

## DEPLOYMENT OF DISTRIBUTED ON-LINE PARTIAL DISCHARGE MONITORING DEVICES ON MEDIUM VOLTAGE ELECTRICITY NETWORKS

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### ABSTRACT

*This paper describes the development and deployment of new portable on-line partial discharge (PD) monitoring devices for the condition monitoring of medium voltage (MV) cables and switchgear. In order to provide a complete MV network monitoring solution, devices for monitoring of PD at both primary and secondary substations are necessary. The authors describe the technologies and methodologies which have been developed to enable complete network monitoring to be achieved in both small and large MV distribution networks. With such technologies in place it is possible for the PD activity on a particular item of plant to be measured over a short periods of time (days/weeks/months) with advanced diagnosis and PD location carried out as a follow up, if and when required. The distributed monitoring devices which are used at secondary substations can assist in testing longer circuits (>1.5km in length) which cannot be solely monitored at primary substations due to the effects of PD signal attenuation on the cables. Precedence-based data capture with multiple PD sensors has also been applied for use at secondary substations which is of particular use in determining which circuit the PD is on and which direction the PD activity is coming from.*

*Whilst to date the majority of PD monitoring has involved the use of permanent devices (which requires a large capital expenditure when put across an entire network), the portable PD monitoring technology allows for more flexible operation with units moved between different parts of the network to observe short-term trends in PD activity. In this way the technology can be focused on problem areas in a network, with significantly reduced investment required when compared to installing permanent systems.*

### INTRODUCTION

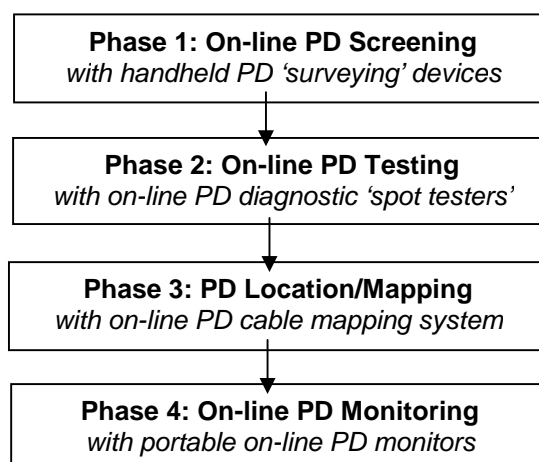
If carried out carefully, the introduction of diagnostics (such as on-line PD testing) into the maintenance and operation of medium voltage (MV) distribution networks (cables, switchgear and other plant) can provide cost benefits through more cost-effective asset management. Through the collection and 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.

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 to see!

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.



**Figure 1: 4-Phase Approach for the On-line PD Test and Monitoring of MV networks.**

## THE TECHNOLOGY DEVELOPED

The authors have built-up significant experience in the application of *on-line PD testing and cable PD mapping (location)* over a period of 10+ years. The application of the new on-line PD test technology began in the UK in 1998 when the first series of on-line PD tests were carried out by the authors on in-service, 11kV paper-insulated (PILC) cables in the London Power (now EDF Energy) Network.

The new on-line technique for insulation condition testing of in-service cables was made possible by the development of *inductive PD sensors*, clip-on High Frequency Current Transformers (HFCT). These are attached to the earth bar/strap of the cable termination under test, with no outage required. The initial work focused on the PD testing, PD mapping (PD site location) and PD monitoring of older (50-60 years old) in-service, underground paper-insulated cables (PILC). The business driver behind this decision was stated in the paper presented at the CIRED 2001 Conference by Cliff Walton of London Power Networks, as follows [1]:

*“Some 98% of the supply incidents that occur in London, arise from cable systems and terminations (rather than transformer and switchgear failures). Network performance statistics also indicate that incidents on the 11kV (& 6.6kV) MV systems affect the most customers.”*

*“LPN have recently commenced installing live line multi-functional monitoring equipment on 300 higher fault rate feeder circuits. Preliminary results of live line condition monitoring have shown very encouraging results in being able to detect and locate failure BEFORE it occurs.”*

Over the 8 year period since the above was reported LPN/EDF Energy have presented a number of papers at CIRED (in 2003, 2005, 2007 and now 2009) on the further development of this on-line PD monitoring technology and methodology. Today, EDF Energy have over 1,000 of their 11kV cable feeders being monitored using the latest web-enabled, remote-access PD monitors. The data from these monitoring systems is being used to support a condition-based asset management decisions by the company.

In recent years the authors have also worked in close collaboration with other UK utilities (Scottish Power Systems and Scottish & Southern) on the development of portable, remote-access PD monitoring technology. This new technology is in the form of *portable*, remote-access PD monitors which can be moved around large, utility distribution networks to carry out short-term monitoring of PD activity (typically for periods of 1 week). Through the use of portable PD monitors, moved around the network and positioned at both primary and secondary substations (for 1 week per sub), it is possible for *PD monitoring* to be achieved at a fraction of the cost of permanent systems.

## Multiplexed and Synchronous PD Detection

The main costs in modern PD monitoring systems lie in the high resolution analogue to digital converters, be it with an oscilloscope, PC based ADC card or custom electronics. To develop an economical monitoring system, multiplexers are utilised to allow multiple cable feeders to be tested with one device; for example all of the cables on a busbar at a primary substation. As a result of multiplexing the time between data captures is reduced, care must be taken to ensure this time does not become too great, with a 16 channel system developed each sensor can be sampled up to every 10-15 minutes.

At ring main units (RMU), whilst multiplexing is not necessary, what does become very important is the synchronous capture of PD signals. As the RMU does often not represent a significant impedance change from the characteristic impedance of the cable, the PD signals can propagate through the RMU with little attenuation. This is good from the point of view that PD monitoring equipment does not necessarily need to be installed at all RMUs; however, this leads to difficulties when determining on which feeder at the RMU is the source of the 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. HFCTs are installed with their windings in the same direction with respect to the flow of PD currents from either feeder (see Figure 2) thus 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.

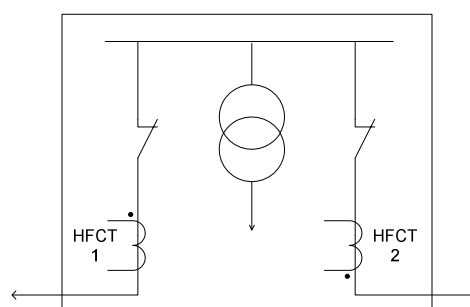
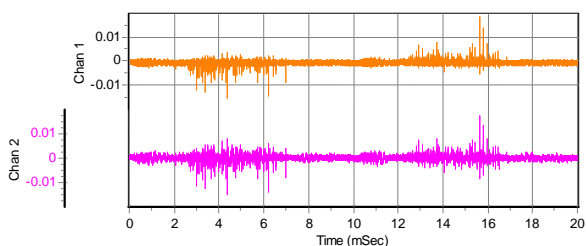
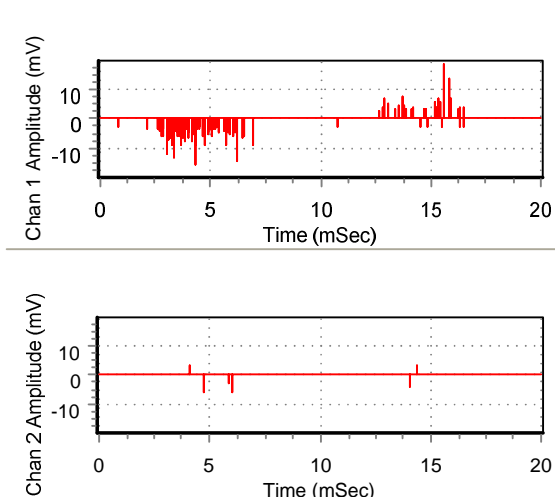


Figure 2: HFCT Installation at Ring Main Unit

Figure 3 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 4.

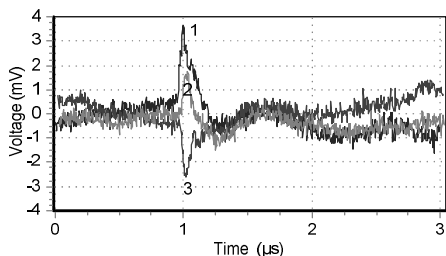


**Figure 3 Unprocessed power cycle of data captured by two HFCT sensors at a RMU**



**Figure 4 Data from Figure 3 processed with PD pulse precedence analysis showing pulses that arrived first on channel 1 (top) and channel 2 (bottom)**

Strong propagation of signals across an RMU is however not always the case and thus signals can be attenuated more rapidly than expected. Figure 5 shows one such example from an 11 kV RMU where the transformer cable was quite long (> 10m). As a result of this, its cable was seen as a second feeder at the RMU. it can be observed that the signal entering the RMU is split in two with half of the original signal propagating down transformer cable and half down the other feeder.

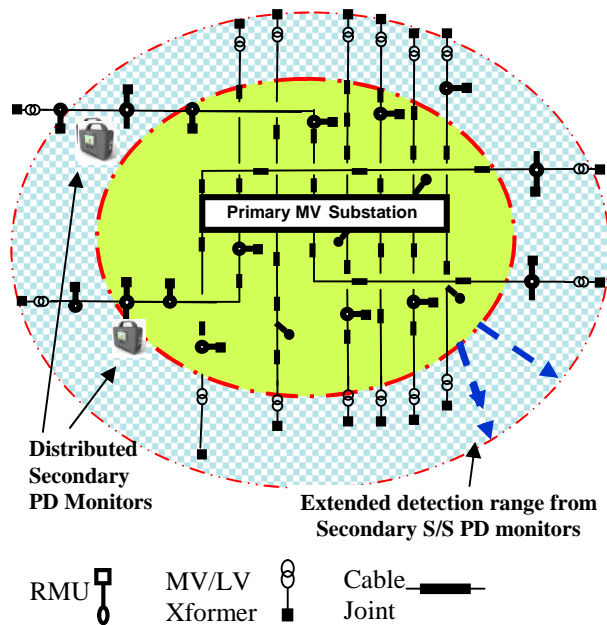
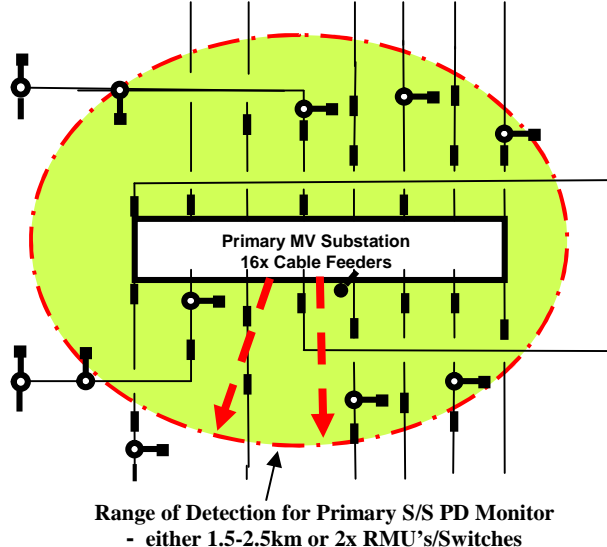


**Figure 5 PD Pulse from feeder 1 propagating down feeder 2 cable and transformer cable (3)**

**Primary and Secondary Substation Monitors**

The primary substation monitor allows for PD monitoring at primary substations and can ‘see’ down cables of lengths of up to 1.5km for paper-insulated cables and up to 2.5km for

polymeric-insulated cables. A further extension of PD monitoring into the network, beyond the ‘reach’ of any PD monitors installed at primary substations is achieved by using portable, secondary PD monitors situated at Ring Main Units and other secondary switchgear. This combined, wide-area network monitoring solution is illustrated below in Figure 6. With the combined use of PD monitors at both primary and secondary switchgear, cables of lengths of up to 5 km and four RMUs/switches can be monitored.



**Figure 6 Wide-Area MV Network Monitoring with portable PD monitors at both primary and secondary switchgear**

**Remote-access Communications**

Remote-access communications with distributed PD monitors is achieved using internet connections from either HSDPA (3G mobile phone) or GSM/GPRS modems. These

communications systems enable the remote PD monitoring of wide-area networks to be achieved without the need for landline telephone or LAN connections inside of the substation.

The increased speed of HSDPA makes this the preferred option for the primary substation PD monitors where large amounts of data is accessed and downloaded through an HTML interface. With mobile internet services over the HSDPA network becoming more common and affordable. For the secondary substation PD monitors, where a much lower amount of data is downloaded, GSM/GPRS modules are considered to be suitable and fit-for-purpose.

From the experience of the authors of using these communication technologies, it is known that the security of connection can be sporadic, often with network operators imposing time-outs on the connections. Special 'watchdog' software is thus required to maintain the internet connections to ensure the monitoring units remain accessible at all times.

## DIAGNOSTICS AND SYSTEM ECONOMICS

Timely location and targeted replacement of specific sections of unsatisfactory circuits enables the effective service life of the whole circuit to be economically extended. The next generation of condition-based, asset management tools will be focused on enabling increasingly limited capital expenditure investment to be directed at those networks with the poorest performance, highest operational costs or the largest potential gains in terms of customer satisfaction and customer minutes lost (CML).

Diagnostics for MV cable networks is a valuable tool to help improve the network performance. However, as with all such tools, they will cost something to gain these improvements, and the question arises "*Is it worth it?*".

Studies carried out to date by the authors have ranged from PD testing of large, public electricity utility networks through to small industrial customer networks. A large part of the asset management strategy for a cable network comes from the owner's cable replacement policy, which is normally linked to the failure rate. For example, the utility cable owner with severely failing assets due to an ageing population has a different problem to the factory owner with a large, new cable network, but no failures to date. Prediction of failure rates into the future can give an estimate of the likely future costs and it is recommended that all asset owners should do this. For large networks, the failure rates are not too difficult to predict in the short and medium term. All the costs can then be estimated, and a decision made about diagnostics, replacement and priorities.

For large utility MV networks, the largest savings are to be

made in *deferring and/or targeting capital replacement programmes* of the cable population. This is simply due to the capital cost of replacement being so large when compared to the other costs that by saving even a small amount of this cost tends to dominate the other costs. For example, in many utilities, the cost of an interruption is perceived as merely the cost of the repair, particularly when automatic re-configuration of the network is available.

Similar studies on *industrial customer networks* show that this is not the case as here the cost of an interruption can dominate the capital cost of cable replacement. Oil platforms, industrial processes, nuclear reactors, hospitals and other high profile or sensitive power supplies can have a very large cost of interruption (running into Millions of Euros). Such customers have less difficulty in justifying the cost of diagnostic measurements, or complete system monitoring. If the cost of an outage is greater than say €200k/day, such asset owners tend to be very focussed on the condition of their plant!

The costs of installing permanent PD monitoring technology to monitor 100% of large utility networks are presently prohibitive (although this may change in the future). For example, for a utility with 1,000 primary MV substations, and a typical cost per monitor of €30,000, the projected costs for 100% coverage are €30 Million!

The alternative of using portable PD monitors, moved between different substations for a week at a time requires significantly less capital investment. For example, assuming 80% monitoring utilisation (of 40 weeks per annum), 25x portable units would be required (at a capital price of €750k, or \$750 per substation). These portable monitors would require test technician resources, to install and de-commission the portable monitors on a weekly basis. With 25 units, 3x test technicians would be required at an estimated cost of €300k per annum. With analysis, databasing and reporting labour costs estimated at a further €150k a total cost operating cost of €450k per annum is estimated, or €450 per substation.

## CONCLUSIONS

It is clear from the simple analysis above that an alternative to the large-scale installation of permanent PD monitors for large-scale MV networks possible. The new portable PD technologies described in this paper, when incorporated into a structured, condition-based asset management plan such as the 4-phase plan described herein can offer an alternative.

## REFERENCES

[1] Cliff Walton, 2001, "Detecting and locating MV failure before it occurs", CIRED