MV CABLE DIAGNOSTICS

APPLYING ONLINE PD TESTING AND MONITORING

The cable fault rate in most UK electricity distribution companies, has been gradually increasing over the past decade and this trend is considered to be likely to accelerate as the average 'asset age' of the cable network continues to rise.

By Dr Lee Renforth, IPEC Engineering Ltd, UK; Dr Ross Mackinlay, High Voltage Solutions, UK; and Matthieu Michel, EDF Energy, UK

The increasing asset age of installed MV cables in the UK can be explained by observing the historical installation rate (see Figure 1 below) which shows the heaviest installation rate having occurred in the 1950's and 1960's. It can be noted that, based on the present cable replacement rate of MV cables by UK Utilities (which is very low), it would take an average of ***over 700 years to replace the entire network!***

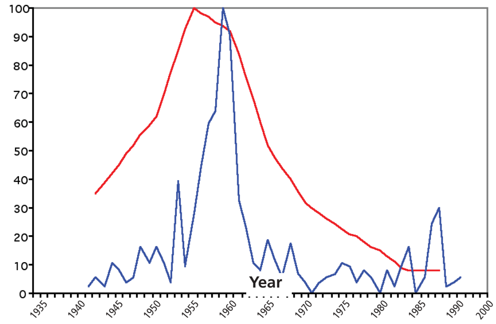

Figure 1: Typical UK MV Plant Install Rate (1940 to 2000)

The above point can be placed into some context by considering Table 1 which shows the typical 'Design Life' ascribed by UK Utilities for various types of MV transformers, switchgear and cables. Table 1 shows that these range from 40 years (Outdoor Switchgear) to 70 years (6.6/11kV underground cables). By comparing the historical MV Plant installation rates in Figure 1 with the Design Life Data in Table 1, it can be noted that a lot of installed MV plant in the UK is now approaching the end of its original life expectancy.

ASSET TYPE	'DESIGN LIFE' (YEARS)
Transformers	
Transformers (> 11kV)	50
11kV ground mounted	45
11kV pole mounted	45
Switchgear	
Indoor Switchgear	45
Outdoor Switchgear	40
Cables	
132kV cables	60
33kV cables	60
6.6/11kV cables	70

Table 1: UK Utility 'Design Life' of MV Plant

The other main 'business driver' in the development of the condition assessment technologies are the UK Regulatory Incentives which require all electricity utilities company to continuously improve network performance, to operate the network 'smarter' and to reduce operational costs.

These drivers underpin the need for a ***condition-based approach*** to the management of these ageing cable assets. In order to achieve an effective condition-based asset management policy it is proposed that MV cable condition is checked both regularly and in a systematic manner. This paper describes how this is being achieved in the EDF Energy MV Cable Network through a combination of three types of test equipment; 1. Online PD Cable Tester, 2. Online PD Mapping System and 3. On-Line PD Monitor.

RELIABLE ASSESSMENT OF THE CONDITION

EDF Energy's stated aim for on-line condition monitoring is to develop a comprehensive suite of tools that can provide a '*reliable assessment of the condition of the network*'. This data can then be used to direct the company's Asset Managers as to where best to target limited resources. As the financial and environmental cost of replacing all older cables is prohibitive, EDF Energy is seeking targeted maintenance and replacement strategies that can defer asset replacement and avoid unplanned outages. The on-line PD test technology presented in this paper has thus been developed with a specific view towards the ***Reliable Life-Extension of MV Cables*** up to and beyond their estimated 'Design Life'.

EDF Energy's longer term objectives from applying the PD Test Technology include:

- Reducing the overall level of risk on the power system.
- Targeting replacement/refurbishment programs by identifying and locating high risk sections of cables and/or reconfiguring networks.
- Developing systems and tools that can later be applied to other power systems assets

TESTING OF MV CABLE NETWORKS

At a simplistic level, cables with high PD activity can be classified as having a greater risk of failure than cables in which no PD activity can be detected. Once PD activity has been identified, the defects which are causing the PD need to then be located (on-line or off-line PD Mapping) and an action plan drawn up for what to do next (repair, replace, PD monitoring etc).

Partial Discharge testing is becoming increasingly viewed as the best diagnostic for cable insulation, particularly for on-line measurements. Clearly this applies primarily to insulation which both exhibits and is degraded by PD activity. However, even for insulation which is designed to be PD free (such as XLPE cable installations) the knowledge that the system is actually PD free by testing is still a vital part of the diagnostic process. Hence PD measurements which are accurate and reliable will always contain important information about the condition of the plant under test. On-line PD testing can also be used as part of the commissioning process for new cable installations to ensure cable accessories have been made-up correctly.

Partial discharges (PD) in voids and cavities will produce very similar pulse shapes with very fast pulse widths of a few tens or hundreds of picoseconds being typical. In the special case of PD in cables, the cavity responsible for the PD discharges into a real impedance (the 'surge impedance' of the cable) which is purely resistive at the point of launch. The resulting PD pulse is virtually monopolar with a fast pulse risetime and very short pulse width. This pulse travels outward from the originating site, and arrives at the detection point (at the switchgear termination) both wider and smaller due to attenuation and dispersion on its travel down the cable.

As the PD pulses travelling down the cable to the termination have an equal and opposite polarity on the conductor and screen respectively, it does not matter whether the HFCT's are placed in the earth strap, or the conductor.

The important criterion is that only one of the earth or conductor currents is intercepted (if they are both intercepted then they effectively 'cancel each other out'). A typical, monopolar cable PD pulse is shown below in Figure 2 which is shown with computer-generated cursors to measure the risetime, falltime and other pulse properties.

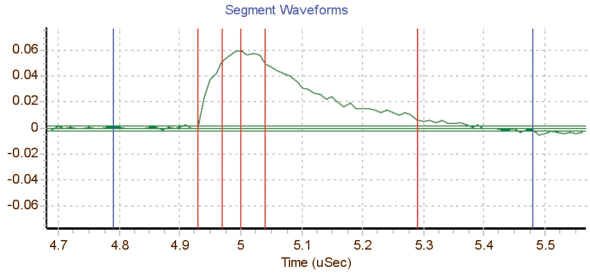

Figure 2: Pulse from a PD site in a cable

With the development of on-line PD methods, several technical problems need to be solved to yield the optimum diagnostic solution for insulation. These are…

- To remove noise interference from RF radio signals;
- To remove other types of noise interference without 'masking' the PD pulses amongst them;
- To identify and classify specific Types of Discharge (cable PD, switchgear PD, transformer PD etc);
- To locate the origin of PD pulses on cables (mapping) and other MV plant.

On-line PD detection in MV cables is achieved in practice by using split-core High Frequency Current Transformers (HFCT's) which are connected either to the earth strap of the cable or around each of the single cores of the cable. Figure 3 below shows the HFCT connection arrangements for a 33kV XLPE cable, where the HFCT's have been placed around each of the single cores, above the earth strap take off point.

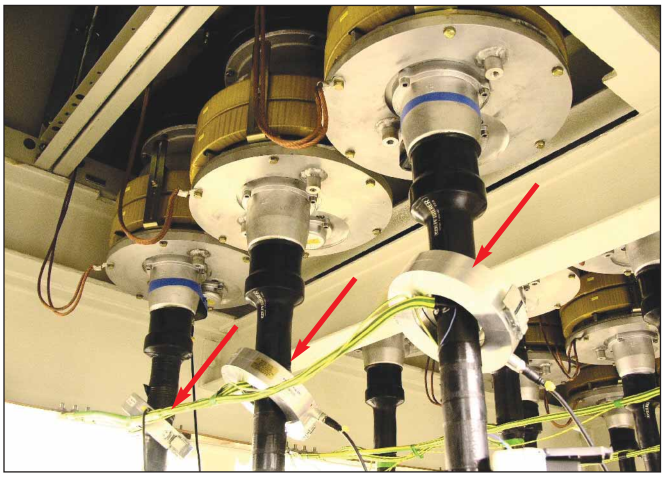

Figure 3: HFCT's around cores of 33kV XLPE cable

ON-LINE MEASUREMENT OF PD IN PICOCOULOMBS

The new on-line PD technologies described have been developed with new software and hardware solutions to solve the measurement problems listed in the previous section. The core of the technology is the 'Event Recogniser' software that applies knowledge-based algorithms that analyse the waveform shape of the PD (and noise) pulses. The software allows the user to automatically distinguish between noise and PD activity type such as cable PD, switchgear PD and transformer PD.

One of the biggest advantages of carrying out PD detection using the waveform analysis technique illustrated in Figure 2 is that the ***PD can be measured in picoCoulombs's (pC's)*** on-line (as long as the HFCT used is properly calibrated). This is a much more reliable method for measuring the severity of the PD activity than looking at the pulse magnitude (as in previous generations of on-line PD test equipment) as it is much less sensitive to the effect of signal attenuation along the cable from the PD source to the measurement point. This is achieved in practice by digitising the PD pulse and then integrating the area under the current curve using the following equation:

$$Charge = \int_{start\_of\_pulse}^{end\_of\_pulse} I*dt = \int_{start\_of\_pulse}^{end\_of\_pulse} const*V*dt$$

This means that it is now possible to carry out On-line PD testing of cables, without the need for an external calibrator, with the PD levels expressed in picoCoulombs (pC's).

LOCALISATION OF PD EVENTS ALONG MV CABLES

In the special case of testing cables, the usefulness of measuring PD activity is vastly increased if a localisation (mapping) of the PD site(s) can be made. Due to the nature of the geometry, the cable acts as a 'waveguide' for the PD pulse and when a PD event occurs, pulses will travel outwards in both directions from the originating site (at an average speed of 150-160m/μsec). The first pulse to arrive at the measurement end is the pulse which has travelled directly to this end (the 'Direct Pulse'), 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 (Figure 4).

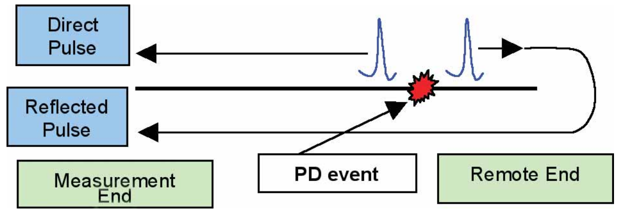

Figure 4: 'Single-Ended' PD location method

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.

It has been found in practice that it is often too difficult to carry out the locations using this simple single ended method, as the reflected pulse is either too small or it is confused with a lot of other pulses which may be present due to other reflections, noise, or some other 'distortion' of the waveform. Hence if the second pulse can be made to 'stand out' from the noise, then location is much easier to achieve.

A simple method has been adopted to achieve this which uses a new device called a 'Transponder' which consists of a PD detector and trigger unit which is linked to a 200V, 1 μSec pulse generator. This unit is used to detect the PD pulse at the far end of the cable (detected with a split-core HFCT sensor) and then launches a large pulse back onto the cable under test using a second HFCT sensor, as shown in Figure 5 below.

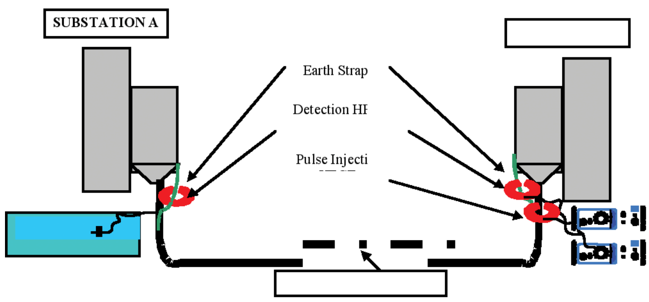

Figure 5: 'Double-Ended' PD Location with Transponder

The Portable Transponder system has been used successfully to locate PD sites on MV cables of up to 5 km in length. Figure 6 shows the results of carrying out the locations of PD sites on a 750m long cable with and without the help of the Transponder.

In this case the location of the PD event was very close to the measurement substation, and the very large, transponded pulse is clear to see in the top graph.

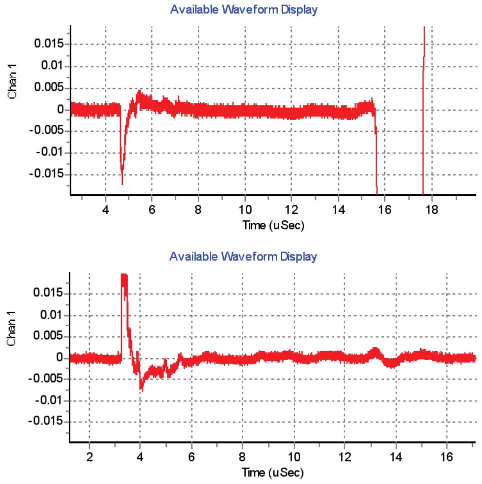

Figure 6: Location of PD pulses with Transponder (top graph) and without Transponder (bottom graph).

EXPERIENCES IN CARRYING OUT ON-LINE PD MAPPING

On-line PD Mapping is a relatively new technology, having been introduced into the industry only 4 years ago. From the field experience built-up over this period the following points are seen as being the key towards the successful application of the technology:

- The new technology is particularly effective when applied to 'Teed' or jointed cables with multi-reflections and also Cables with many Ring Main Units which can cause signal attenuation and (part) reflections of pulses.

- On-line Detection of PD pulses on the earth strap or cable core can be difficult if the cable termination is not provided with an insulated earthing gland.

- Field tests have proven that PD pulses propagate through the common busbar as they arrive at the substation. As a result of this pulses from a cable may be seen on the earth bar of adjacent MV panels. It is necessary in such cases to carry out a simple check to measure "which pulse comes first" to confirm the origin of the PD's. Figure 7 below shows that the cable with original PD has a higher magnitude and arrives before the pulses that propagated through the busbar to the adjacent panels (the pulses for the adjacent panels were negative but have been inverted to facilitate the comparison).

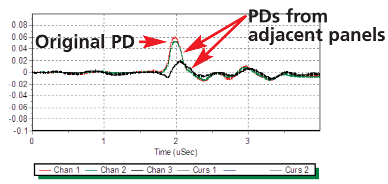

Figure 7: PD waveform captured on three adjacent panels.

- If there is more than one Partial Discharge event (defect) occurring on a circuit, then there will be a number of pulses of different shapes and magnitudes. The user must ensure that the 'detection threshold' is carefully set during testing so that all of the PD events are captured, whilst rejecting background noise.

- 24-hour On-line PD monitoring (see Figure 8 below) has shown that PD activity can in some cases follow the cable loading pattern. This cable feeder had an greater load during the night (due to a Newspaper printing works load) but little or no PD activity during the day.

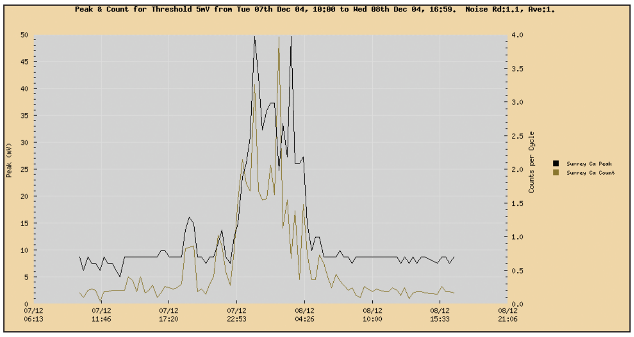

Figure 8: On-line PD Monitoring trend showing high PD activity during the night and low PD activity during the day.

CONTINUOUS ONLINE PD MONITORING OF MV FEEDERS

The process which is recommended for the detection and location of Partial Discharge (PD) on MV cables can be summarised as:

SITE SURVEY – MONITORING – MAPPING

This PD Diagnostic process involves a combination of the on-line PD Spot Test Equipment (for the Site Survey), continuous 24/7 on-line PD Monitoring, and culminates in on-line PD Mapping of those feeders which are showing either high or increasing levels of PD. This on-line PD Diagnosis process provides the utility's asset managers with a *real time* method for evaluating the network risks and provides quantifiable data to support an appropriate action plan.

EDF Energy are presently monitoring over 600 MV cable feeders with permanent, web-based on-line PD monitors.

Figure 10 below shows a PD trend before failure on one of these cables over a 10-day period before failure. PD activity is often observed to fall immediately prior to failure (fault to earth or phase-to-phase) as carbonised voids stop discharging and start to conduct at the very last point before failure.

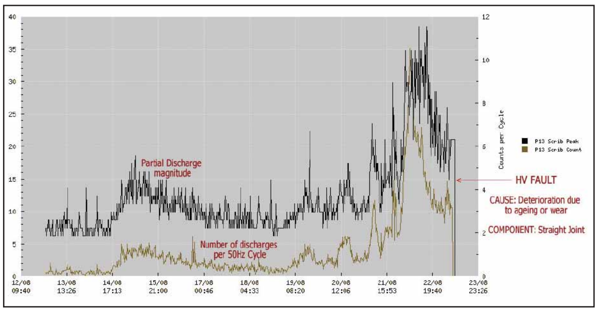

Figure 10: Partial Discharge trend immediately before failure.

The on-line, web-based PD Monitors used by EDF Energy are combined with the latest IT infrastructure to allow on-line PD data to be remotely downloaded and then automatically analysed and displayed on the web front end. Automatic analytical processes and 'knowledge rules' classify the 'criticality' of each circuit (depending on the PD magnitude and activity trend) to enable circuits requiring further investigation to be quickly identified (see Figure 11).

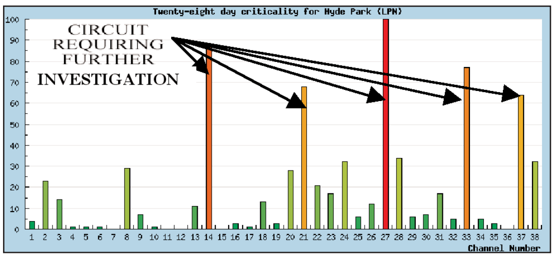

Figure 11: Cable 'Criticality' classification for a 38 Panel substation.

The data collected from the above automated PD Monitoring process is used to select those circuits with high 'criticality' for the on-line PD mapping process as a prelude to preventative maintenance, replacement or repair.

ON-LINE VS OFF-LINE PD MAPPING TECHNIQUES

Off-line cable mapping such as Very Low Frequency (VLF) testing and oscillating wave (OWTS) techniques were developed in the 1980's and many utilities around the world are currently using them as a diagnostic tool for their in-service cables. These technologies have a number of practical restrictions in their widespread application and uptake as a routine cable condition diagnosis system with the most notable being:

- High Costs in terms of capital expenditure and also high running costs of operating a cable test van.
- The application of off-line testing is in most cases limited to circuits with no Tee junctions.
- A considerable amount of bulky equipment is required and the cable section under test needs to be switched off and isolated.

It has been noted by the authors that the industry is now looking towards easier, faster and cheaper solutions for cable condition assessment that offers on-line PD testing, mapping and monitoring techniques which can achieve similar results to the established off-line test technology.

On-line PD mapping techniques such as the Transponder technology are becoming increasingly recognised by the industry as the way forward as they are more portable, easier to use and cheaper to implement than the off-line techniques.

Figure 12: Transponder and Off-line VLF testing equipment.

A number of EDF Energy's MV cable feeders were tested with both the On-line and Off-line PD Mapping technologies to compare the results obtained. Figures 13 and 14 show the location of the PD pulses detected on-line using the Transponder; and off-line, using VLF test equipment.

The off-line PD maps were plotted (the pulse locations are represented by crosses) and the on-line location was added on the same graph as well as the average magnitude of the pulses detected on-line.

- Circuit 1: Bulwer St Panel 2:
  Length = 1115 metres
  Discussion: The location found on-line is the same as that found off-line (main PD site at 220m) although the off-line result gives wider spread of PD's around the main site.

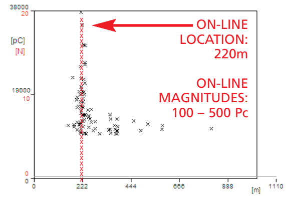

Figure 13: On-line vs. Off-line comparison N° 1.

- Circuit 2: Hyde Park A, Panel 10, Length= 890 metres
  The most active site is the same for on-line and off-line testing (main site at 65m). The off-line testing also shows less dense areas of PD's spread across the first half of the circuit.

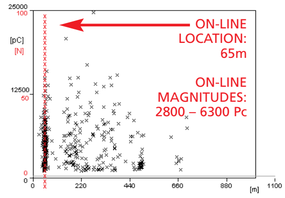

Figure 14: On-line vs. Off-line comparison N° 2.

CONCLUSIONS

Following the trials carried on the EDF Energy network, it has been concluded that the best strategy is to use a combination of the on-line and off-line PD Mapping techniques.

On-line, remote-access PD monitors can be strategically deployed at 'critical' or troublesome substations in order to observe the evolution of any pd activity. With automatic software analysis tools, the monitor can provide a 'criticality rating' of circuits at most risk of failure which can be used to target mapping (on-line or off-line, depending on the case).

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For further information, please contact Trevor Lord:
Australia Tel 1800 128 000 New Zealand +64 3 348 5999