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Application of Superluminescent Light Emitting Diode to Electrooptic Modulator Based PD Continuous On-line Monitoring System

Y Tian [1]*, P L Lewin [1], J S Wilkinson [2], S J Sutton [3] and S G Swingler [1]
[1] Electrical Power Engineering Group, School of Electronics and Computer Science, University of Southampton, Highfield, Southampton, SO17 1BJ, UK
[2] The Optoelectronics Research Centre, School of ECS, University of Southampton, Southampton, SO17 1BJ, UK
[3] National Grid Transco plc, NGT House, Warwick Technology Park, Gallows Hill, Warwick, CV34 6DA, UK
* E-mail: ytian@soton.ac.uk

Abstract: Partial discharge monitoring provides effective evaluation of power cables, particularly of joints that are installed on site. Continuous on-line monitoring can provide information about progressing degradation under operational stresses, thus reducing the likelihood of breakdown. A novel PD continuous online monitoring technique has been developed by the authors. The mechanism applies PD signals across a LiNbO3 electro-optic modulator to modulate the intensity of the transmitted light. This technique does not require a voltage supply near the cable joints as the EO modulator is passive. In earlier investigations a fibre laser was used as the light source. The polarisation state of the laser light needs to be maintained to suit the polarisation dependent EO modulator. This paper investigates the application of a superluminescent light emitting diode, which provides unpolarised light, as the light source. The alternative monitoring system is investigated using both simulated experiments and practical PD tests on a 132 kV prefabricated cable joint.

INTRODUCTION

Partial discharge (PD) monitoring provides effective evaluation of power cables, particularly of joints that are installed on site. Continuous on-line monitoring can provide information about progressing degradation under operational stresses, thus reducing the likelihood of breakdown. Additionally, the measured data and experience obtained over the cable circuit service time will be valuable for condition assessment as the system ages.

PD acquisition in cable systems usually involves non-conventional electrical coupling techniques such as capacitive couplers [1,2], high frequency current transformers [1], directional couplers [3], or foil electrodes on joints [4]. High frequency components of PD signals are rapidly attenuated as they propagate along a HV cable. Sensors must be placed near to a PD source in order to obtain good sensitivity. The detected PD signals from cable joints need to be transmitted over a long distance to the substation for further signal processing and analysis. Generally measured PD signals are fed into an optical transmitter or an acquisition unit with digitizer and communication port, and then transmitted over the standard optical fibre or digital fibre. However, either the optical transmitter or acquisition unit, which are placed nearby the PD sensors and cable joints, require a power supply to operate, though they can work on battery for a few hours. Although such systems may be suitable for after-laying commissioning PD tests, they are not suitable for continuous monitoring in situations where no power sources are available, e.g. buried cable circuits.

A novel PD continuous monitoring technique has been developed by the authors [5-10]. The measurement mechanism applies capacitive coupler measured PD signals across a $LiNbO_3$ electro-optic modulator (EOM), which modulates the intensity of the transmitted laser light as an approximately linear function of the voltage applied across it. For the developed technique a Koheras® fibre laser that provides linearly polarised light output was used as the light source. The laser light was transmitted over an optical fibre to the EOM. The polarisation state of the laser light needs to be maintained to suit the polarisation dependent EO modulator. The modulated light is then transmitted over another optical fibre to be picked up by the optical receiver. This PD monitoring technique does not require a power supply near to the cable joints as the EO modulators are passive.

This paper investigates the application of a superluminescent light emitting diode (SLED), which directly provides unpolarised light, as the light source. The revised monitoring system has been investigated using both simulated experiments and practical PD tests on a 132 kV prefabricated cable joint.

ELECTRO-OPTIC MODULATION TECHNIQUE USING A FIBRE LASER

The laser source used so far is a compact single wavelength distributed feedback fibre laser designed to provide narrow line width, long coherence length, low relative intensity noise (RIN) and phase noise, and very good wavelength stabilization. It is suitable for use in optical sensing and interferometry. For the developed technique two measurement methods were applied. Figure 1 shows the measuring technique using a polarisation controller and electro-optic modulator. The fibre laser provides linearly polarised 1550 nm light which is transmitted via standard single mode (SM) fibre to the EOM. The laser is controlled using a combined temperature and current controller. The laser has a controller current range of 200 mA and maximal optical power of 9.3 mW. The polarisation controller is used to control the polarisation state of the laser light to match with the polarisation sensitive EOM. The PD sensor-measured signal is used to modulate the intensity of the transmitted laser light, which is then fed back into an optical receiver and then measured using a LeCroy digital oscilloscope with 500 MHz bandwidth.

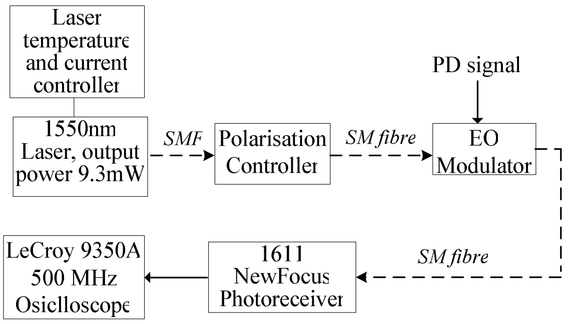

Figure 1 the laser-controller-EOM approach

The disadvantage of this method is that the polarisation controller needs to be tuned by hand to ensure the modulator functions efficiently. However, this is not practicable for continuous on-line monitoring as automatic data acquisition is desirable. Thus an alternative measuring arrangement was also applied, as shown in Figure 2. Instead of a polarisation controller, a scrambler that employs a mechanical, magnetically driven fibre squeezing technique is applied. It is controlled by three ±5V voltages. Each channel is set to a unique frequency: 11Hz, 31Hz and 71Hz respectively. The scrambler is used to scramble the linearly polarised light from the laser source. The resultant unpolarised light is then transmitted over standard SM fibre to feed into a polarizer. The output polarisation state of the polarizer has been aligned with the input polarisation requirement of the EOM.

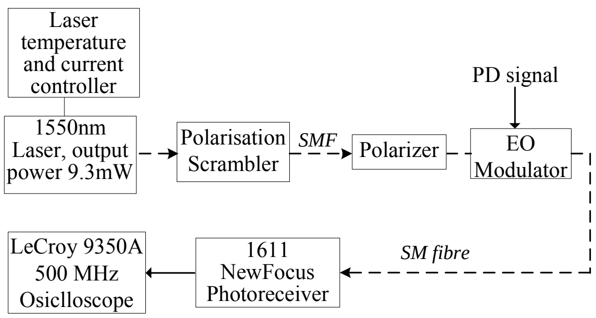

Figure 2 the laser-scrambler-polarizer-EOM approach

Both methods do not require a power supply near to the cable joints as the polarizer and EOM are passive.

USING SUPERLUMINESCENT LIGHT EMITTING DIODE AS LIGHT SOURCE

By its nature a laser diode provides polarised light output. An extensive search has been carried out to find an alternative light source that can provide unpolarised light. The Covega® model 1006 SLED is a high power, de-polarised, broadband superluminescent light emitting diode used for spectrum sliced WDM telecommunications, instrumentation, low coherence interferometry, embedded sturctural sensors, medical and fibre gyro applications. The model 1006 SLED is offered as a module with integral thermoelectric cooler and temperature sensor. The model 1006 is supplied with a single mode fibre. It has a light output power greater than 20 mW, broad optical bandwidth of 40 nm and degree of polarisation (DOP) less than 2%. Like the used Koheras® fibre laser, the SLED is also controlled using the Profile® T510 laser temperature and current controller. The controller thermistor is set as 10 kΩ and the maximal current limit is set to 700 mA.

Figure 3 shows the alternative PD detection system using EO modulation technique with SLED as the light source. Compared with Figures 1 and 2, the polarisation controller or the polarisation scrambler is not needed. The SLED was connected to the polarizer using a standard single mode fibre.

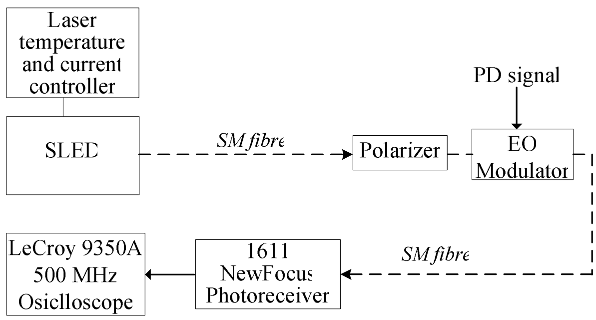

Figure 3 Using superluminescent light emitting diode as the light source

FEASIBILITY TEST

The characteristics of the measuring system noise were investigated using the arrangement shown in Figure 3. In this case there was no RF input signal for the EOM. Various laser controller currents of 120, 200, 300, 350 and 400 mA were used. Figure 4 shows the measured signals from the optic receiver for for five laser controller currents. Obtained results indicate that the noise level increases from about 2 mV to about 30 mV with the increase of laser controller current from 120 mA to 400 mA. This also proves that the noise is not external but due to the measuring system itself. Frequency characteristics of the noise are investigated by performing FFT of the noise signals, as shown in Figure 5. The noise spectra is broadband and dominantly below 200 MHz.

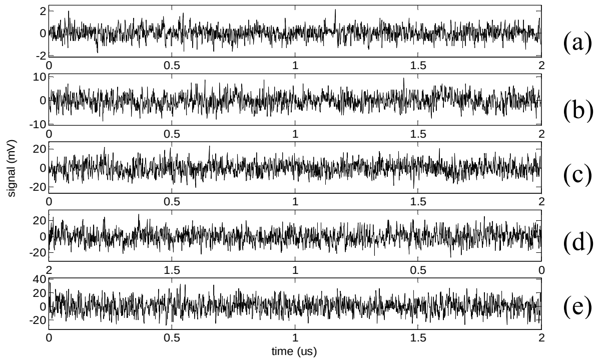

Figure 4 Measurement system (SLED) noise vs. laser controller currents
(a) 120mA; (b) 200mA; (c) 300mA; (d) 350mA; (e) 400mA

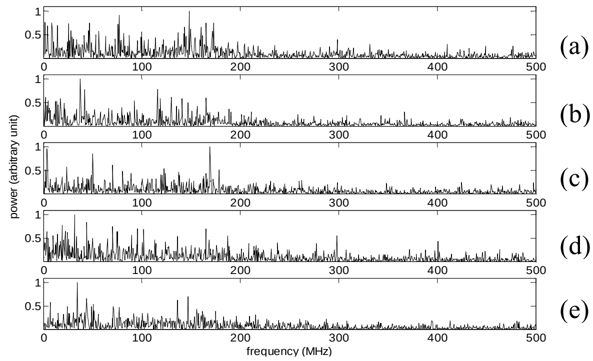

Figure 5 Measurement system (SLED) noise spectra vs. laser controller currents
(a) 120mA; (b) 200mA; (c) 300mA; (d) 350mA; (e) 400mA

To investigate the response of the optical measurement system (using SLED) to typical PD signals that occur within cables, a simulation experiment has been undertaken (Figure 6). In this case capacitive coupler signals were used as the electrical modulation inputs for the EO modulator. The capacitive coupler was installed on a 3m cross-linked polyethylene (XLPE) 66 kV cable section. The sensitivity of capacitive couplers in PD measurement has been demonstrated as PDs less than 3pC can be clearly detected by capacitive couplers installed 1.5m away from the PD source. A step wave from the pulse generator was injected into one cable end via a 10pF capacitor. In theory the equivalent discharge quantity can be consider as the multiplication between the capacitor capacitance and the magnitude of the step wave.

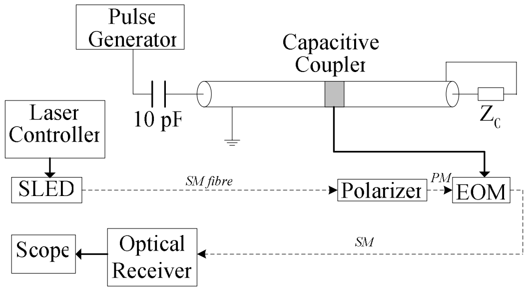

Figure 6 The optical measurement system (using SLED) with capacitive coupler and simulated PD

Figure 7 shows the capacitive coupler measured signal, when a step wave of 2V and rise time of 1ns was injected into the cable via a 10 pF capacitor. Figure 8 shows the optical receiver measured signal using SLED as the light source (Figure 6), at laser controller currents of 290mA, 350mA and 400mA respectively for the SLED. For comparison, experiments were also carried out using the fibre laser plus polarisation scrambler measurement arrangement (Figure 2). Figure 9 shows the optical receiver measured signals at laser controller currents of 70mA, 100mA and 150mA respectively for the fibre laser. The current limit for the fibre laser was set to be 200mA. Obtained results indicate that the measurement sensitivity using the SLED arrangement is lower than using the fibre laser plus scrambler arrangement. The inherent noise level of the SLED is higher than the fibre laser, resulting in lower signal to noise ratio for the SLED. However, obtained results indicate that 20pC of simulated charge can still be measured using the optical measurement arrangement using the SLED as the light source.

The EO modulator has a maximal sampling rate of 2.5 GS/s and the optical receiver has a frequency bandwidth up to 1 GHz. Consequently the frequency response of the optical measurement system is determined by the capacitive coupler, which in general operates in the very high frequency range of approximately three hundred MHz.

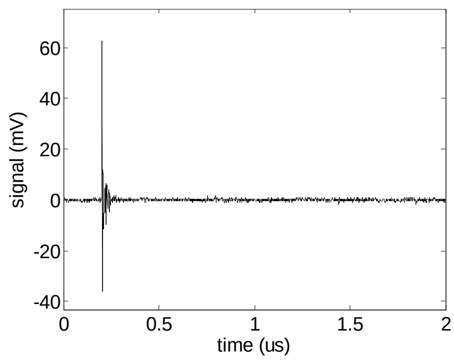

Figure 7 Measured capacitive coupler signal with an equivalent charge of 20 pC

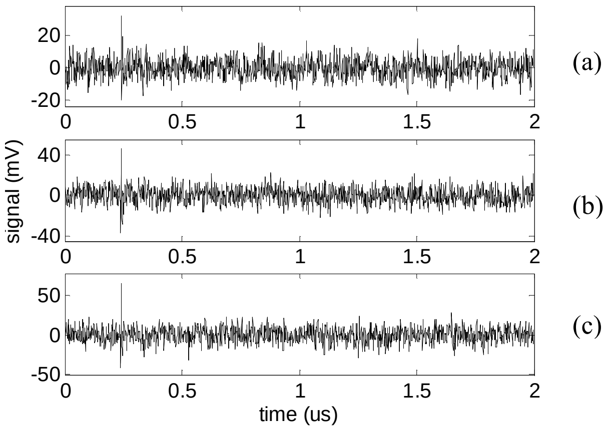

Figure 8 Optical receiver measured signal vs. laser controller currents, using ‘SLED’
(a) 290mA; (b) 350mA; (c) 400mA

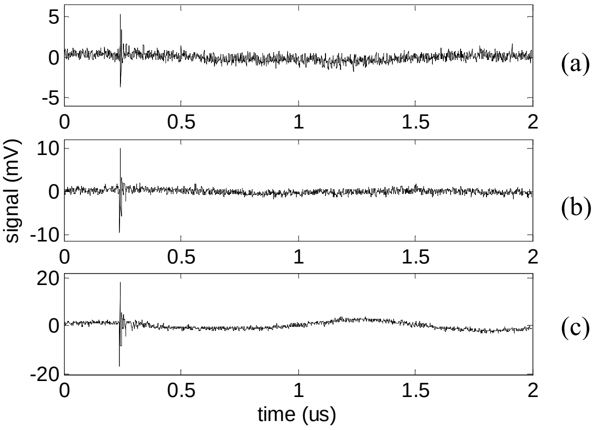

Figure 9 Optical receiver measured signal vs. laser controller currents, using ‘Fibre Laser + scrambler’
(a) 70mA; (b) 100mA; (c) 150mA

PD DETECTION IN A 132 KV CABLE JOINT USING SLED AS THE SYSTEM LIGHT SOURCE

The optical measurement system using the SLED as light source was applied to detect practical PDs produced from a 132kV cable/joint loop. The test arrangement is shown in Figure 10. Two 132kV XLPE cable sections were connected by a prefabricated cable joint. The main insulation material of the cable joint is ethylene propylene rubber. The cable ends were connected to oil-filled cable terminations. Conventional PD electrical detection was also applied to provide the PD discharge quantity. The PD detector used is a Robinson® model 5 type 700. A conducting paint in the shape of ‘v’ was installed on top of the cable XLPE between the cable joint stress cone (conductor) and the cable joint outer semiconducting layer. This acts as the PD source within the cable joint. The capacitive couplers were installed on the cable section close to the cable joint. A surge protector with a bandwidth of 1000 MHz was placed between the capacitive coupler and EO modulator. The surge protector was used to protect the EO modulator from any possible over-voltage or breakdown, even though the EO modulator itself has a passive nature. In addition, the optical fibres between the HV cable system and the measuring equipment provide electrical isolation, thus preventing any damage to the measurement equipment should the HV cable breakdown. Figure 11 shows the photo of the PD test arrangement in the HV Laboratory at the University of Southampton.

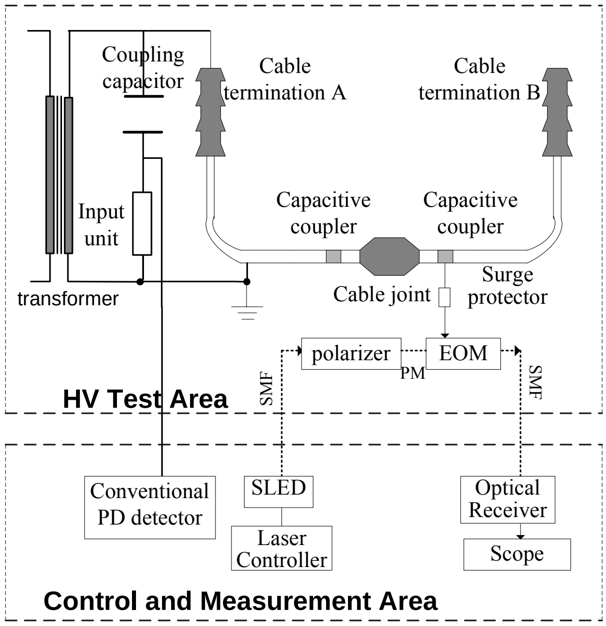

Figure 10 Application of the SLED-based optical remote sensing system to detect PDs produced from a 132 kV cable joint

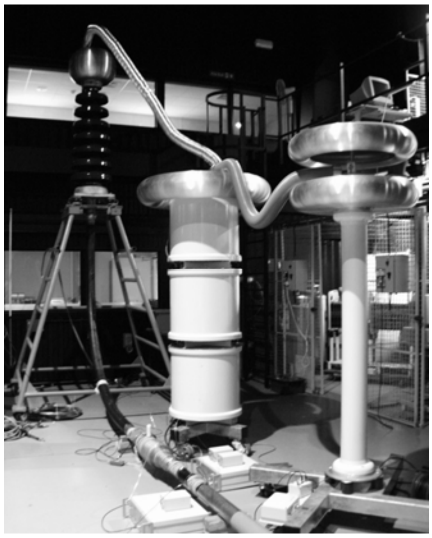

Figure 11 Photo of the PD test arrangement for a 132 kV cable joint

Figure 12 shows a PD signal measured by the optical receiver and the Robinson® PD conventional detector, together with the 50 pC calibration pulse on the

Robinson® detector. The applied voltage in this case is 35 kV, and the laser controller current for the SLED is 350 mA. For this particular set of data the discharge quantity is about 75 pC and the relevant optical receiver signal magnitude is around 60 mV. The background noise level for the optical receiver signal is about 15 mV. The measurement sensitivity of the optical measuring system using SLED as the light source can be estimated as approximately 30-50 pC, if a minimum signal to noise ratio of two is to be achieved. For this measurement the sampling rate is 1GS/s. As shown in Figure 12 the PD signal is presented as a pike from the optical receiver, but as an extended waveform form the Robinson® PD conventional detector, which operates in the frequency range up to only several hundred kHz.

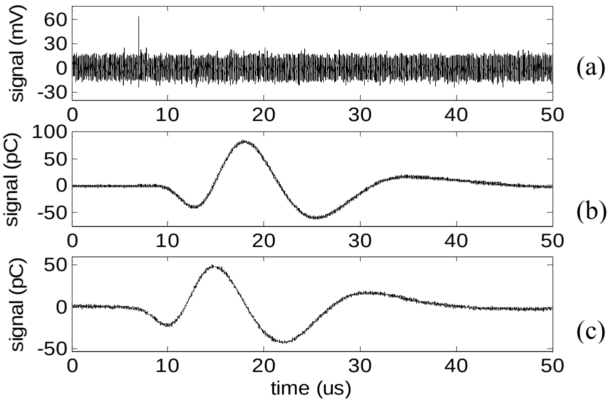

Figure 12 PD from the 132 kV cable joint measured by the optical receiver and conventional detector
(a) optical receiver; (b) Robinson® PD detector; (c) 50 pC calibration pulse

Figure 13 shows the detailed PD waveform measured by the optical receiver and its respective capacitive coupler output signal. In this case the laser controller current for the SLED is 400 mA. There are reflected pulse on the signal output, and investigation indicates that these reflections occur at the two oil-filled cable terminations.

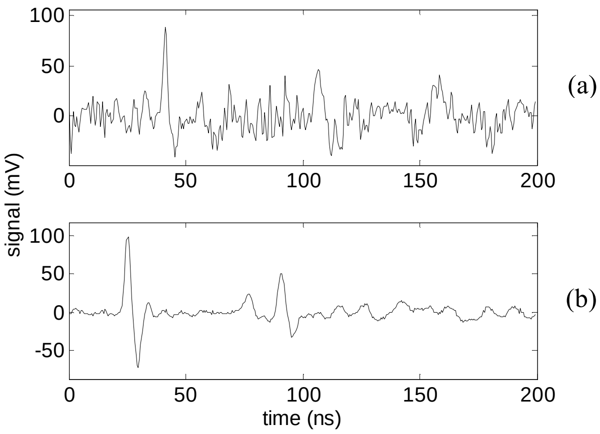

Figure 13 PD signal from the 132 kV cable joint measured by the optical receiver and capacitive coupler
(a) optical receiver; (b) capacitive coupler

CONCLUSIONS

This paper describes the recent development into an electro-optic modulator based optical remote sensing technique which is suitable for the continuous on-line monitoring of partial discharges in underground cable circuits. A superluminescent light emitting diode was used as the light source to replace the fibre laser that was investigated earlier. The SLED provides de-polarised light output, which can be directly fed into the polarizer and the EO modulator over a standard single mode fibre. The SLED is also much cheaper than the earlier used fibre laser. However, investigation in this paper indicates that the SLED has lower signal to noise ratio compared with the fibre laser, resulting in lower PD measurement sensitivity using the optically based PD monitoring technique. Practical PD measurements on the 132 kV cable joint indicates that partial discharges of 30-50 pC can still be detected by the alternative system. For application to PD continuous on-line monitoring for underground HV cable systems, this sensitivity might be sufficient to prevent the occurrence of cable circuit breakdown.

ACKNOWLEDGEMENTS

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