Continuous On-line Condition Monitoring of HV Cable Systems

P L Lewin
The Tony Davies High Voltage Laboratory, University of Southampton, Southampton SO17 1BJ, UK
Email: pll@ecs.soton.ac.uk

***Abstract*: This paper discusses data acquisition, transmission and processing methodologies for continuous on-line monitoring of partial discharges in high voltage cable systems. A PD continuous on-line monitoring system for underground cable circuits using capacitive couplers, $LiNbO_3$ electro-optic modulators, laser, optical switch and optical fibers has been developed. Future research will consider effective data processing methods that will allow continuous monitoring of asset health and possibly facilitate lifetime prediction.**

INTRODUCTION

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 defects introduced during transportation or installation. In particular continuous on-line monitoring provides additional information about progressing degradation or deterioration under operational stress, thus preventing the occurrence of breakdown. 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 due to the installation procedure and operational stresses.

This paper provides a detailed review of PD data acquisition, transmission and processing methodologies. A continuous PD on-line monitoring system for cable joints of underground cable circuits, based on the optical sensing technique using electro-optic (EO) modulators [1], is proposed. 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 distribution assets over their effective lifetimes.

DATA ACQUISITION AND TRANSMISSION METHODOLOGIES

Data acquisition for PD detection in cable systems usually involves non-conventional electrical coupling techniques including coaxial cable sensors [2]; inductive high frequency current transformers (HFCT) either around the cable itself [3] or the earth connection [4]; directional couplers [5]; and foil electrodes on cable joints [6]; as well as acoustic emission (AE) techniques [7]. Electrical coupling techniques work on various frequencies, ranges from a few MHz to several hundred MHz. 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 with 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 frequencies of discharge signals are rapidly attenuated on a HV cable line. 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 inside the cable tunnel may need to transmit over a significant distance e.g. several kilometres to the measuring 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 measuring 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 of the measuring equipment. Generally discharge signals detected by the sensors are fed 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 [5, 8]. 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 [2, 5, 6], so far there has not been continuous PD monitoring for practical underground cable circuits especially where a mains supply is not available.

A CONTINUOUS OPTICAL PD ON-LINE MONITORING SYSTEM

A novel PD on-line monitoring technique using a $LiNbO_3$ electro-optic (EO) modulator has been developed at the University of Southampton[1]. The measurement mechanism uses the measured PD signal and applies it across an optical fiber coupled $LiNbO_3$ waveguide modulator, which modulates the intensity of the 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 $LiNbO_3$ modulator input, and monitors the optical output from the modulator using an optical receiver. The EO modulator is compact and passive requiring no power to operate. Since a capacitive coupler has been demonstrated to be an effective PD on-line detection sensor [9, 10], it was used as the PD sensor in the EO modulator-based monitoring technique. The principle of this optical technique is shown in 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 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 is between 10-20 pC.

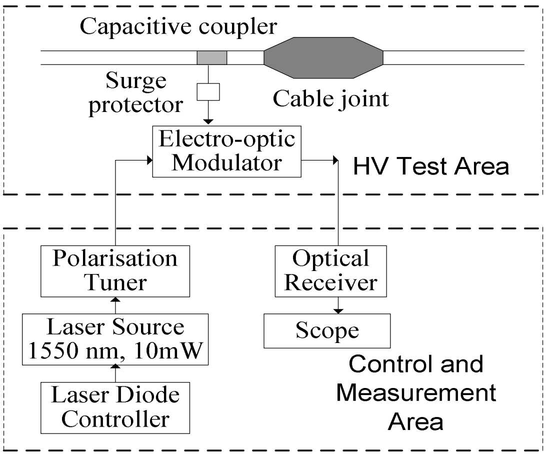

Figure 1 Principle of the EO-modulator based monitoring technique

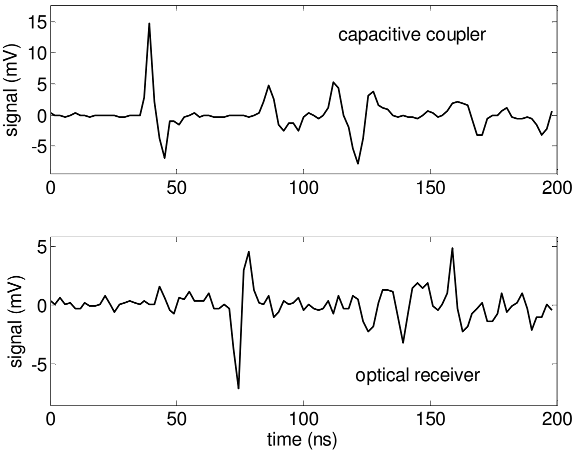

Figure 2 PD signals from the cable joint detected by the capacitive coupler and the optical receiver

Although very simple in approach, unfortunately this system has one major disadvantage – it would prove very expensive to implement. For example Polarization Maintaining (PM) fibre costs $1300 per kilometer. Figure 3 shows a modified design that uses Single Mode (SM) fibre ($300 per kilometer). The new design requires a polarizer to be placed near to the EOM close to the measurement point. To ensure reasonable transmission to the polarizer the laser light is scrambled.

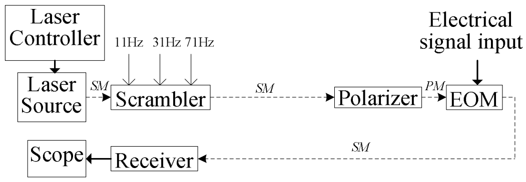

Figure 3 Revised PD optical remote sensing system

Obtained results using the revised sensing system are shown in Figure 4

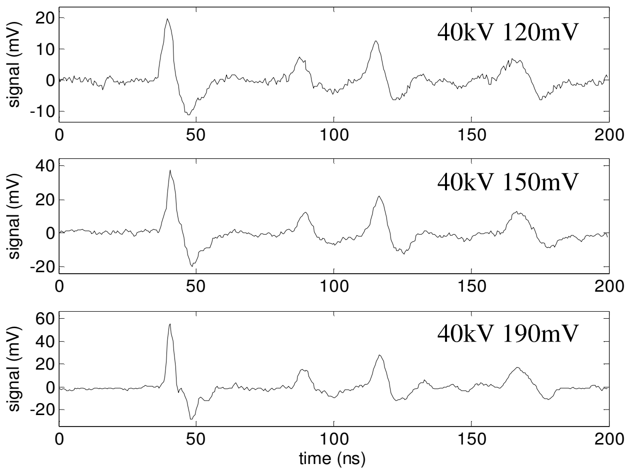

Figure 4 100pC discharge signals for an applied voltage of 40kV at different laser currents

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 are 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 traveling along the long cable line. Thus the noise level at the site of a cable joint is limited. Only one capacitive coupler is installed close to a cable joint, 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 optical fibers connected to the EO modulator outputs are bundled together before feeding into the optical receiver. Any light within a single optical fiber 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 inside the cable tunnel is the EO modulator, 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 fibers and new joints could be designed to include optical network ready PD sensors.

With current established analytical approaches, the optical receiver-measured signals can be input into a spectrum analyzer, a digital oscilloscope or the signal processing unit for phase-related plots, statistical distribution and trend analysis. 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 alarm should be given in order to prevent the occurrence of breakdown. Telecom interfaces such as modems and optical links will be available to allow remote control and data download. The development of data processing methodologies capable of analyzing data from the remote sensing system needs further consideration

CURRENT DATA PROCESSING METHODOLOGIES

Spectrum, Pulse Shape & Time of Flight

The signal spectrum can be compared with the noise spectrum to find the frequency range with the best signal to noise ratio, which can be used for zero-span to display the PD signals over one or more power cycles. This information can also be helpful in choosing the filter tuning range for signal acquisition. Spectrum can also be obtained using the FFT of the measured signals. PD can be recognized by specific pulse characteristics like pulse width. For example, it may be assumed that only PD close to the sensor will have a pulse width of a few ns, while all noise and PD from other locations will have a larger pulse width due to the cable attenuation characteristics. PD location by time of flight analysis has been investigated and verified by applying two capacitive couplers either side of a cable joint [9]. 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 [10]. For the PD continuous on-line monitoring system, once a faulty cable joint is identified, it would be possible to apply another capacitive coupler onto the other side of the joint. In this way and through time of flight analysis, the exact location of PD site within the joint could be determined. In addition, time of flight analysis can be helpful in discriminating signals due to cross-bonding of the three-phase system, and signals propagated from neighboring cable joints along the cable line if they are still detectable at the local joint.

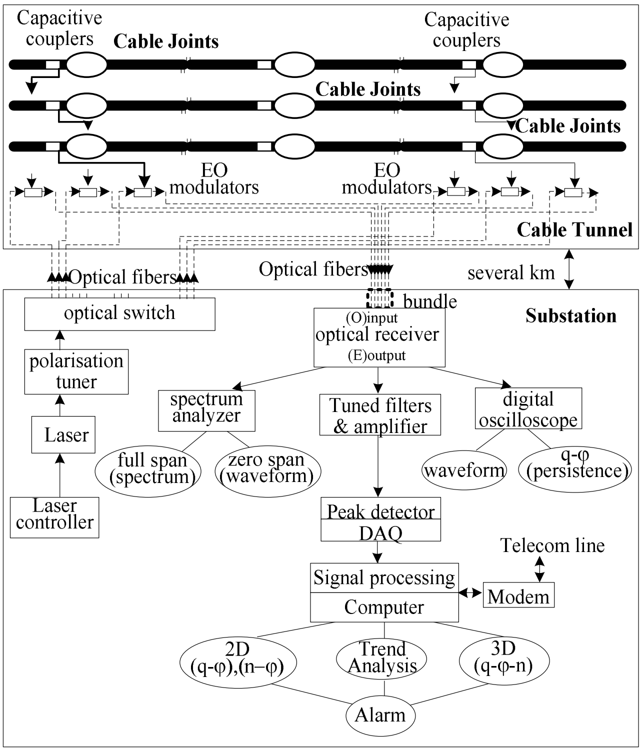

Figure 5 Continuous on-line PD optical monitoring system for underground cable circuits

Phase-Resolved Histograms and Three-Dimensional φ-q-n Patterns

By measuring pulse distribution as a function of the phase angle, it is possible to obtain information about the phenomena that cause the distribution. Phase-resolved PD patterns have been proved to be effective and adopted by many commercial monitoring equipment. Within the Tony Davies High Voltage

Laboratory at Southampton we have developed computer programs to display the pulse magnitude distribution q-φ, pulse count distribution n-φ, and three-dimensional φ-q-n patterns (Figure 6). Phase-resolved 2D patterns can also be obtained using a modern digital oscilloscope, as shown in Figure 7

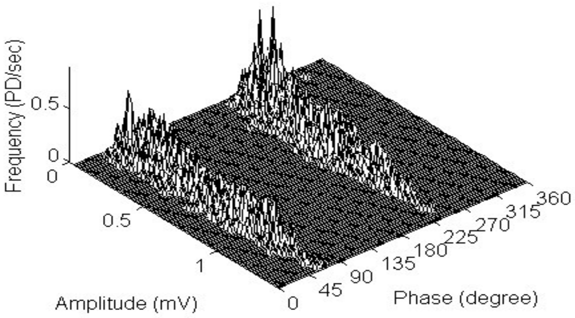

Figure 6 PD φ-q-n pattern due to an internal void

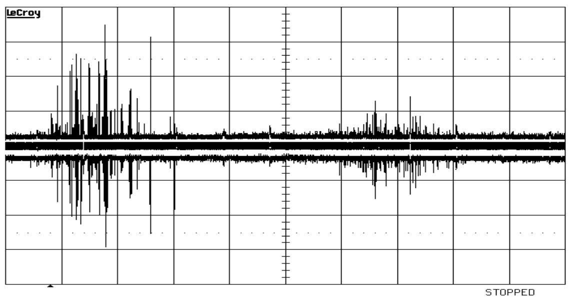

Figure 7 Persistent plot of surface discharges

Trend Analysis

Insulation failure is usually unpredictable and often violent. Therefore the deterioration of HV cable insulation is a matter of continuous concern. Continuous monitoring of PD activity over long periods and the analysis of trend is desirable, as it has the advantage of providing the necessary field data to better understand in-service insulation behavior, particularly insulation degradation, thus preventing catastrophic damage to property and risk to human life. Peak amplitude and count rate are the most suitable parameters to reveal long-term trends in PD activity. They have been used by the authors for PD continuous monitoring [11]. The trending information as well as the phase-resolved patterns should be kept as discharge history for later assessment.

Wavelet-Based De-noising

The existence of excessive interferences on-site will significantly influence the measurement sensitivity especially when PD measurements are carried out at the substation. For PD monitoring at cable joints within the cable tunnel, the noise level is limited due to the attenuation along the long cable line from the substation. 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 [9, 12]. Obtained results indicate that through appropriate selection of wavelet family and number of decomposition levels, wavelet analysis technique can effectively discriminate real PD pulses among corona discharge, narrow-band radio interference and random noises. Further removal of these interferences has been achieved by applying level dependent threshold values.

Alarm Strategy

If measured signals are beyond a specified level, the monitoring system should update phase-resolved patterns and trending histogram more intensely. When necessary the automatic alarm will sound and automatic alarm text will appear on the monitor. Though the automatic alarm strategy is adopted, it is still recommended that the final discrimination should be made by experienced operators via visual observation.

Telecommunication

The interpretation of the test results and assessment of equipment condition should involve human expertise rather than completely left to a computer. In order to reduce costs and efforts a remote controlled monitoring system is better to be equipped with telecom interfaces. This allows experts to access data remotely over a telephone or internet connection using a standard internet browser, monitor on site activity and implement remote control.

CONCLUSION

This paper has reviewed data acquisition and transmission methodologies for on-line monitoring of partial discharges in HV cable systems. The advantages and limitations of the present signal optical fiber transmission techniques were detailed. Based on the electrooptic modulator-based monitoring technique, this paper proposes a PD continuous on-line monitoring system for cable joints of underground cable circuits. The system includes laser source, polarization controller, optical switch, a number of electro-optic modulators and optical receiver. The monitoring system is sensitive, safe, compact, with very little transmission attenuation, immune from electromagnetic interference and does not require power supply near the joints. Current data processing methodologies adopted for the monitoring system have been detailed, which include pulse shape and spectrum analysis, time of flight analysis, phase-resolved two-dimensional histograms and three-dimensional φ-q-n patterns, trend analysis, wavelet-based denoising, alarm strategy and telecommunication functions. Future developments of this monitoring approach are twofold, firstly to continue to develop the sensing technique - maintaining measurement sensitivity, whilst reducing system cost and secondly to investigate methods of analysing continuous condition monitoring data including the application of machine learning algorithms, genetic algorithms and stochastic analysis.

ACKNOWLEDGMENT

The financial support from the National Grid Transco plc for this research is gratefully acknowledged.

REFERENCES

1. Tian Y., 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
2. Henningsen C., K. Polster, B. A. Fruth, D. W. Gross, "Experience with an On-line Monitoring System for 400 kV XLPE Cables", Record of IEEE T&D Conf. Pp. 515-520, 1996
3. Ahmed, N. H. and N. N. Srinivas, "On-line Partial Discharge Detection in Cables", IEEE Trans. DEI, Vol. 5, pp. 181-188, 1998
4. Faraday House Group Ltd, "CableTrend-Continuous Monitor for PD in Power Cables"
5. Plath R., U. Herrmann, K. Polster, J. Spiegelberg, P. Coors, "After Laying Tests of 400 kV XLPE Cable Systems for Bewag Berlin", Proc. of 11th ISH, Vol. 5, pp. 276-279, London, 1999
6. Ota H., 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, April 1995
7. Tian Y., P. L. Lewin, A. E. Davies, G. Hathaway, "Acoustic emission techniques for partial discharge detection within cable insulation", Proc. of 8th DMMA, pp. 503-508, Edinburgh, Sep. 2000
8. Ontario Hydro, "OHT Partial Discharge Detection Instrument – Functional Description", user manual, 1997
9. Tian Y., P. L. Lewin, A. E. Davies, S. J. Sutton, 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, August 2002
10. Tian Y., P. L. Lewin, A. E. Davies, S. J. Sutton, S. G. Swingler, "Partial Discharge Detection in Cables using VHF Capacitive Couplers", IEEE Trans. DEI, Vol. 10, No. 2, pp. 343-353, April 2003
11. Tian Y., 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", Proc. of 13th ISH, Netherlands, August 2003
12. Wang P., P. L. Lewin, Y. Tian, S. J. Sutton and S. G. Swingler, "Application of wavelet-based denoising to online measurement of partial discharges", Proc. of International Conf. on Solid Dielectrics, Toulouse, July 2004

APPENDIX

The Tony Davies High Voltage Laboratory

Tony Davies, who was Professor of Electrical Power Engineering from 1994 until his untimely death on 4 July 2002, joined the University of Southampton in 1978 as the Pirelli Lecturer in the Department of Electrical Engineering. High voltage research was then conducted in the 'cables hut'.

The laboratory moved to its current site in 1991 with funding provided by STC Submarine Systems. Continued growth in activity, both research and commercial testing, was hampered by a fire in November 1997 that largely destroyed the main hall. Within 9 months the laboratory was re-equipped and fully functional. The laboratory continued to grow and early in 2002 it was decided to build an extension comprising of a second hall and an additional materials/measurements laboratory - funded under the SRIF initiative.

In recognition of the enormous personal contribution to the establishment of a world-class high voltage facility, University Council has decided that the extended laboratory should be renamed the Tony Davies High Voltage Laboratory.

Currently, the laboratory consists of five members of academic staff, five full-time research staff and twelve full-time postgraduate students, who are supported by an engineer and three technicians. In 2003 members of the laboratory published 18 journal papers and 36 refereed conference papers. In 2007 the 9th IEEE International Conference on Solid Dielectrics will be held in Southampton.

The Laboratory supports industrial customers through a range of commercial testing activities including;

- development testing
- type approval
- material characterisation
- forensic analysis

Facilities include;

- 2 main halls
- 11 discrete high-voltage test areas
- Faraday room
- Salt-fog chamber
- specialist workshop
- materials preparation and testing suite

HV supplies;

- 1MV lightning impulse generator
- 300kV ac
- 600kV dc

MV supplies;

- 380kV lightning and switching impulse
- 200kV ac/dc set

Contact Information:

General research enquiries:
Dr Paul Lewin (pll@ecs.soton.ac.uk)

Commercial testing enquiries:
Neil Palmer (nlp@ecs.soton.ac.uk)