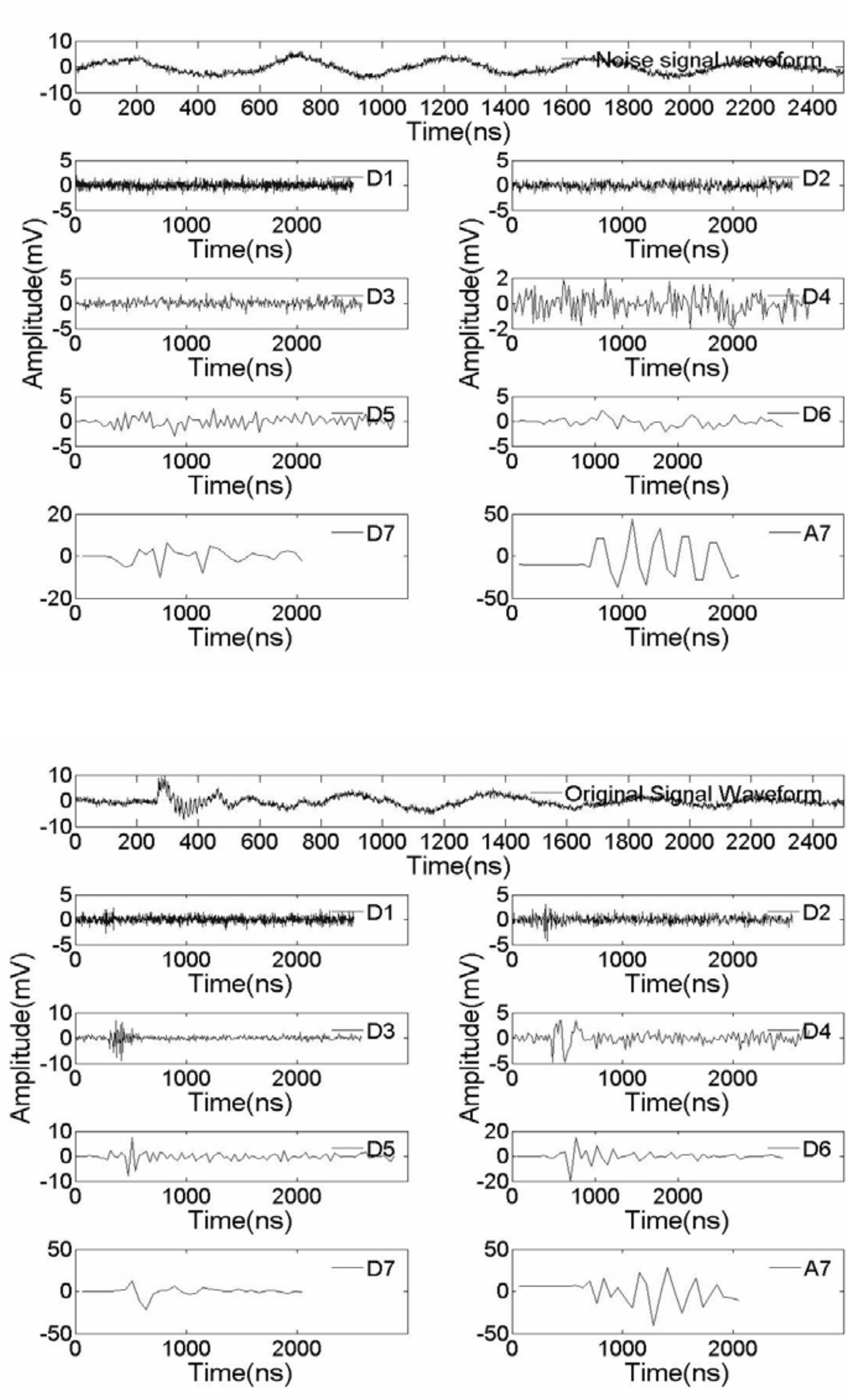

Figure 10 Wavelet decomposition coefficients

6 Conclusions

This paper has described the continuing development of a PD detection technique based on the electro-optic modulator.

The potential application of the technique for PD monitoring in high voltage transformers has been assessed using a simple laboratory experiment. Results indicate that it is possible to detect internal discharge activity above 40pC using a RFCT at the bushing tap point to modulate transmitted laser light via a waveguide modulator.

Practical PD measurements on both a 132 kV cable joint at the University of Southampton and 400 kV cable joints at Südkabel GmbH, Germany, have demonstrated the effectiveness of the technique for monitoring high voltage cable assets. PD of 10-15 pC could be clearly measured using the optical remote sensing technique. The measurement sensitivity of this technique can be further increased by applying suitable filters and amplifiers to process the optical receiver output signals and remove any inherent noise of the measuring system.

The combination of digital filtering and a pattern recognition tool (wavelet analysis and the support vector machine) can achieve substantial improvement in the detection and measurement of PD in noisy environments.

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http://www.supergen-amperes.org

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