# CONDITION MONITORING OF POWER CABLES

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

*The Tony Davies High Voltage Laboratory, University of Southampton, Southampton, United Kingdom
`pll@ecs.soton.ac.uk`

**Keywords:** HV transmission cables, PD measurement.

## Abstract

A National Grid funded research project at Southampton has investigated possible methodologies for data acquisition, transmission and processing that will facilitate on-line continuous monitoring of partial discharges in high voltage polymeric cable systems. A method that only uses passive components at the measuring points has been developed and is outlined in this paper. More recent work, funded through the EPSRC Supergen V, UK Energy Infrastructure (AMPerES) grant in collaboration with UK electricity network operators has concentrated on the development of partial discharge data processing techniques that ultimately may allow continuous assessment of transmission asset health to be reliably determined.

## 1 Introduction

The use of high voltage (HV) polymeric cable circuits within transmission networks is increasing worldwide, not only because of the need to supply increasing load within large densely built conurbations such as London, Berlin and Tokyo, but also because of political and environmental concerns. The cost of undergrounding existing overhead line circuits or installing new transmission cable routes is significant and it is therefore very important that these assets operate reliably over a long lifetime. Comprehensive afterlaying tests ensure that any installation or significant manufacturing defect are identified and rectified prior to energisation. Once the circuit is operational, the modern practice of installing distributed temperature sensing (DTS) along the outer sheath of one of the phases as well as the use and development of bespoke cable rating calculations [1] ensure that potential problems such as thermal runaway are avoided. However, over time the cable insulation will age and will experience thermal, mechanical and transient electrical stressing due to switching or lightning events. Defects that were not detectable during afterlaying tests may develop due to these processes and ultimately the dielectric properties of the cable insulation may degrade. The process of ageing leading to degradation is unlikely to be readily identified from analysis of DTS data. Partial discharge (PD) activity is a prominent indicator of insulation defects. PD conventional electrical measurement has been used for many years as a non-destructive off-line testing technique for insulation evaluation. Conventional PD measurement can detect the permissible discharge quantity, but it is not suitable for on-line applications due to its requirements for a coupling capacitor etc. PD on-line measurements provide information about insulation faults under operational stress or the development of defects introduced during transportation or installation. In particular continuous on-line monitoring provides additional information about progressing degradation or deterioration under operational stress, thus reducing the likelihood of breakdown. Cross-linked polyethylene (XLPE) cable itself has undergone manufacturing quality control as well as PD testing at the factory before delivery. In most cases the cable defects have been removed. For this reason on-line PD monitoring systems for cables should predominantly cover the accessories, which are more prone to problems over time due to the installation procedure and the operational stresses that they experience.

Continuously monitoring a large distributed asset, such as a 400 kV XLPE cable circuit, is highly problematic because there will be significant distances involved between the measurement points (i.e. the cable joints, terminations) and the location for data processing. Given the environment, i.e buried within backfill, within a cable trough or tunnel, it is necessary to ensure that the measurement sensors and associated local equipment are robust, reliable, maintenance free and have a lifetime greatly in excess of the asset itself. Working within these constraints, a series of research projects funded by National Grid have considered the problem and developed a solution that has potential to be widely applied to other transmission assets as well as high voltage cable circuits.

The proposed continuous PD on-line monitoring system for cable joints of underground cable circuits is based on the optical sensing technique using electro-optic (EO) modulators [2]. This monitoring system does not require a power supply at the site of the cable joints and hence may find wide application for continuous monitoring of transmission and possibly distribution assets over their effective lifetimes.

### 1.1 Review of data acquisition and transmission technology

Data acquisition for PD detection in cable systems usually involves non-conventional electrical coupling techniques including coaxial cable sensors [3]; inductive high frequency current transformers (HFCT) either around the cable itself [4] or the earth connection [5]; directional couplers [6]; and foil electrodes on cable joints [7]; as well as acoustic emission

(AE) techniques [8]. Electrical coupling techniques work over various frequency ranges from a few MHz to several hundred MHz. For polymeric HV cables, an effective PD sensor should be compact and easy to install, sensitive to PDs of a few pC with a good signal to noise ratio, and potentially calibratable against a discharge quantity in pC. The acoustic emission technique has the advantage of being immune from electrical interference. However, acoustic emission attenuation significantly reduces measurement sensitivity and makes it impossible to calibrate. AE techniques are more suitable for PD monitoring in power transformers, switchgear or GIS, due to the existence of excessive electrical noise at the measurement site. High frequency components of discharge signals are rapidly attenuated within a HV cable. Sensors must be placed near the discharge source to obtain good sensitivity. The simplest and cheapest way for PD signal transmission is via electrical coaxial cables. However, PD signals detected by sensors near the cable joints (within a cable tunnel, for example) may need to transmit over significant distances of several kilometres to the processing equipment at the substation. This could result in very significant signal attenuation and consequently decrease the measurement sensitivity. Electrical interference is easily coupled into the sensor lead and later captured by the processing equipment and this further decreases the detection sensitivity. Electrical noise is significant at substations and in some situations may totally bury the real PD signal.

A method to overcome transmission attenuation and electrical interference is to use an optical fiber for signal transmission. PD signal transmission via optical fiber shows much reduced attenuation compared with electrical transmission, and is immune from electrical interference. The optical fiber also provides electrical isolation for the processing equipment with respect to the measurement point. General practice is to feed the discharge signals detected by the sensors into an optical transmitter and converted into optical signals, which are then transmitted along an optical fiber and measured using an optical receiver. Alternatively, the signals from PD sensors can first be digitized, then transmitted via a digital optical fiber and acquired by an acquisition unit [6, 9]. A distinct advantage of the digital optical fiber is that all acquisition units near the cable joints inside the tunnel can be connected via one single optical fiber, in a way that they are addressed and controlled over the same line by the main unit at the substation. However, the optical transmitter or acquisition unit with digitizer and communication port requires a power supply to operate, although they can work on battery power for a few hours. Though there has been some experience of after-laying PD tests for practical long cable circuits [3, 6, 7], so far there has not been continuous on-line PD monitoring for practical underground cable circuits especially where a mains supply is not available.

## 2 Continuous on-line PD detection and transmission using an Optical Phase Modulator

The PD on-line monitoring technique, developed at Southampton, uses a Lithium Niobate ($LiNbO_3$) electro-optic modulator [2]. The measurement approach is to use the measured PD signal and apply it across an optical fiber coupled LiNbO3 waveguide modulator, which in turn modulates the intensity of any transmitted laser light as an approximately linear function of the voltage applied across it. The optical network supplies polarized laser light via optical fiber to the LiNbO3 modulator input, and monitors the optical output from the modulator using an optical receiver. The EO modulator has the advantages of being compact and passive requiring no power to operate. Since a capacitive coupler has been demonstrated to be an effective PD on-line detection sensor for HV XLPE cables and accessories [10, 11], it has been used as the PD sensor for the EO modulator-based monitoring technique. The basic principle of this optical technique is shown in Figure 1. With reference to Figure 1, the laser source, which is controlled by a temperature and current laser diode controller, has a wavelength of 1550 nm and maximal 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.

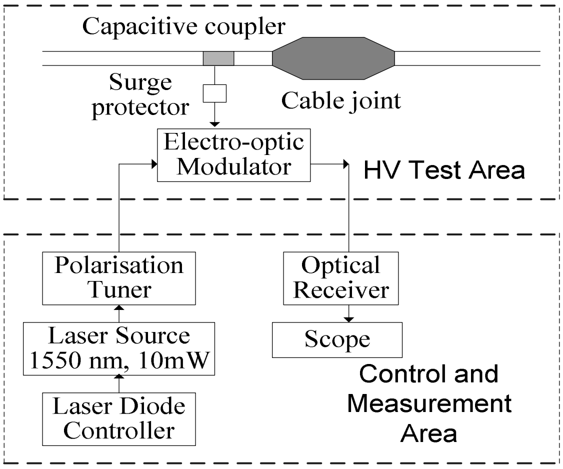

Figure 1 Principle of the EO-modulator based monitoring technique

This arrangement has been evaluated in the Tony Davies High Voltage Laboratory using a 132 kV cable test loop, containing a joint which has a known discharge source (conducting paint applied to one stress cone). Figure 2 shows the discharge signal as measured by the capacitive coupler and optical receiver respectively. The concurrent measurement from the Robinson® conventional PD detector indicated that the PD level during this experiment was between 10 and 20 pC.

Although very simple in approach, unfortunately this system has one major disadvantage – it would prove relatively expensive to implement. This cost may be insignificant when compared to the total infrastructure cost for a 400 kV three phase circuit installed in a bespoke tunnel, but may well limit the possibility of use at lower transmission voltages. The most significant component for a practical application is the

Polarization Maintaining (PM) fibre which costs $1300 per kilometre. Research into less expensive approaches (that have similar levels of PD detection sensitivity) has yielded a modified design that predominantly uses Single Mode (SM) Fibre [12]. This represents a saving of $1000 per kilometre. Figure 3 details the modified design, which requires a polarizer to be placed near to the EO modulator close to the measurement point. To ensure reasonable transmission to the polarizer the laser light is scrambled.

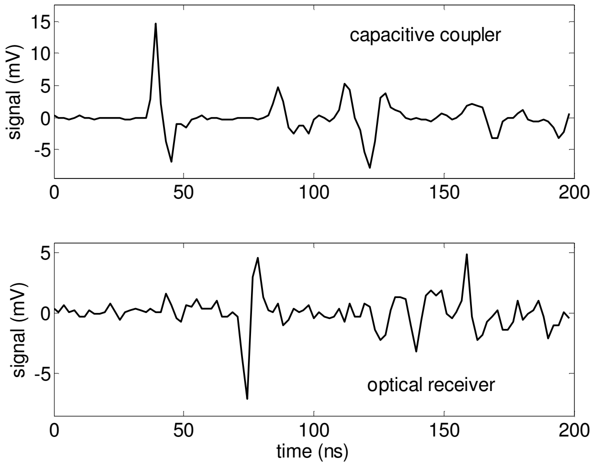

Figure 2 PD signals from the cable joint detected by the capacitive coupler and the optical receiver

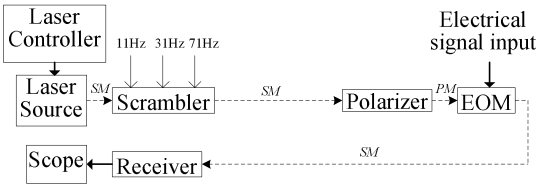

Figure 3 Revised PD optical remote sensing system

Obtained results using the revised sensing system on the same 132 kV test loop are shown in Figure 4. With reference to Figure 4, it can be seen that sensitivity can be improved by increasing the laser current.

## 3 Towards a practical on-line monitoring system

Based on the general principle of remote sensing described above, a PD continuous on-line monitoring system for practical three-phase underground cable lines can be proposed (Figure 5). To further reduce cost, only one laser source, one polarization tuner and one optical receiver per phase may be required for the whole monitoring system. The optical switch acts as an optical multiplexer to enable the laser light via an optical fiber to pass into one EO modulator. Although electrical noise at a substation is excessive, it is significantly attenuated while travelling along the long cable conductor. Thus noise levels at the site of a cable joint are limited. The optical fibres connected to the EO modulator outputs are bundled together before feeding into an optical receiver. Any light within a single optical fibre from the EO modulator will provide the optical input into the optical receiver. The selection of a particular cable joint, EO modulator and the relevant optical path is realized by the optical switch. For this monitoring system, the only thing to be placed along the cable route is the EO modulator (and if using SM fibre a polariser),

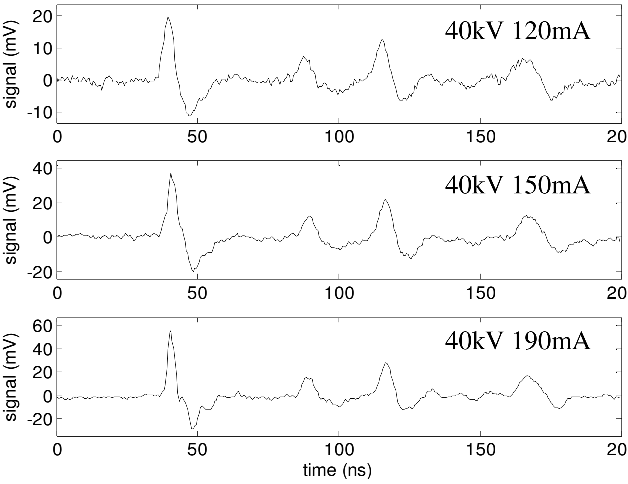

Figure 4 100pC discharge signals for an applied voltage of 40kV at different laser currents

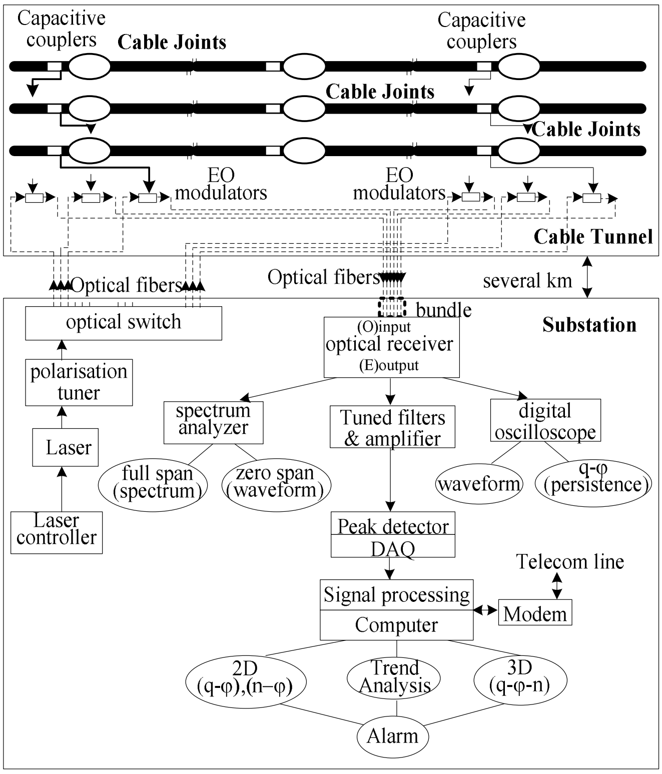

Figure 5 Continuous on-line PD optical monitoring system for underground cable circuits

which is totally passive without any power requirements. All other instruments are placed at the substation, where a mains supply is available. Potentially, new cables could be laid together with optical fibres and new joints could be designed to include optical network ready PD sensors. This approach would have a clear advantage because over the lifetime of the transmission cable asset the substation instrumentation/software can be easily accessed allowing the on-line system to match any technological improvements.

With current established analytical approaches as shown in Figure 5, the optical receiver-measured signals could be input into a spectrum analyzer, a digital oscilloscope or a bespoke signal processing unit for phase-related plots, statistical distribution and trend analysis [13]. A peak detection circuit could be used to obtain the peak value of every signal waveform. When the measured signal amplitude, histogram or trend turns abnormal, attention should be raised and if necessary an alarm should be given in order to warn of the likely occurrence of breakdown. This approach would create a system that still requires the expertise of a cable engineer in order to make an informed decision based on the information provided by the system (e.g. is it a false alarm?, should the circuit be derated? Should the circuit be switched out?). Consequently, the development of data processing methodologies capable of analyzing data from the remote sensing system in order to assist with this process is under consideration.

### 3.1 Limiting the number of required sensors

With reference to Figure 5, only one capacitive coupler installed close to a cable joint is proposed, and any measured PD signal can be considered to be from the cable joint itself. Thus three EO modulators are needed for a set of three-phase cable joints. The feasibility of this approach has been investigated using a simple model to represent a three phase joint bay, where the cable joints contain an earth sheath interruption and earthing continuity is achieved using cross-bonding links (Figure 6) [14].

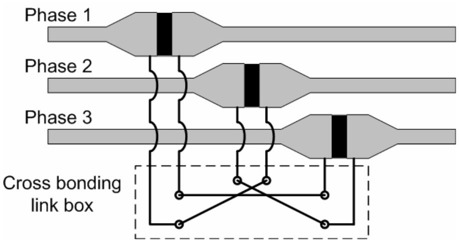

Figure 6: Schematic diagram of a cross-bonded three-phase cable system

The presence of cross bonding means that should there be a PD source in one of the joints then a resulting PD pulse, propagating along both the core conductor and outer earth sheath of the faulty phase will be observed by sensors on the other 2 phases. The experimental model consists of three 2m long XLPE 66kV cable sections having an outer semiconducting layer but no outer sheath (Figure 7). The cable sections were wrapped with aluminium foil to simulate the real cable earthing sheath. A 20cm sheath interruption was created on each cable section by removing the relevant length of aluminum foils. The cable sections were terminated at both ends with a resistor (R) of 30Ω to reduce pulse reflections due to impedance mismatch except the one end where external pulses were injected. Cable sections were earthed at both ends. The cross bonding links were made at the sheath interruption using aluminium braid. The three capacitive couplers (CC) were pre-installed on the same side of the sheath interruption of each phase. As shown in Figure 7, CCY, CCB, CCR represent the capacitive couplers on yellow, blue and red phase respectively. The couplers have a bandwidth of 300 MHz and detection sensitivity of 3 pC. A HP 8082A pulse generator (PG) was used to generate the injected square wave to the cable system. The generated square wave has a rising/falling time of 1ns and frequency of 25kHz. A 10pF capacitor was used with the pulse generator to inject pulses at the cable end. Therefore, the equivalent charge injected to the cable system is the multiplication of the step voltage and the capacitance. A Tektronix digital oscilloscope DPO7254 with a bandwidth of 2.5GHz and 40GS/s maximum sampling rate was used to display, analyse and store the captured signals. The four channels of the oscilloscope were connected to the three CCs and the PG for simultaneous acquisition.

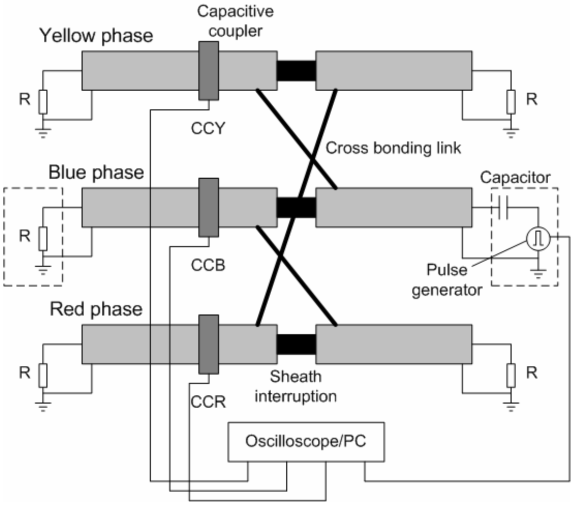

Figure 7: Experimental model of a cross-bonded arrangement

Obtained results were analysed with the aim of trying to automatically identify the faulty phase. It was found that using the signal energy, E, defined as

$$E = \sum_{1}^{N} |x_n|^2 \qquad 1$$

combined with pulse position (i.e the faulty phase signal will be detected by its own coupler first and will have the highest signal energy) creates clustered data points. A typical result is shown in Figure 8, where 'internal' represents a 10 pC signal injected into the blue phase as shown in Figure 7 and 'external' represents a signal injected into blue phase on the same side as the capacitive coupler.

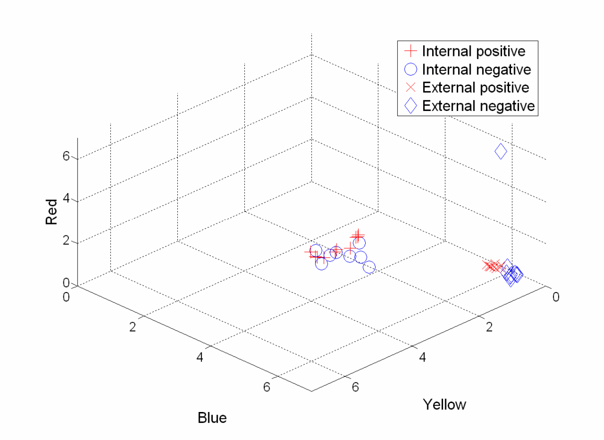

Figure 8 Signal energy pulse position clusters

Obtained results and subsequent analysis infer that providing all joints within a joint bay are monitored simultaneously that it should be possible to determine a faulty phase using a single capacitive coupler per joint as the sensing element.

Determining the location of a PD source within a specific joint may require further investigation. PD location by time of flight analysis has been investigated and verified by applying two capacitive couplers either side of a cable joint [10]. It has also been proved that cross-correlation techniques, either time-based algorithm or FFT-based algorithm, can be useful in determining the time of flight [11]. For the PD continuous on-line monitoring system, once a faulty cable joint is identified, it may be necessary to apply another capacitive coupler onto the other side of the suspect joint. In this way and through time of flight analysis, the exact location of PD site within the joint could be determined.

### 3.2 Improving the PD detection sensitivity

The existence of excessive interference on-site will significantly influence the measurement sensitivity especially when PD measurements are carried out at the substation (i.e on the cable terminations). For PD monitoring at cable joints within the cable tunnel, the noise level is limited due to the attenuation. However, it would still be necessary to apply de-noising techniques for better SNR. The application of multi-resolution wavelet transform to denoise PD signals has been investigated at Southampton [10, 15]. Obtained results indicate that through appropriate selection of wavelet family and number of decomposition levels, the wavelet analysis technique can effectively discriminate real PD pulses among corona discharge, narrow-band radio interference and random noise. Further removal of interference has been achieved by applying level dependent threshold values.

This area of work has also assessed the use of wavelet packets [16] to remove measurement noise/interference from PD data measured in the field using radio frequency current transducers (RFCT). Results indicate that when wavelet packet denoising was applied to experimental field data obtained from cables in normal operation then the algorithm was capable of denoising signals (PDs and sinusoids) of various shapes that were heavily corrupted by noise without assuming any *a priori* knowledge of the PD signal characteristics.

Extending this idea 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 [17]. The approach combines wavelet filtering with a SVM which is based on statistical learning theory and structural risk minimisations principles. In theory, the SVM is equipped with a greater capability of generalization than traditional neural network approaches. It is particularly useful for applications involving sparse data sets and its application to PD signal processing has been investigated at Southampton [18, 19].

To generate suitable data, an experiment based around a 60 kV bushing has been developed (Figure 9). An RFCT (bandwidth 200 MHz) measures the current from the bushing tap point to earth. PD signals are simulated using a UHF calibrator injecting calibration pulses directly into the bushing core bar. Conventional PD measurements were also taken using a Robinson ® detector.

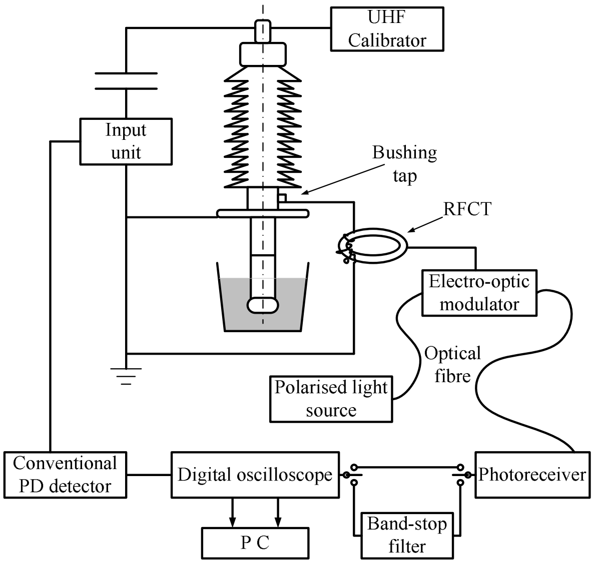

Figure 9 Experiment to simulate PD data buried in noise

In this experiment the minimum detectable PD level by eye was 160 pC as shown in Figure 10. Applying a band-stop filter (540 kHz – 1.6 MHz stop band) increased the sensitivity to 50 pC as it successfully depressed noise generated by the optical circuit itself.

Previous work has shown that wavelets have the advantage of combining time domain and frequency domain information which provides more useful information to analyze the signal than using a single domain. Research to date has proposed that the Daubechies family order 7 (db7) may give good results [20]. Therefore in this application, the db7 was chosen as the mother wavelet. Figure 10 shows the decomposition coefficients at seven different levels for noise and 160pC data respectively.

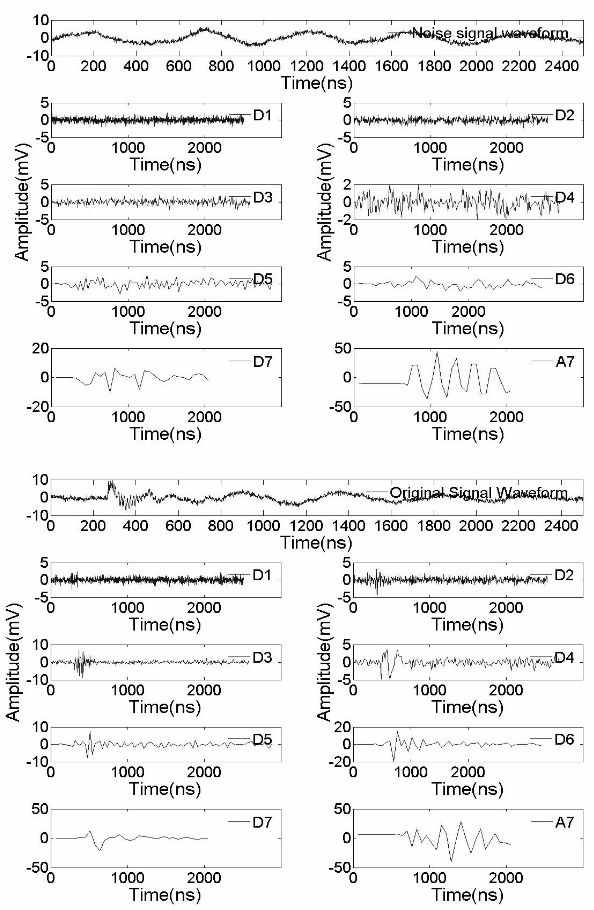

Figure 10 Wavelet decomposition coefficients

With reference to Figure 10, the detail coefficients at level 3 (WDEC3) clearly discriminate between noise and the presence of a PD signal. Therefore the detail coefficients at level 3 were used as the feature for SVM discrimination. The SVM used a Gaussian-RBF (Radial Basis Function) kernel,

$$K(x_i, x_j) = e^{\left\{-\gamma \left\| x_i - x_j \right\|^2\right\}} \tag{2}$$

was selected as it has been shown to have a good performance for this type of application [18]. Having used the 160 pC data to provide the feature for discrimination, a range of different discharge magnitudes were tested. In all cases 2800 sets of data were analysed for each level of discharge. Obtained results are shown in Table 1. The SVM can reliably identify discharge activity to 50 pC and only failed to recognise 1 in 200 events at 30 pC.

| 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 by using WDEC3 feature.

## 4 Other Applications

A related project at Southampton has concentrated on detecting internal PD activity in 400kV autotransformers, by measuring the current flowing to earth from the bushing tap point. This has been achieved by using a broadband (i.e a useful bandwidth of 200 MHz) radio frequency current transducer as the sensor. Field trials as well as laboratory-based experiments have shown that this approach is feasible [21]. The possible application of the EO modulator system has been investigated using the model shown in Figure 9 replacing the calibrator with a range of PD sources [22]. One reason for considering this application is that optical transmission of signal data is preferable in electrically noisy environments typically associated with high voltage substations. Another benefit is that the low levels of signal attenuation associated with optical transmission mean that anyone analysing the data may work at a very safe distance from the discharge source. Results have been obtained from two different pd sources; one designed to represent external corona and the other floating discharges in oil. Using the band-stop filter it was possible to detect both internal and external PD events providing their apparent charge was greater than 40pC. From frequency analysis of measured data it is clear that the RFCT output for a floating discharge pulse contains higher frequency components than those of the corona discharge and that although attenuated they are present in the photodiode output. Consequently, as with other PD detection systems for power transformers [23] it should be possible to discriminate between internal and external events, using time/frequency information from the photodiode output signal. The EO modulator transmission system contains an inherent delay and if several bushing tap points were to be monitored simultaneously identical transmission circuits will be required to ensure that it is possible to determine the measurement point nearest to the PD source. As with the cable transmission system, measurement sensitivity can be improved by use of an SVM or by improving the sensitivity of the RFCT itself.

The EO modulator-based system could find wider application on transmission assets, as the only requirement for a sensing element is that its maximum output voltage is limited to ensure that the EO modulator operates within its linear range.

## Conclusions

A method of on-line continuous monitoring that uses passive components at the measuring points has been developed and implemented at the University of Southampton. Its primary purpose is to facilitate the continuous on-line monitoring of transmission cable accessories. Possible application to other transmission assets has been considered.

Future work will concentrate on improving the detection sensitivity as well as considering the development of analytical tools capable of providing informed support for the transmission system operator.

## Acknowledgements

This paper summarises research completed with financial support from the National Grid and currently being funded through the EPSRC Supergen V, UK Energy Infrastructure (AMPerES) grant in collaboration with UK electricity network operators working under Ofgem's Innovation Funding Incentive scheme; - full details on http://www.supergen-amperes.org.

## References

[1] D.J. Swaffield, P.L. Lewin and S.J. Sutton, 'Application of Finite Element Analysis to externally forced water cooled cable circuit ratings' *Proceedings of 9th IEEE International Conference on Solid Dielectrics*, pp. 67-70, Winchester, UK (2007)

[2] Y. Tian, P.L. Lewin, D. Pommerenke, J.S. Wilkinson and S.J. Sutton, 'Partial Discharge On-line Monitoring for HV Cable Systems Using Electrooptic Modulators', *IEEE Trans DEI.* Vol. 11, No. 5, pp 861-869, September (2004)

[3] C. Henningsen, K. Polster, B.A. Fruth, D.W. Gross, 'Experience with an On-line Monitoring System for 400 kV XLPE Cables', *Proceedings of IEEE T&D Conf.* pp. 515-520, (1996)

[4] N.H. Ahmed, and N.N. Srinivas, 'On-line Partial Discharge Detection in Cables', *IEEE Trans. DEI*, Vol. 5, pp. 181-188, (1998)

[5] Faraday House Group Ltd, 'CableTrend-Continuous Monitor for PD in Power Cables

[6] R. Plath, U. Herrmann, K. Polster, J. Spiegelberg, P. Coors, 'After Laying Tests of 400 kV XLPE Cable Systems for Bewag Berlin', *Proceedings of 11th ISH*, Vol. 5, pp. 276-279, London, UK (1999)

[7] H. Ota, M. Ichihara et al, 'Application of advanced after-laying test to long-distance 275 kV XLPE cable lines', *IEEE Trans. Power Delivery*, Vol. 10, No. 2, pp. 567-579, (1995)

[8] Y. Tian, P.L. Lewin, A.E. Davies and G. Hathaway, 'Acoustic emission techniques for partial discharge detection within cable insulation', *Proceedings of 8th DMMA*, pp. 503-508, Edinburgh, Sep. (2000)

[9] Ontario Hydro, "OHT Partial Discharge Detection Instrument –Functional Description", user manual, (1997)

[10] Y. Tian, P.L. Lewin, A.E. Davies, S.J. Sutton and S.G. Swingler, 'Comparison of On-line Partial Discharge Detection Methods for HV Cable Joints', *IEEE Trans. DEI*, Vol. 9, No. 4, pp. 604-615, (2002)

[11] Y. Tian, P.L. Lewin, A.E. Davies, S.J. Sutton and S.G. Swingler, 'Partial Discharge Detection in Cables using VHF Capacitive Couplers', *IEEE Trans. DEI*, Vol. 10, No. 2, pp. 343-353, (2003)

[12] Y. Tian, P.L. Lewin, J.S Wilkinson, G. Shroeder, S.J. Sutton and S.G. Swingler, 'An improved optically based PD detection system for continuous on-line monitoring of HV cables'. *IEEE Trans DEI,* Vol 12 No. 6 pp. 1222-1234 (2005)

[13] Y. Tian, P.L. Lewin, M. Webb, S.J. Sutton and S.G. Swingler, 'Continuous monitoring of partial discharges in power cables using capacitive couplers and trend analysis', *Proceedings of the 13th ISH*, pp CD-ROM, Delft, Netherlands, August (2003)

[14] L. Hao. P.L. Lewin and S.J. Dodd, 'Partial Discharge Source Characterization within a HV Cable Joint', *Proceedings of 9th IEEE International Conference on Solid Dielectrics*, pp. 577-580, Winchester, UK (2007)

[15] P. Wang, P. L. Lewin, Y. Tian, S. J. Sutton and S. G. Swingler, 'Application of wavelet-based denoising to online measurement of partial discharges', *Proceedings of 8th IEEE International Conference on Solid Dielectrics*, pp 619-622, Toulouse, France (2004)

[16] A. Kyprianou, P.L. Lewin, V. Efthimiou, A. Stavrou and G.E. Georghiou, 'Wavelet packet denoising for online partial discharge detection in cables and its application to experimental field results'. *Measurement Science and Technology* 17(9) pp. 2367-2379. (2006)

[17] L. Hao, P.L. Lewin and S.J. Dodd, 'Extraction of PD Signals from an Electro-optic Modulator Based PD Measurement System'. *Proceedings of 2006 IEEE Conference on Electrical Insulation and Dielectric Phenomena*, pp. 623-626, Kansas City, Missouri, USA. (2006)

[18] L. Hao, P.L. Lewin and Y.Tian, 'Partial Discharge Descrimination Using a Support Vector Machine' *Proceedings of the 14$^{th}$ ISH,* pp CD-ROM, Beijing, China, (2005).

[19] L. Hao, P.L. Lewin and S.J. Dodd, 'Comparison of Support Vector Machine Based Partial Discharge Identification Parameters' *Proccedings of 2006 IEEE International Symposium on Electrical Insulation,* pp 110-113, Toronto, Canada (2006).

[20] X. Ma, C. Zhou and I.J. Kemp 'Interpretation of Wavelet Analysis and its Application to Partial Discharge Detection' *IEEE Trans DEI,* Vol. 9, No. 3, pp 446-457. (2002).

[21] B. Han, P.L. Lewin, Y. Tian, Z.D. Wang and P. Jarman, 'Measurement of Discharge Signal Propagation within a Dry-type Transformer Model', *IEE Proc Int Conf on Reliability of Transmission and Distribution Networks*, pp 283-286, London, UK (2005)

[22] L. Hao, P.L. Lewin, Y. Tian, J.S. Wilkinson, S.G Swingler and S.J. Sutton 'Application of Electro-optic Modulation Technique for PD Monitoring of Power Transformers'. *Proceedings of 2006 IEEE International Symposium on Electrical Insulation*, pp. 412-415, Toronto, Canada. (2006)

[23] J. Fuhr, "Procedure for Identification and Localization of Dangerous PD Sources in Power Transformers" *IEEE Trans DEIS*, Vol. 12, No. 5, p1005-1114, (2005)