Continuous Online Monitoring of Partial Discharges in High Voltage Cables

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Abstract: **This paper reviews data acquisition, transmission and processing methodologies for continuous online monitoring of partial discharges in power cable systems. A PD continuous online monitoring system for underground cable circuits using capacitive couplers, $LiNbO_3$ electro-optic modulators, laser, optical switch and optical fibers has been proposed. Data processing methods include pulse shape and spectrum analysis, time of flight analysis, phase-resolved two-dimensional histograms, three-dimensional φ-q-n patterns, trend analysis, wavelet-based denoising, alarm strategy and telecommunication function to enable remote control and data download.**

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 online applications due to its requirement on coupling capacitor etc. PD online measurements provide information about insulation faults under operational stress or defects introduced during transportation or installation. In particular continuous online 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. Any defects such as particles and voids have been removed. For this reason an on-line PD monitoring system for cables should predominantly cover the accessories, which are more prone to the installation procedure and operational stresses.

This paper provided a detailed review of PD data acquisition, transmission and processing methodologies. A continuous PD online monitoring system for cable joints of underground cable circuits, which was based on the optical sensing technique using electro-optic (EO) modulators as investigated by the authors [1], was proposed. This proposed monitoring system does not require any power supply at the site of the cable joints, as the EO modulators are passive.

PD SIGNAL 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]; screen interruptions [5]; directional couplers [6]; and foil electrodes on cable joints [7]; as well as acoustic emission (AE) technique [8]. The 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 a few pC of PD level, good signal to noise ratio, and calibratable with discharge quantity in pC. Acoustic emission technique has the advantage of being immune from electrical interference. However, the acoustic emission attenuation significantly reduces the measurement sensitivity and makes it impossible to calibrate. AE technique is more suitable for PD monitoring in power transformers, switchgears and GIS, due to the existence of excessive electrical noises at substations.

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 (maybe several kilometers) to the measuring equipment at the substation,. This could result in very significant signal attenuation and consequently decrease the measurement sensitivity. Electrical interference is easy to be coupled into the sensor lead and later captured by the measuring equipment and further decrease the detection sensitivity. Electrical noise is significant at substations and in some situations may totally bury the real PD signals.

A method to overcome transmission attenuation and electrical interference is to use 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 were 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, either optical transmitter or acquisition unit with digitizer and communication port requires power supply to operate, although they can work on battery power for a few hours. Though there have been experiences of after-laying PD tests for practical long cable circuits [2, 6, 7], so far there are few experiences of continuous PD monitoring for practical underground cable circuits especially where mains supply is not available.

A CONTINUOUS OPTICAL PD ONLINE MONITORING SYSTEM

A novel PD on-line monitoring technique using $LiNbO_3$ electro-optic (EO) modulator has been investigated by the authors [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 capacitive coupler has been demonstrated to be an effective PD on-line detection sensor [10, 11], it is used as the PD sensor in the EO modulator-based monitoring technique. The principle of this proposed 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 indicate that the PD level is between 10-20 pC.

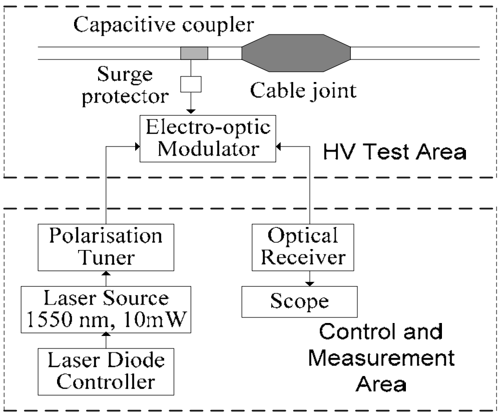

Figure 1 Principle of the EO-modulator based monitoring technique

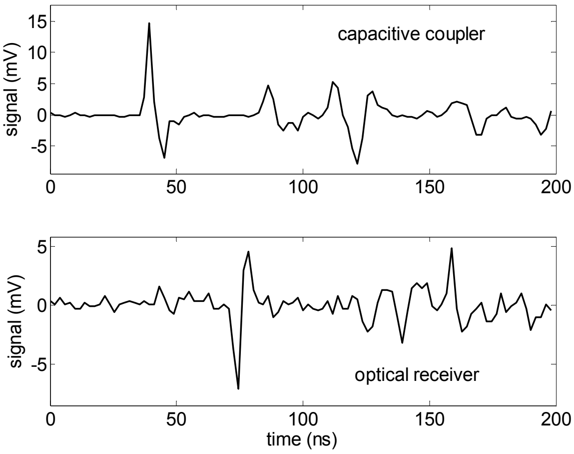

Figure 2 PD signals from the cable joint detected by the capacitive coupler and the optical receiver

Based on the investigated technique, a PD continuous online monitoring system for practical three-phase underground cable lines was proposed (Figure 3). To reduce cost, only one laser source, one polarization tuner and one optical receiver were used for the whole monitoring system. The optical switch acts as an optical multiplexer to enable the laser light via an optical fiber pass into one EO modulator. Although electrical noises at a substation are excessive, they are significantly attenuated while traveling along the long cable line. Thus the noise level at the site of cable joints is limited. Only one capacitive coupler is installed close to a cable joint, and any measured PD signal was considered to be from the cable joint. 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 power requirement. All other instruments are placed at the substation, where mains supply will be available. Potentially, new cables could be laid together with optical fibers and new joints could be designed to include optical network ready PD sensors.

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 is 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 optolinks will be available to allow remote control and data download.

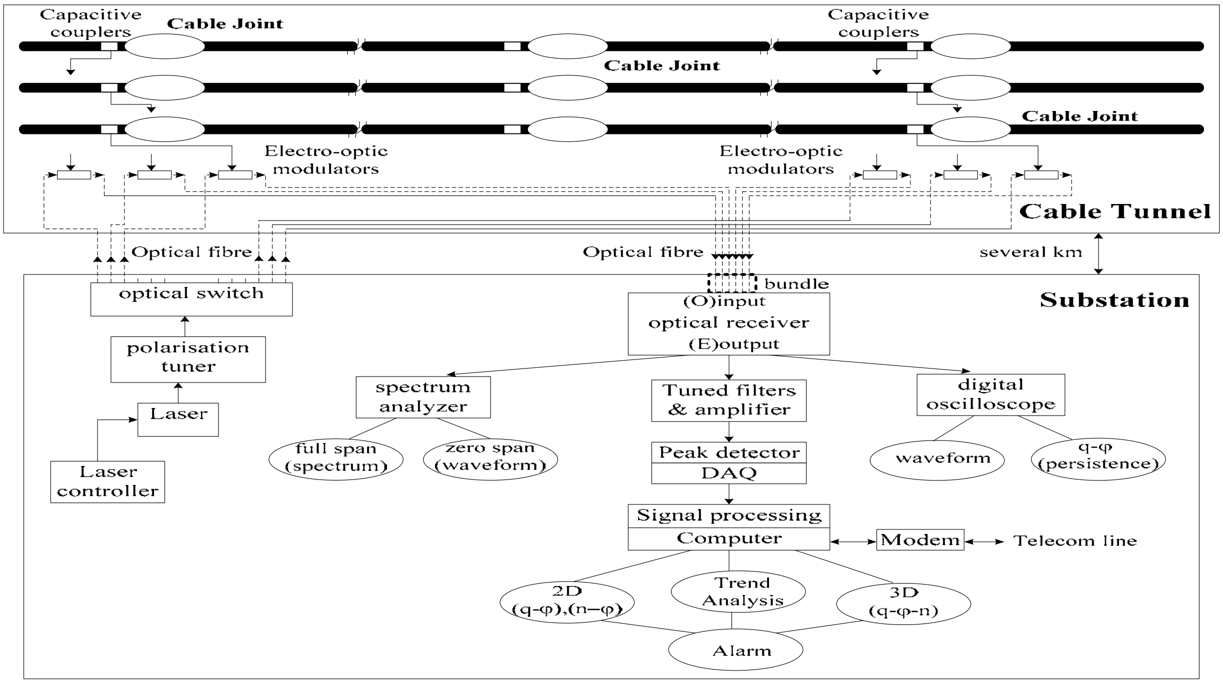

Figure 3 Continuous online PD optical monitoring system for underground cable circuits

DATA PROCESSING METHODOLOGIES

Spectrum, Waveform, Time Of Flight Analysis

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 by doing 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 [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 online 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-talk 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.

Phase-Resolved Two-Dimensional 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 equipments. The authors have also developed computer programs to display the pulse magnitude distribution q-φ, pulse count distribution n-φ, and three-dimensional φ-q-n patterns. Phase-resolved 2D pattern can also be obtained by modern digital oscilloscopes

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 [12]. The trending information as well as the phase-resolved patterns should be kept as discharge history for easy access.

Wavelet-Based De-noising

For on-site situations, the existence of excessive interferences will significantly influence the measurement sensitivity especially when PD measurements are carried out at the substation. For on-line monitoring of partial discharges 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 by the authors [10, 13]. Obtained results indicate that through appropriate selection of 'mother' wavelet 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 such as modems. 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, thus avoiding ambiguities introduced by insufficiently trained personnel.

CONCLUSION

This paper has reviewed data acquisition and transmission methodologies for on-line monitoring of partial discharges in power cable systems. The advantages and limitations of the present PD signal transmission via optical fiber were detailed. Based on the electrooptic modulator-based monitoring technique that was investigated earlier, 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. Data processing methodologies adopted for the monitoring system have been detailed. The measured signals can be fed into a spectrum analyzer, a digital oscilloscope or signal processing unit for further analysis. Data processing methods 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 technique, alarm strategy and telecommunication functions.

ACKNOWLEDGMENT

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