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On-line Partial Discharge (PD) Spot Testing and Monitoring of High Voltage Cable Sealing Ends

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SUMMARY

The authors present a paper detailing some recent on-line partial discharge (PD) testing and software data analysis work carried out to develop a suitable and robust method for on-line PD spot testing and monitoring of in-service, energised high voltage outdoor cable sealing ends. The work was carried out in follow-up to several failures of 132kV and 220kV HV cable sealing ends at electricity transmission utilities in Europe. One of the main challenges encountered when testing HV cable sealing ends is to differentiate between the highly dangerous internal PD activity within the sealing ends from the large number of external, high frequency impulsive interferences originating from other nearby items of plant. Sources of such interference include corona and discharges on the surfaces of ceramic insulators related to atmospheric pollution and weather. New techniques have been developed that involve synchronously capturing data from four sensors and comparing the signals in order to identify internal PD activity in the sealing end. The system can be used as a tool for commissioning new cable sealing ends and also assessing the insulation condition of aged ones.

KEYWORDS

On-line Partial Discharge Detection - HV XLPE Outdoor Cable Sealing End

1. INTRODUCTION

Partial discharge (PD) testing has been widely accepted as a means for assessing the insulation health of high voltage cable systems and can act as a tool for predictive maintenance and avoiding failure. The advent of on-line PD testing allows the entire installed cable system (cable, joints and terminations) to be assessed under normal working conditions on-site without any need to de-energise or to take out the cable out of service. Over the past 20 years XLPE insulation has become the insulation of choice for almost all new HV transmission class cable installations, and in such systems it is the cable joints and terminations that are most susceptible to PD activity and failure.

In cases where cables are terminated in outdoor environments, for example at air-insulated substations or cable to overhead line interfaces, a porcelain or composite cable sealing end termination is used. When PD testing these terminations, the measurement system is exposed to various sources of

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impulsive electromagnetic interference from discharges on other items of plant in the vicinity. This interference can also be coupled onto the cable and be detected at other measurement points, for example the other end of the cable or at a cross-bonding points [1]. As the source of interference is often on another circuit, de-energising the cable for off-line testing does not necessarily remove this interference [2]. In order to identify the source of any signals as originating on the cable sealing end, suitable test methods for discrimination of this interference must be employed.

2. PARTIAL DISCHARGE IN OUTDOOR HV CABLE SEALING ENDS

2.1 Types of Partial Discharge

Partial discharge can occur at various sites in cable sealing ends due to the different insulating materials that make up its structure and its installation environment. These different types of PD can be summarised as:

- PD in the bulk of the XLPE cable insulation
- PD in the stress relief components inside the cable sealing end
- PD at interface between XLPE cable insulation and stress relief component
- PD in the insulating oil inside the cable sealing end
- Corona at the high voltage conductor connections
- Surface discharges on the outside of the insulator surface due to pollution/atmosphere/weather

As corona and surface discharges are external to the sealing end, any failure from these phenomena (however unlikely) will probably be by external flashover. Optical and acoustic signals observable by eye (under low-light conditions) and ear are often dissipated from these discharges, although specialist test instruments are sometimes needed. Partial discharge internal to the sealing end poses a much more serious threat due to the consequences of a failure, in which the arc between high voltage and earth can cause the insulation to explode out of the equipment. For example, with HV porcelain sealing ends, this type of explosion can result in porcelain 'shrapnel' being thrown up to 100 metres from the site. It is thus very important to be able to distinguish between the different types of PD event.

2.2 Internal PD Propagation

The electrical impulse from a PD between conductor and earth in the cable sealing end will propagate down the cable away from the PD site; with the cable acting as a waveguide for this signal. When the pulse reaches the other end of the cable some of the pulse may be reflected back due to the impedance change. If direct and reflected pulses are detected with a sensor coupled to the sealing end, time domain reflectometry (TDR) methods can be used to locate the PD. It can be assumed that the signal originated at one of the cable ends if the time difference between the pulses is equal to the return time of the cable. However attenuation due to the frequency response of the cable and earth sheath cross-bonding means the reflected pulses may not be detectable on some circuits. This can be overcome by making simultaneous measurements with detection devices at both ends, or to have distributed detectors along the cable such as an oscilloscope and transponders [3] or with synchronised measurement instruments [4].

2.3 Noise and Impulsive Interference

There are several sources of noise that can hamper the ability to detect the PD pulses, these include RF interference and Gaussian white noise, with much research focussing on digital filtering techniques to remove these [e.g. 5]. Impulsive noise interference from discharges on other items of plant can be a more pertinent problem as the signals bear similar characteristics to real PD signals and thus cannot be easily discounted as interference using PD event recognition techniques. One such method to combat this is to combine pulse shape analysis and noise-gating [6].

The radiation of RF electromagnetic energy from PD sites has led to some solutions being developed that use antenna arrays to detect and locate the impulsive PD signals to their co-ordinates in the substation [7, 8]. This has clear advantages in that the source of all these signals becomes known from just a few measurement points. However for a PD site internal to the sealing end, the energies of the radiated electromagnetic signals can often be too low for accurate detection remotely and thus direct, local coupling of sensors remains the only option here.

The exposed HV conductors at the cable ends can act as antennae for interfering signals and thus impulsive interference can also travel down the cable from the termination at the other end. The stripping of the high frequency components from these transient signals as they propagate down the cable means that they can often resemble mono polar cable PD pulses by the time they arrive at the measurement point. It is often the case that the earth cables from three phases will be connected to a common point and thus PD cross-talk from the adjacent phases can be a problem. In addition, the cable earth strap can act as an antenna and thus PD signals radiating through air from other items of plant can be inadvertently detected.

3. ON-LINE PARTIAL DISCHARGE DETECTION AND LOCATION

3.1 Measurement System

Measurements are made using a wideband (0-400 MHz) four channel Digital Storage Oscilloscope (DSO) with the sampling rate set at 500 MS/s. Data traces of one 50/60 Hz power cycle in length (20/16.67 ms) are captured synchronously on all channels for post processing in software. This detection system has been used predominantly for short-term spot tests of around 5 to 30 minutes, although site-permitting, short-term monitoring can be carried out over longer periods. In this monitoring mode, days or even weeks of PD monitoring is possible.

3.2 Sensor Connections

Non-intrusive sensing techniques are used that allow connections to be made without de-energising the circuit. Whilst no connection is made directly to the HV components when installing sensors, the operator still must take care not to impinge safety distances (two examples of sensor attachments which did not contravene 2x utility’s safety requirements are shown in Figure 1). The approach taken focuses on the detection of the electromagnetic energies that are dispersed from the PD site. Two sensors are installed at the sealing end: a split-core, high frequency current transformer (HFCT) and a transient earth voltage (TEV) sensor. The HFCT is installed around the cable earth strap at the sealing end termination and detects the internal PD pulses that occur between the conductor and cable earth. The TEV sensor, which has conventionally been applied to PD testing of metal-clad MV switchgear, is used to detect any electromagnetic radiation from PD sites induced onto the earthed surface at the base of the sealing end. This local coupling of both an inductive (HFCT) and a capacitive (TEV) sensor to the sealing end allows for both a high sensitivity to PD measurement and also the opportunity to cross-correlate the PD signals (an internal PD signal will show on both sensors).

In addition to these local sensors, remote electromagnetic sensors, such as RF antennae are used to aid in the discrimination of interfering signals. The placement and number of antennae used is very much dependent on the location of the plant under test in relation to surrounding items of plant that are all potential sources of interfering signals. With the four channel detection hardware used in this work, it was found that two local sensors (HFCT and TEV) and two RF antennae were adequate for most cases in which interference arrives from several directions. An example of the sensor and antennae connections and positioning on a 275kV cable sealing end is shown in Figure 2.

Figure 1 Sensor attachment to 132kV (left) and 220kV (right) cable sealing ends (Note: safety clearances to the exposed high voltage conductors were not breached)

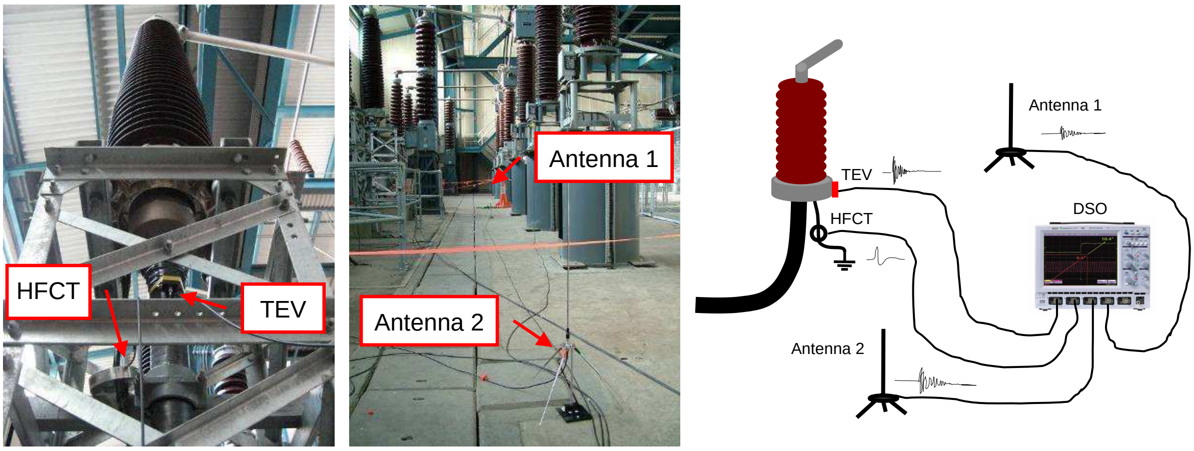

Figure 2 Sensor connections at 275kV sealing end

3.3 Discriminating PD from Interference

In order to eliminate interference and identify local PD activity in the sealing end, precedence detection is applied. This involves the synchronous capture of signals from two or more sensors; the arrival time of pulses is then calculated on each sensor and diagnosis performed based on this information. With this approach additional sensors such as RF antennae can be used to discriminate interfering electromagnetic signals that have originated on items of plant other than that under test and the direction of the source can be indicated without any specific locations being made.

3.4 Probability of Coincidence

Impulsive interference from other discharges can be discounted with the precedence methods presented, however what must also be taken into account is the probability of the interfering pulses coinciding, i.e. being received simultaneously with internal PD pulses from the sealing end under test. In the majority of cases the likelihood of this happening is relatively small, however it has been observed that the number of interfering events can increase dramatically when the outer insulator surfaces are wet or dirty, causing surface discharges. An example of this can be seen in Figure 3.a and Figure 3.b, which show measurements made on the same sealing end under wet and dry conditions. It has been observed that rises in cumulative energy of PD pulses with time may give an indication of coinciding events [9], but without knowing the exact shape of the original event without any coinciding pulses, it is likely that only evidence of coincidence could be achieved.

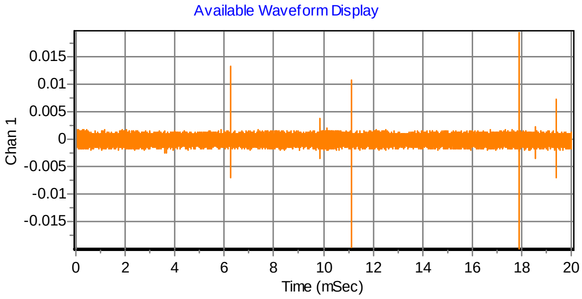

Figure 3.a TEV PD measurement dry conditions

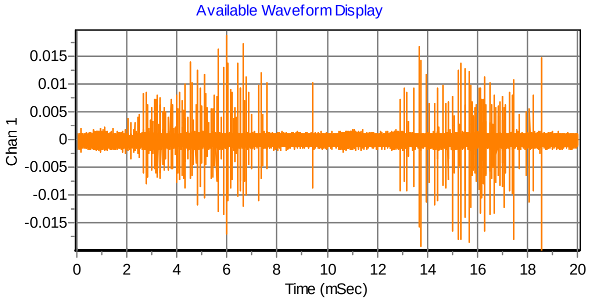

Figure 3.b TEV PD measurement wet conditions

3.5 PD Event Recognition, Location and Noise Discrimination

Due to the abundance of interfering signals, raw data is captured from all channels synchronously with the power cycle, as opposed to capturing individually triggered events. This ensures that any low level internal PD events will still be captured for recovery in the post-processing stage and this also allows phase relationships of the pulses to be observed. Event recognition is then carried out in software to find all the transient events that occur over the power cycle and analyse their characteristics against a set of PD knowledge rules using a similar method that has been widely applied for testing of MV plant [10]. The PD events which occur on more than one sensor are precedence detected to find which sensor they are most local to, by measuring the time at which the first edge of the signal rises above a set threshold. As a final stage the PD events are diagnosed as being local internal PD, external PD or other interference.

4. FIELD EXPERIENCE: MEASUREMENTS OF PARTIAL DISCHARGE AND IMPULSIVE INTERFERENCE

4.1 PD in HV Cable Sealing Ends

The measurement system described here has been applied extensively in the field, predominantly to carry out partial discharge spot tests. As an example of internal PD detected, Figure 4.a shows the activity across one power cycle for four sensors (3x TEVs & 1x HFCT) when testing a 132kV cable sealing end, the cable length being approximately 250m. Several impulses are clearly observable on the TEV sensors, whilst the majority of the activity on the HFCT is noise from the cable earth strap. Short impulses are however still observable on this sensor through event recognition.

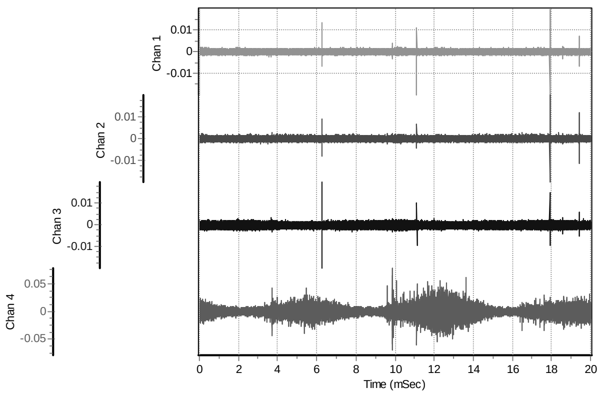

Figure 4.a Measured activity across power cycle
Ch 1: Local TEV, Ch 2: Remote TEV 3m from SE,
Ch 3: Remote TEV 6m from SE, Ch 4: HFCT

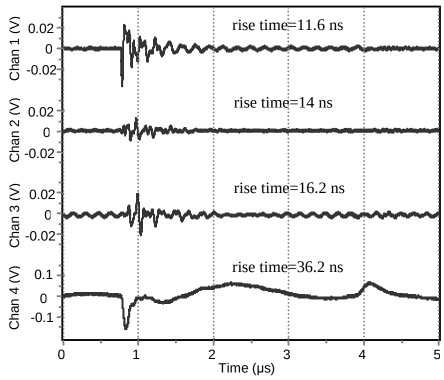

Figure 4.b Internal PD event
Ch 1: Local TEV, Ch 2: Remote TEV 3m from SE,
Ch 3: Remote TEV 6m from SE, Ch 4: HFCT

From all of the events detected, only one was deemed to be internal PD, as shown in Figure 4.b. It is clear from this that the local TEV sensor (Ch 1) detects the pulse in advance of the two remote sensors and also has the fastest rise time (11.6ns) with its highest peak on the first edge. A large mono-polar pulse is observable on the HFCT coincident with the local TEV pulse. A second pulse is also observable on the HFCT which is a reflection from the far end of the cable. Measuring the time difference between these pulses confirms this, and thus the source is confirmed as from inside the sealing end.

4.2 Interfering Signal Propagation Paths: HV Cable and Air

The multiple propagation paths of the electromagnetic energy from discharge signals can also be a frequent cause of disturbance to measurements and are a particular problem when the cable length is short. With the measurement set-up shown in Figure 5 PD activity was recorded at the cable sealing ends at the OHL tower.

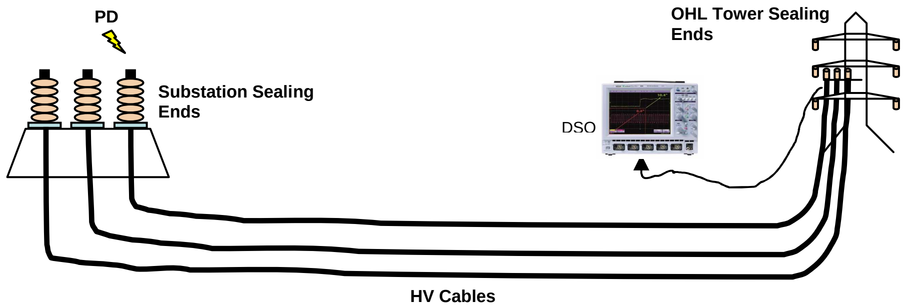

Figure 5 Measurement set-up at overhead line cable sealing ends

Figure 6.a shows one power cycle of activity, there are clearly many pulsed events happening synchronously on all channels. Figure 6.b shows one typical event in detail. The precedence analysis found the signal to arrive on an antenna first and thus the source is confirmed as interference from another item of plant. The HFCT (Ch 4) clearly shows two pulses; the first pulse has travelled through air and the second through the cable, with the time difference between the arrival of these being due to the difference in pulse travel speeds in air and along the XLPE cable, which are $3\times10^{8}\,ms^{-1}$ and $\approx 1.6\times10^{8}\,ms^{-1}$ respectively. This also explains why the signals on the TEV sensors appear to have two transient bursts.

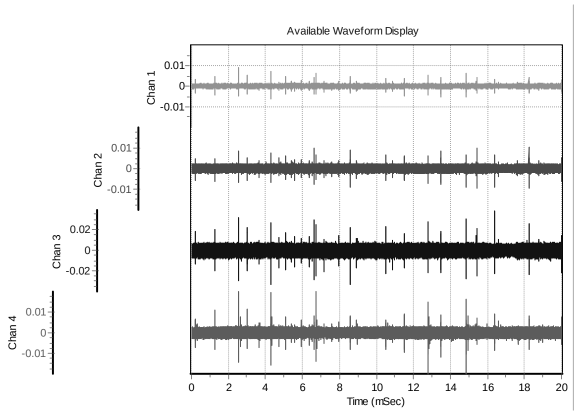

Figure 6.a Measured activity across power cycle Ch 1: Y phase TEV, Ch 2: B phase TEV, Ch 3: Antenna 13m from SE, Ch 4: HFCT

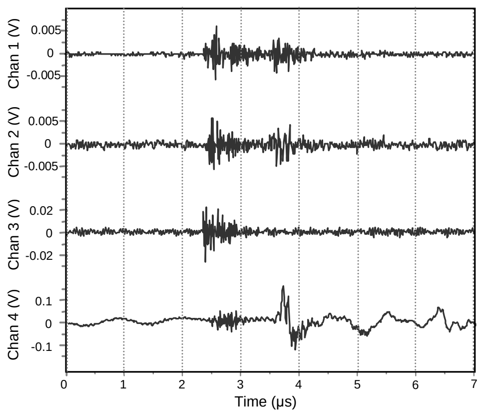

Figure 6.b Interfering PD pulse waveform Ch 1: Y phase TEV, Ch 2: B phase TEV, Ch 3: Antenna 13m from SE, Ch 4: HFCT

5. SPOT TEST VS MONITORING

Through spot tests carried out on the same sets of sealing ends over 3 months, PD levels have been found to vary quite dramatically, with circuits showing a high level of PD in one test and no PD in a subsequent test. This intermittent nature of the discharges highlights one limitation of short duration PD spot-testing as this may miss intermittent discharges. The interfering events are also intermittent as has been observed in short-term monitoring tests carried out by the authors. There are clear benefits to monitoring the sealing ends over extended periods to capture these trends and better understand the threat that PD is posing to the sealing end, see Figure 7.

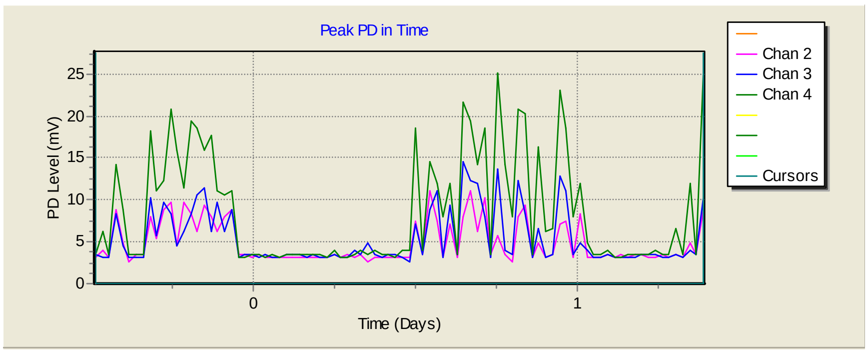

Figure 7 275kV XLPE cable sealing end PD activity over 48 hours. Ch2: Y TEV, Ch3: B TEV, Ch4: Antenna

6. PD LEVEL SEVERITY

When any PD is detected on-line it is crucial to diagnose the severity in order to establish the danger it is posing. With the non-conventional sensors used, IEC 60270 PD levels in picoCoulombs (pC) are not easily obtainable and no specific standard yet exists for making On-line PD measurements with these techniques. Other parameters that can be used are the amplitude of the first edge of the pulse, cumulative energy of discharge and number of pulses per cycle. With these, some estimation of the levels of severity can be calculated based on the magnitude and recurrence of PD activity.

7. CONCLUSIONS

Making measurements on outdoor transmission class cable terminations is made difficult from several points of view. Interference from electromagnetic sources and other PD sites in the switchyard make measurements difficult from the signal-to-noise perspective. Also the magnitude of significant PD activity which can be regarded as important is much smaller in transmission class cables than their distribution class equivalents. This paper shows that some of these problems have been addressed and the conclusions made from the research are:-

- PD event recognition gives very good immunity from noise.
- The use of precedence algorithms (especially developed for outdoor equipment) can provide good immunity from nearby and unwanted PD and electromagnetic interference.
- The PD activity can be determined for any individual sealing end/termination
- Weather and PD activity on the outside of the sealing ends clearly causes interference with any PD originating within the sealing end
- Currently, the sealing end PD activity cannot be easily distinguished from PD events originating within the transmission cable, or even at the far end of the cable if this is short. For longer cables, activity from the far end will be attenuated and the event recognition algorithms can make this distinction.
- Measurements have shown that the PD activity on some sealing ends can be variable and intermittent. Measurements over several hours or days are recommended to be able to make a full assessment of insulation condition.

The development of more specific algorithms to allow full recognition of all the PD activity types originating within sealing ends is under way by the authors, which will result in PD measurement systems which are even more robust than the current generation. There is also clear advantage in being able to automatically monitor PD activity on-line in all three phases with one test system. For this 3-phase measurement new hardware capabilities are required including multi-channel synchronous acquisition. For example, the number of channels would need to be increased to 10 in order to install one HFCT and TEV on each phase of a 3-phase system with four RF antennae to discriminate against external interference. As with the current 4-channel system, synchronous measurements (within 1-2 ns) on all channels at a high sampling resolution will need to be achieved. Such a system will allow for the automated differentiation of interference and PD signals between the phases which, depending on voltage level of the plant, could be spaced by as little as one metre apart.

The authors are presently developing a 10-channel synchronous PD monitor system which will meet the requirements listed above. It is hoped that this system will be fully automatic to enable test technicians of all levels to carry out the on-line PD testing, thereby doing away with the present requirement for testing to be carried out by highly trained and experienced PD measurement experts.

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