INTRODUCTION

The paper presents the application and recent experiences of on-line partial discharge (PD) measurements on electricity distribution networks. Such testing allows the insulation condition of cables and plant to be assessed without de-energisation and can be used as a tool both for substation safety and to ensure reliability of the network. Several aspects of such testing are discussed including signal detection, location, diagnosis, continuous monitoring and trending. The site suitability for attachment of non-intrusive sensors for decoupling of PD signals is described. The use of at-site spot test measurements to identify PD activity combined with wide scale PD monitoring of sections of the network is discussed. Such an approach allows for the most economical use of available technology.

PD IN MV NETWORKS

PD activity in cables and plant is an indication of a weak insulation system and of incipient faults. The focus of this paper is the on-line PD detection for cables and switchgear in medium voltage distribution networks. The ability to detect PD on-line with the equipment in service allows plant to be assessed in normal working conditions and is one of the few insulation diagnostic techniques that can be deployed without the need for outages.

PD testing is useful both to improve network reliability in a condition based maintenance program and for safety, by ensuring the plant is not at risk of failure when personnel are working nearby.

If carried out carefully, the introduction of diagnostics (such as on-line PD testing) into the maintenance and operation of medium voltage (MV) distribution networks can provide cost benefits through more cost-effective asset management. Through the collection and processing of diagnostic test data, it is possible for asset managers to better understand the condition of their assets using a condition-based ‘Criticality Index’ measurement. By understanding the ‘Criticality’ of a cable and thus the consequential risks of failure, it is possible to implement more efficient and targeted replacement, repair and investment programs.

In a modern electricity distribution business, condition-based asset management is one of the essential tools to enable the reliable, cost-effective life extension of existing plant and cables to be achieved. Timely location and the targeted, pinpointed replacement of specific cable sections and accessories of unsatisfactory circuits enables the effective service life of the whole network to be economically extended.

ON-LINE PD DETECTION AND MEASUREMENT

The new generation of condition-based, asset management tools is aimed at directing limited investment to those networks with the poorest performance, the highest operational costs and the largest potential gains in terms of customer satisfaction. Condition-based maintenance techniques are, in fact, the only real alternative to wholesale renewal of aged underground cable networks. With replacement rates of in-service cables in UK and other European utilities remaining at very low levels (typically less than 0.5% per annum in many cases) the need for an alternative asset management solution is very clear.

This paper presents the technology and methodology which has been developed and applied over the past 10 years to produce a condition-based asset management of MV networks by applying PD diagnostic testing and monitoring in a 4-phase approach shown below in Figure 1. This encompasses the use of simple handheld PD detection units, PD diagnostic and location devices and continuous PD monitoring devices. Some examples of the technology are shown in Figure 2.

Figure 1 4-Phase Approach for the On-line PD Test

Figure 2 Handheld, diagnostic and monitoring on-line PD devices
ON-LINE PD SENSORS
In order to detect PD activity on-line, non-intrusive sensors must be utilised. The on-line detection techniques generally focus on electromagnetic and acoustic energies that are radiated from PD sites. These signals can be decoupled using non-intrusive sensors attached in many cases to outer earthed surfaces of the equipment under test. By using a combination of sensors, sensitivity to different types of PD can be obtained and the measurements from different sensors correlated to aid in the diagnosis. The sensors used for on-line PD detection in this work are the high frequency current transformer (HFCT) for detection of the current impulses from PD in the cables and plant and switchgear and transient earth voltage sensors (TEV) for detection of electromagnetic radiation from local PDs in the plant nearby to the sensor attachment point.

HFCT Sensors
The main attachment points for the HFCT sensor for cable PD detection are onto the cable sheath or cable with sheath brought back through. A key requirement is the cable earth sheath has a single connection. Both positions are illustrated in the picture in Figure 3.

![Figure 3 HFCT sensors installed on 11kV paper-insulated cable. (A: HFCT on cable with earth brought back through; B: HFCT on earth)](image)

Unfortunately not all cable terminations are suitable for sensor installation, notably where the cable earth connections are made inside of the cable box. In some cases the termination may be modified; in the case of dry-type cable boxes, permanent HFCT sensors may also be installed inside of the cable box.

TEV Sensors
In order to test medium voltage, metal-clad solid-insulated switchgear (SIS) and air-insulated switchgear (AIS) for PD, TEV sensors are utilised. The occurrence of PD within the equipment induces a voltage on the inner surface of the earthed housing. The pulse will emerge on the outer surface through breaks in housing such as vets, joints or seams.

The TEV sensors are attached to the outside of the switchgear panel to capacitively couple these signals.

ON-LINE PD DIAGNOSIS AND LOCATION
After the initial detection of any PD signals of a moderate to high level, the next step is to locate the source. This can be locating to a point on the cable or to an item of plant. Due to different cable insulation types having different tolerances to PD and cable accessories having a higher tolerance to PD than the cable insulation, the PD location is of particular use for correct diagnosis. As all plant is interconnected in the on-line case PD signals can cross-couple between circuits and phases, it is important to be sure of the location of any PD site for accurate diagnosis. This section describes some of the measurement techniques utilised to achieve this using a wideband oscilloscope-based measurement instrument.

Location of PD in power cables
When a PD occurs within a power cable, pulses will travel outwards in both directions from the originating site. The first pulse to arrive at the measurement end is the pulse which has travelled directly to this end whilst the pulse which allows the PD site to be located is the pulse which set off in the opposite direction and has been reflected from the far end. In the ideal situation, with both the direct pulse and the reflected pulse being identifiable, the location of the site of the PD event is relatively easy to measure. The time difference between these two pulses (ΔT), then locates the site of the PD event. A PD location map showing several PD sites on a 20kV paper cable is shown in Figure 4.

![Figure 4 PD location map for 436m 20kV paper cable](image)

However in practice it is often too difficult to carry out the locations on-line using the single ended method as the reflected pulse is either too small or it is confused with other pulses which may be present due to noise interference. A simple method has been adopted to achieve this which uses a Transponder unit at the remote cable end to detect the PD and then launch a large pulse back onto the cable to compensate for the low level/undistinguishable reflected pulse. The test set-up is shown below in Figure 5. A typically observed waveform used to make the PD locations is shown in Figure 6, it should be noted that only the direct pulse and transponder pulse are used to locate the PD site. This system has been used successfully to locate PD sites on MV cables of up to 5 km in length.
Cable PD propagation across ring main units

When a cable circuit contains ring main units (RMU), in many cases the RMU does not represent a significant impedance change from the characteristic impedance of the cable thus cable PD signals can propagate through the RMU with little attenuation. This is good from the point of view that PD detection equipment does not necessarily need to be installed at all RMUs to test the cables; however, this leads to difficulties when determining on which feeder at the RMU is the source of a PD. Any PD testing at these sites must capture data synchronously on both feeders so that the time difference and pulse polarity of PD pulses can be analysed. A set-up in which HFCTs are installed with their windings in the same direction with respect to the flow of PD currents from either feeder is shown in Figure 7. In this case for a PD on either feeder both sensors will detect pulses with the same polarity. There will be a short time delay between the two sensors which is used to determine the source feeder. Pulses of opposite polarity observed by the HFCTs are indicative of an origin within the RMU, for example from the transformer.

Figure 8 shows one power cycle of data captured synchronously from HFCT sensors on either side of a 20 kV RMU. It can be observed that at first glance the signals have a similar amplitude and phase characteristics on both feeders. Precedence analysis that looks at the polarity and arrival time of each of the PD pulses detected can reveal the true source of most of this activity to be on the Channel 1 HFCT, the processed data is shown in Figure 9.

Location of PD on switchgear panels

The source of partial discharge activity can be located along a row of switchgear panels by using two or more TEV sensors and applying Time of Flight (TOF) analysis to the measured signals. A typical set-up is shown in Figure 10.
Figure 11 shows the results from the TOF measurement of a PD signal measured using four TEV sensors placed at different positions on an 11kV AIS panel. In this case the signal is emerging from a PD site close to the Channel 4 TEV sensor.

CONTINUOUS PD MONITORING
Continuous PD monitoring is carried out to trend PD activities over time, for example in the case of paper cables where load varying PD trends are often observed. Monitoring also allows detection of PD level rises or other changes in the PD activity trend that have been observed to occur immediately before failure [1] and detection of intermittent PD occurrences.

PD monitoring can be carried out with both temporary or permanent equipment. In many cases it can be more economical to utilise temporary monitoring in an integrated program [2].

Wide area network monitoring
To combat attenuation of PD signals as they propagate down power cables, it is often necessary to install distributed PD monitors at the primary substation and RMUs in order to effectively monitor the cables.

As a general rule of thumb distributed monitors should be installed on cables with lengths exceeding 1.5km for paper-insulated cables and 2.5km for polymeric-insulated cables. This combined, wide area network monitoring solution is illustrated in Figure 12.

PD monitoring devices are equipped with remote communications, generally using mobile telephone networks to allow all data to be uploaded to a central server. This also allows for data from multiple monitors to be collated with a web interface for viewing data from multiple devices.

PD MONITORING CASE STUDIES
11kV Cable network with distributed PD monitoring
A continuous PD monitor was installed at an 11kV RMU. As discussed in the previous section the RMU monitors have synchronous capture from HFCT sensors attached to the two cables to allow counting of pulses that arrive first on each sensor. After around eight days of monitoring there was a fault at another point on the network; following this the PD activity had a significant rise as shown in Figure 13. It can also be observed that the PD levels are very similar on both feeders.

Figure 14 shows the precedence PD counts for PD pulses that arrive first on each of the feeders. It is clear from this that most of the activity is arriving first on the feeder 2 cable, indicating that it is the source cable.
11kV Substation with intermittent PD in air-insulated switchgear

A PD monitor was installed at an 11kV primary substation to monitor two adjacent switchgear panels with suspicious local PD activity. TEV sensors were attached to the switchgear. The PD activity logged by these sensors over 29 weeks is shown in Figure 15. It can be observed that the PD is occurring intermittently in nature, Figure 16 shows detail of a three weeks burst in activity between weeks 10 and 12. This is an indication of surface discharge activity and also possible relation to humidity. Similar PD levels were observed on the two adjacent switchgear panels. The precedence graph showing PD counts that arrive first on the two TEV sensors is shown in Figure 17, this shows most of the activity to be coming from the feeder 2 sensor.

CONCLUSION

This paper has described the use of on-line PD detection for MV networks. With non-intrusive sensors detection can be made on cables and plant without need for de-energisation. The different aspects of detection, location and diagnosis and continuous monitoring of PD activity have been described. Essential to the diagnosis is the ability to determine which feeder or plant item is the source, in particular at RMU substations where PD signals can couple well between cables. A phased approach is key to the use of PD detection, diagnosis and monitoring technologies is for effective use of on-line PD technologies with often limited asset management resources; and to ensure test time is focussed on those items plant most at risk.

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REFERENCES
