ON-LINE PD TESTING – NOW A FIELD REALITY

Dr Lee Renforth & Malcolm Seltzer-Grant
IPEC Engineering Ltd - UK

Dr Ross Mackinlay
High Voltage Solutions Ltd - UK

Main Author Contact e-mail: lee@ipeceng.com

1. INTRODUCTION

This paper describes the application of a range of **On-line Partial Discharge (PD) Test Technologies** suitable for the On-Line PD testing, monitoring and screening of both medium voltage (MV) and high voltage (HV) plant. The technologies and techniques described have been developed through direct industrial application over an 8-year period, initially in the UK, and more recently (over the past 5 years) in an increasing number of countries around the World. This development has been made in conjunction with HV plant end users (utilities and private plant owners), test service providers and MV/HV plant manufacturers.

The new technology has been built around the development of the versatile PDGold© software which is used in conjunction with high-speed, digital storage oscilloscope (DSO) technology to produce the robust and portable OSM-Longshot© PD 'Spot' Tester for the On-line diagnostic PD testing of HV plant insulation. The applications to which the technology has been applied include:

- **MV Cable PD testing, monitoring and mapping (PD site location)**
- **MV Switchgear PD testing and location**
- **MV and HV VT & CT PD testing**
- **MV Rotating Machine PD testing**
- **HV Cable and Cable Sealing End PD testing and cable mapping (PD site location)**

This paper provides a review of these applications.

2. ON-LINE PD TESTING OF MV CABLES

The On-Line Partial Discharge (PD) testing of Medium Voltage cables (voltage range 6.6kV to 66kV) originated in the UK in the late 1990s through the use of split-core, High Frequency Current Transformer (HFCT) sensors which are attached around the earth strap (or the core) of the cable at the switchgear termination with the equipment 'live'. The sensors work through inductive coupling with the partial discharge current pulse being converted to a voltage pulse by the HFCT sensor.

The techniques employed in the new *On-line* PD test techniques have evolved from *Off-line* PD testing of cables (with a VLF or other external HV Power Supply) which was pioneered in the UK, Germany and Netherlands in the 1980s. The move across to on-line pd testing over the past few years has been led by customer requirements to avoid cable outages for their insulation condition testing (for the off-line test the cable needs to be isolated at both ends and the portable HV power supply applied).

The test set-up for the on-line pd testing is inherently safe as the HFCT sensor is normally connected around the earth strap of the cable at the switchgear after it has been 'brought-off' the cable, as illustrated in Figure 1 below.

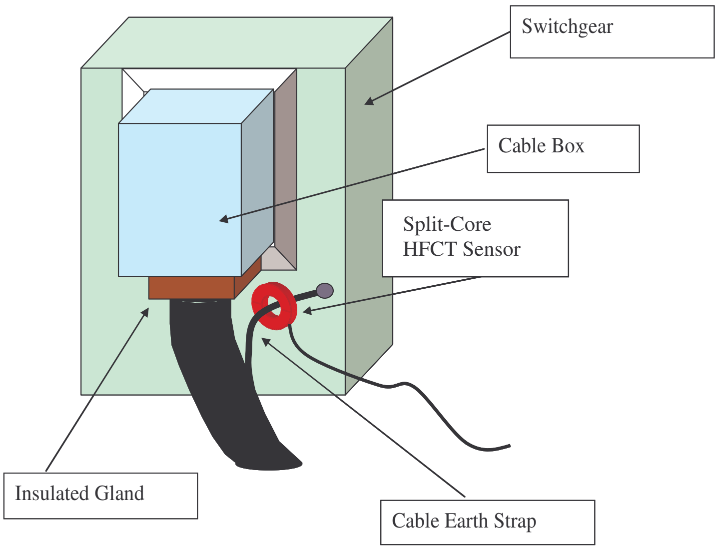

Figure 1: HFCT Sensor Connection on Cable Earth Strap for On-Line PD Testing

An alternative to the earth strap connection is to attach the HFCT sensor around the core of the cable, after the earth screen has been 'taken-off' as shown below in Figure 2.

Figure 2: HFCTs around cores of 33kV XLPE cable

3. PD PULSE RECOGNITION

Partial discharges (PD) in voids and cavities in insulation systems produce very fast pulses with widths of a few tens or hundreds of picoseconds at the source of the discharge 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.

Two PD pulses will travel down the cable to the termination, with one on the conductor and one on the earth screen. These pulses have an equal and opposite polarity and so it does not matter whether the HFCTs are placed on the earth strap, or around the conductor (insulated core). The important criterion is that *only one of* either the earth or conductor PD 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 3. This is shown with computer-generated cursors to measure the risetime, falltime, pulse width and other pulse properties. This analysis of the PD pulse properties is at the core of the new techniques for On-line PD testing as described in the next section.

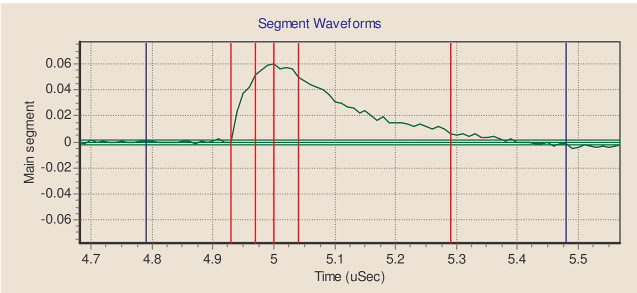

Figure 3: Pulse from a PD site in a cable

4. PDGOLD© 'EVENT RECOGNISER'

If the pulse properties can be measured (as shown in Figure 3) and there is some knowledge of what type of shape and frequency the different types of PD pulses generated from cables and switchgear will look like then it is possible to classify the pulses collected into types. This analysis of pulse shape and frequency is done automatically by the PDGold© Software using the 'Event Recogniser' module which to analyses and characterises the collected pulses into three types: Cable PD, Switchgear/Local Equipment PD and Noise. A screenshot of the PDGold© Event Recogniser page is shown below in Figure 4. This example shows a combination of cable PDs up to 2,500pC (bottom left) and noise pulses of up to 17mV (bottom right).

Figure 4: PDGold© Software Event Recogniser Page

5. PD MAPPING (LOCATION) OF PD IN 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 its 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 between 140-180m/µsec, depending on the cable insulation and geomtery). 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 5).

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.

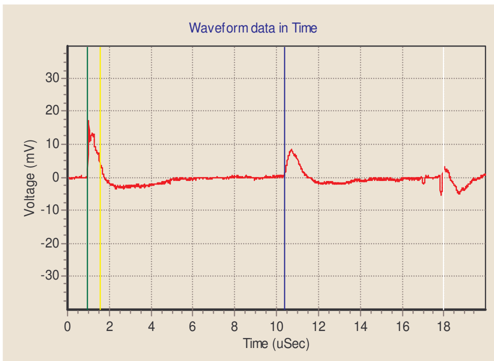

Figure 5: 'Single-Ended' PD location method

However, 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 other pulses which may be present due to noise interference. It is therefore necessary to make the second pulse 'stand out' from the noise in order to make the pd site location 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 100V, 1-10µSec 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. The test set-up and the effect of this method is shown below in Figure 6.

Figure 6 Locating PD pulses using Transponded waveforms

The Transponder method is used in conjunction with PDMap© Software to build up a 'map' of the PD events located along the cable. The Portable Transponder system has been used successfully to locate PD sites on MV cables of up to 5 km in length. Figure 7 below shows the results of carrying out the locations of PD sites on a 2.8km long, 33kV PILC/XLPE 'mixed' cable. This shows PD activity in the cable termination at the measurement end (0%) and at a joint 1270m out (45.5% of cable length).

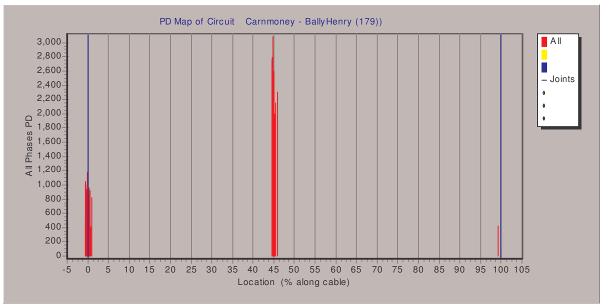

Figure 7: PD Map of 'mixed' 33kV PILC/XLPE Cable

6. MV SWITCHGEAR PD TESTING AND LOCATION

In order to test medium voltage, metal-clad solid-insulated switchgear (SIS) and air-insulated switchgear (AIS) for PD, Transient Earth Voltage (TEV) sensors are utilised. The PD events in switchgear have wavelengths that are similar in size to the physical size of the switchgear which means that the PD events will travel more like microwaves than lumped circuit electrical signals. 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 joints or seams as is illustrated below in Figure 8.

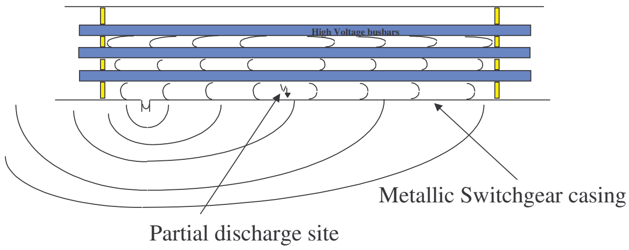

Figure 8: Transient earth voltage radiation of PD

The TEV sensors are magnetically latched onto the outside of the switchgear panel. In this way the TEV sensor works in effect as an external capacitive coupler that detects the PD pulses on the outer surface of the switchgear housing. Figure 9 below shows a TEV sensor connected to cable box of an 11kV solid-insulated switchgear panel (an HFCT sensor is also connected around the earth bar of the switchgear to measure cable PD).

Figure 9: Photo of TEV Sensor Attachment to Cable Box and HFCT connection to Cable Earth Bar

Switchgear PD pulses are characterised by very fast risetimes in the range of a few nanoseconds and a pulse widths of a few tens of nanoseconds. A typical switchgear PD pulse is shown below in Figure 10. It can be noted that this pulse is very different in shape to the PD pulse from a cable (shown previously in Figure 3). Switchgear PD pulses are typically of high frequency (5MHz to 100MHz) and oscillatory in shape due to the original pulse producing multiple reflections within the switchgear panel.

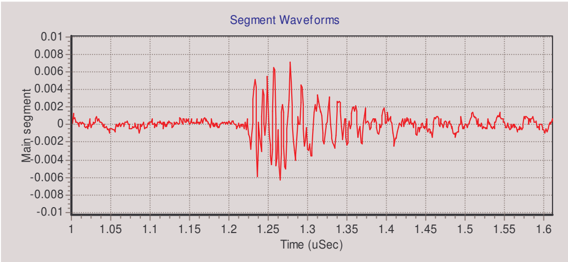

Figure 10: Switchgear PD pulse in 11kV metal clad AIS

As mentioned in Section 4 the PDGold© 'Event Recogniser' module utilises knowledge rules built up over a number of years of On-line and Off-line testing to distinguish switchgear PD pulses from cable PD and noise. A screenshot of the Switchgear PD Event recogniser is shown below in Figure 11.

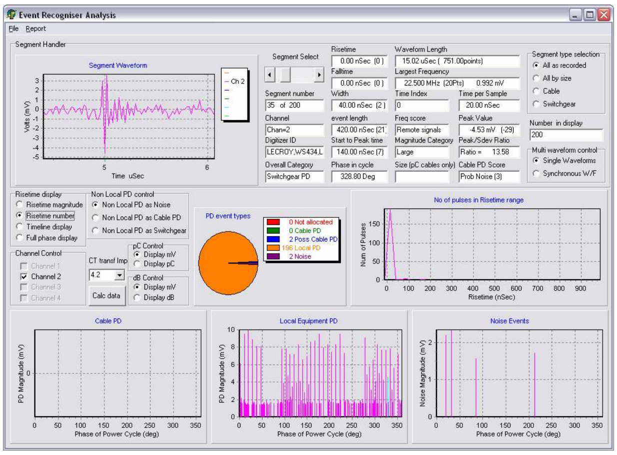

Figure 11 PDGold© Switchgear PD Event Recogniser Page

The source of partial discharge activity can be located along a row of switchgear panels and also within a switchgear panel itself by using two TEV sensors and applying Time of Flight (TOF) analysis. By placing TEV sensors at different points on the switchgear panel and measuring the time of arrival of the PD pulses on each of the sensors a good estimation of the PD origin can be made. Figure 12 shows the results from the TOF measurement of a PD signal measured using 2x TEV sensors placed at different positions on an 11kV AIS panel. The first signal is from a TEV sensor positioned at the busbar section at the top of panel whilst the second signal is from a TEV sensor positioned on the cable box of the panel. The first signal is around 3ns in advance of the second signal which equates to a physical distance of around 3 feet (the propagation speed of TEV signals in air is around 1 foot (30cm) per nanosecond). This confirms that the source of the discharge is within the busbar section of the switchgear.

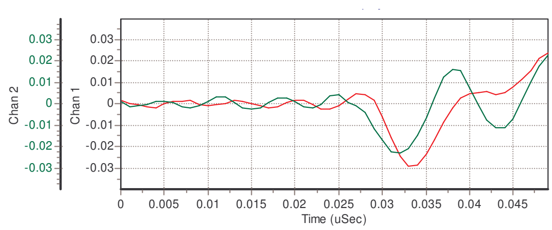

Figure 12: Time Of Flight Measurement for PD Site Location using 2x TEV sensors on an AIS panel

7. PD TESTING OF AIR INSULATED SWGR WITH AIRBORNE ULTRASONIC PROBES

For PDs in air insulation, an air pickup, acoustic/ultrasonic probe is the most sensitive way of measuring PD activity with sensitivities down to 1 to 2pC possible. There are a number of acoustic probes commercially available which can be used to detect surface discharges into air. The HVSL Ultrasonic PD Probe with Amplifier is shown below in Figure 13.

Figure 13: HVSL Ultrasonic PD Probe with Amplifier

For this sensor to work it is necessary that there must be a clear air path from the sensor to the discharge site ('line-of-sight'). This means that fully enclosed switchgear with no grills, vents air gaps etc, will not be suitable for measurements using ultrasonic probes. Also note that if the ultrasonic probe is used in conjunction with a TEV (or other type of electromagnetic PD sensor such as a HFCT), when looking at signals from the same source bear in mind that the ultrasonic signals take time to arrive at the detectors compared with the electromagnetic signals. Delays of a few milliseconds are common. Sound travels at around 330m/sec in air, so a distance of 1m would produce a delay of 3ms between the electromagnetic signal and the acoustic signal.

8. MV/HV CT AND VT PD TESTING

Another application of the OSM-Longshot© unit is the On-Line PD testing of MV and HV solid-insulation CTs and VTs. This testing is carried out using a combination of the HFCT and TEV sensors described previously. An example of this testing is given below for 25kV Resin Cast VTs.

Following catastrophic insulation failure of two in-service VTs on their locomotive trains the decision was made by the customer's engineers to carry out a fleet-wide survey of 106 in-service VTs for partial discharge activity. It was agreed that PD testing would provide a good indication of the insulation condition of the VTs and would identify any VTs that were likely fail in the near future to assist in prioritising the replacement of the existing, in-service VTs.

In this test the HFCT sensor was placed around the winding earth cable at the bottom of the VT to detect PD pulses flowing to earth. The TEV sensor was placed on the surface below the VT to detect PD pulses flowing out of the VT along any close by earthed metal surfaces such as the carriage housing.

The internal PDs in this equipment (see Figure 14) have similar characteristics to those observed in other solid-insulated equipment such as solid-insulated switchgear and cable sealing ends and so can be detected in similar ways.

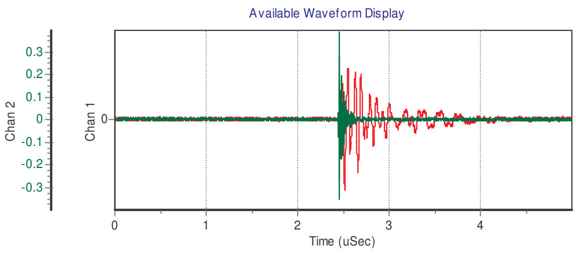

Figure 14: 25kV VT PD pulse detected by TEV sensor (green) and HFCT (red) on

Prior to carrying out this On-Line PD Survey some Off-Line PD testing was carried out on one of these 25kV VTs in the laboratory. In this testing a number of calibration pulses were injected into the test sample and calibration constants for both of the sensors were calculated which allowed the On-Line PD results to be given in picoCoulombs (pC's).

By using the On-line PD Test Method the customer was then able to prioritise which VTs had the highest level of PD activity and these were chosen for replacement first. Further to the measurement of high PD levels (of up to 20,000pC) which were detected in both the Off-line Laboratory PD testing and the On-line PD testing on the trains in a high percentage of the VTs the decision was made to replace the VTs on the entire fleet of trains. Due to supply and operational restrictions this had to be carried out over a 4-month period and the On-Line PD Test Data was used to prioritise this replacement program by targeting those VTs with the highest level of PD acitivity (highest criticality).

9. PD TESTING OF MV ROTATING MACHINES

On-line PD testing is now widely accepted in the industry as the best way to assess the condition of in-service MV motors and generators. To meet this market demand, the PDGold© software includes a dedicated 'Machines Software Module' which has been specifically designed for the PD Testing of MV motors and generators. The technology provides the user with the ability to carry out PD testing of HV machine insulation without the need for an outage.

Whilst the testing of rotating MV machines for PD activity is quite similar in many ways to the PD testing of other items of high voltage plant. There are several notable differences however, which need to be taken into account by the user. The special circumstances are as follows:-

1. Usually the HV machine is tested On-Line as outages are rare in many industrial applications.
2. A Calibration is normally needed to get accurate results of the PD levels in pC (picoCoulombs).
3. The conductors are normally carrying large load currents which has an impact on the sensors used (specially-designed, high current HFCTs are required as standard Ferrite HFCTs saturate at around 300A).
4. The PD information for each winding is important to measure if this can be done i.e. if the sensors can be attached to each phase of the motor/cable.
5. It is now becoming increasingly popular for the owners of Large Generators and Motors to fit High Voltage Capacitive Couplers or Air-Cored Rogowski coils permanently to their machines (normally inside the cable box) to enable on-line PD testing.

Figure 15 below shows an example of the HFCT sensor connections around the outgoing cables in the cable box on each phase of a 6.6kV Generator on a Cruise Ship (the sensors were attached during an outage in this case).

Figure 15: HFCT Connections on 6.6kV Generator

There are two types of PD activity in a stator windings:

- **PD activity in the Slot Sections.** These are Phase-to-

Earth discharges, which can 'eat away' at the insulation in the slot over time.

- **PD activity in the End Winding.** These are Phase-to-Phase discharges which normally occur near to the end of the slot section of the windings.

The PDGold© Machines Module automatically detects whether the PD is **Slot-Type** or **End Winding-Type**. The magnitude of these two categories of pulses are measured in pC's for each phase and presented on the user interface screen shown below. Depending on the results of these calculations, **the PD activity is rated in six scales** spanning the various insulation condition categories. Table 1 below shows the **Guideline PD Level vs Condition** for MV Machines in the voltage range 3.3kV to 13.8kV.

Assessment	Colour Code	PD in Slot Section	PD in End Windings
New/Excellent		<2000pC	<2000pC
Good		2000 – 4000pC	2000 – 4000pC
Average		4000 – 10000pC	4000 – 10000pC
Still Acceptable		10000 – 15000pC	10000 – 15000pC
Probable Inspection		15000 – 20000pC	15000 – 30000pC
Problem/Unreliability		>20000pC	30000pC

Table 1: Guideline PD Levels vs Condition for MV Machines

9. PD TESTING HV CABLES AND CABLE SEALING ENDS/POTHEADS

The consequences of the breakdown of the internal insulation system in a HV cable sealing end are normally catastrophic. Forensic assessments of such failures have shown that internal insulation failure normally causes an explosion of the ceramic or polymeric pothead with debris flying up to 100m from the sealing end. Failures in cable sealing ends can come at any time during their service life although it has been noted that many failures occur within a few weeks of installation due to installation errors.

The On-Line Partial Discharge (PD) testing of high voltage (110kV and above) cables, cable accessories and cable sealing ends is a relatively new application and has been developed by IPEC/HVSL through the application of the OSM-Longshot© PD Test Technology over the past 4 years. Whilst the techniques employed are similar to those developed for MV cables and their accessories there are a number of important differences between the testing of HV cables and MV cables, as described below.

When testing HV cables and cable sealing ends for PD On-line with HFCT and TEV sensors it is normal to suffer a large amount of external Radio Frequency (RF) noise interference. These noise levels are particularly high when the PD measurements are made in outdoor switching yards where the pylons and overhead HV connections act as antennae for radio signals in the air. In these instances any PD activity tends to be mixed together with a lot of noise pulses and thus when making a traditional 'peak and count' measurement , the noise will be counted as PD and a false reading can lead to erroneous conclusions.

Thus, the research and development in PD measurements for HV cables over the past few years have been mostly geared towards separating noise from real PD activity. This work has focussed on combining the PDGold© Software's 'Event Recogniser' and 'RF Noise Reduction' Modules. The software is used in conjunction with the OSM-Longshot© PD Test unit to enable the On-line PD Testing of HV cables by reducing RF noise interference and automatically sorting the pulses received into the three categories of Cable PD (from along the length of the cable), Local PD (in the sealing end) and Noise. A schematic of the sensor connections for HV cable and sealing end PD testing is shown below in Figure 16.

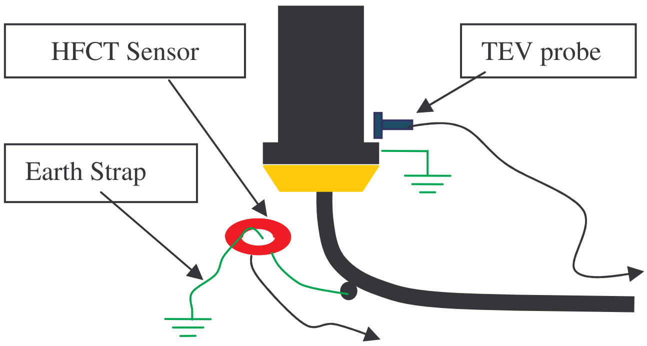

Figure 16: Sensor Connection for HV Cable Testing

Whilst the HFCT connection around the earth strap of the cable is inherently safe and can be employed in almost all installations of HV cables, the TEV connection at the base of the sealing end will be depend on the cable owners safety rules. If the sealing ends are connected directly to the support tower without post insulators then access to connect the TEV sensors is possible without infringing the safety rules. If post insulators are included in the sealing end then access to connect the TEV sensors should be checked with the plant owner's safety rules. In most HV switchyards the bottom of sealing ends are at a level where it is possible to install the sensors using a low-level ladder as shown overleaf in Figure 17.

Personal Protective Equipment should be worn when working nearby to the sealing ends and the time taken to install sensors should be kept to a minimum to mitigate against any exposure to risk of explosion of the sealing end/pothead as shown in Figure 17.

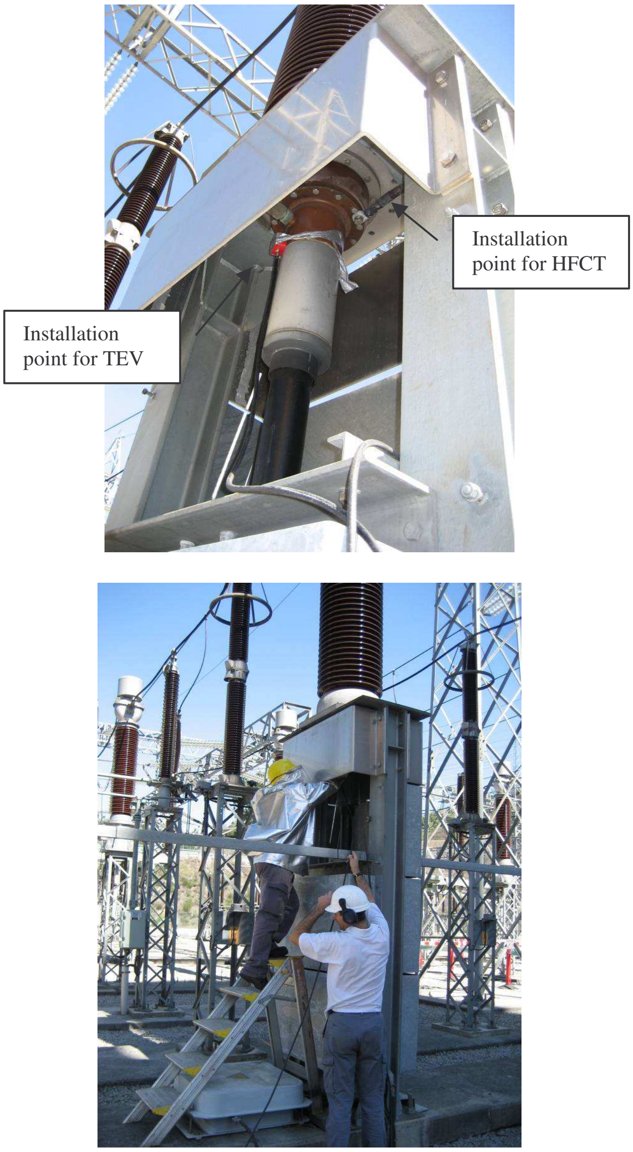

Figure 17: TEV & HFCT Sensor connection and attachment at base of 220kV cable sealing end

IPEC/HVSL are often asked the same question time and again by our MV and HV cable owner customers:

"What is safe level for PD activity in my cables?"

The answer to this can only be, "there is ***no safe level*** for internal discharges in cable systems". All internal discharges will be damaging, and will result in slow damage to the insulating medium, which in turn will lead to failure. Perhaps the only exception to this rule is for outdoor HV insulation, where porcelain sealing ends do not degrade in general under surface PD activity (they can however flash over due to tracking over accumulated dirt, which is why they tend to be replaced by silicone materials in high pollution areas).

Hence in the case of HV XLPE cables, terminations, joints and connectors it would be expected that they should be discharge-free in service. The levels of PD activity in the case where the terminations/sealing ends are not correctly constructed, are difficult to assess, as such occasions are uncommon. However, in general, at transmission voltages, internal PD activity, even at very low levels of a few tens of picoCoulombs, will probably be fatal in service with the only question being the time to failure. Hence it is essential to ensure that these installations are tested to be PD free on commissioning.

Historically, PD tests have been found to be difficult to achieve on site, mainly due to the low levels of PD which would be significant and also due to extraneous interference and noise. As XLPE single core cables are all PD tested in the factory before dispatch they themselves are very unlikely to be the source of any PD activity. With XLPE systems, the difficult components to ensure PD free operation are most commonly the joints and terminations/sealing ends which are made up on site. These accessories are thus the focus for the On-line PD Testing of HV cable systems as described herein.

10. FIRST LINE PD SURVEYING OF MV SWITCHGEAR AND CABLES

Over the past few years IPEC/HVSL have received a number of requests from our customers for a simple, handheld and easy-to-use partial discharge detector for MV plant. These requests have been to provide a test unit with the following features and functions:

- It should be able to be used as a *first-line* PD checker for MV plant, providing the user with the ability to test the condition of the MV plant in seconds.
- It should also double-up as a safety and security device to enable the user to check that their 'working area' in the substation is safe.
- It should be simple to use, sufficiently so that it can be used as a risk assessment tool for *all* operational staff in the substation.

In response to these requests IPEC/HVSL have recently developed the PDSurveyor© Handheld PD Tester (see Fig 18 overleaf). This new unit incorporates *three* individual partial discharge sensors and corresponding measurement circuits which are designed to pick up different types of PD activity in different types of indoor MV plant, as follows:

AA - Acoustic Circuit – Acoustic PD signals are generated by partial discharges into air and are detected using the unit's 40kHz airborne acoustic sensor ('line-of-sight' to pd site required). This sensor is very useful when testing Air Insulated Switchgear as described in section 6.
CT - Cable PD Circuit – Cable PD is measured using an external, split-core, **High Frequency Current**

Transformer (HFCT) sensor which is clipped around the earth strap of the cable. These pulses are generally in the frequency range of between 200kHz – 4MHz and are typically monopolar in shape. The unit measures the Cable PD pulses in picoCoulombs (pC's) by measuring the charge content (area under the monopolar pulse).

TEV Circuit – Transient Earth Voltage (TEV) PD signals are generated by internal partial discharges in switchgear, cable terminations, motors and transformers. TEV signals are in a higher frequency range of between 4MHz – 100MHz and are oscillatory in general. The unit has a built-in TEV sensor which is placed against the equipment under test to measure these signals. The resultant PD signals are measured in dB (decibels), as is the convention for on-line switchgear testing.

Figure 18: The PDSurveyor© Handheld PD Tester

The unit has an easy to read, 7-level, colour-coded PD level indication panel (displayed as a range of LEDs from green to red') which provides an indication as to the PD level of the plant under test. The LED Indication vs PD Signal Level is shown opposite in Figure 19.

The idea behind this system is that it can be used as an initial screening tool for MV Switchgear and Cables and allows for very quick identification of potential insulation defects. In this way large numbers of MV plant items can be scanned for PD activity very quickly to provide the user with a 'look-see' scan of the equipment in the substation. This can save much time when carrying out PD Surveys with a 'typical' indoor substation (with 10x switchgear panels and feeders) being possible to be measured in 10-20 minutes (10 mins if switchgear only, 20mins if switchgear plus cables).

If the unit shows up high PD activity (orange or red LED levels) then the plant under test should be investigated further using a full Diagnostic PD Test System, such as the OSM-Longshot unit described earlier in this paper, or via conventional Off-line PD Test methods.

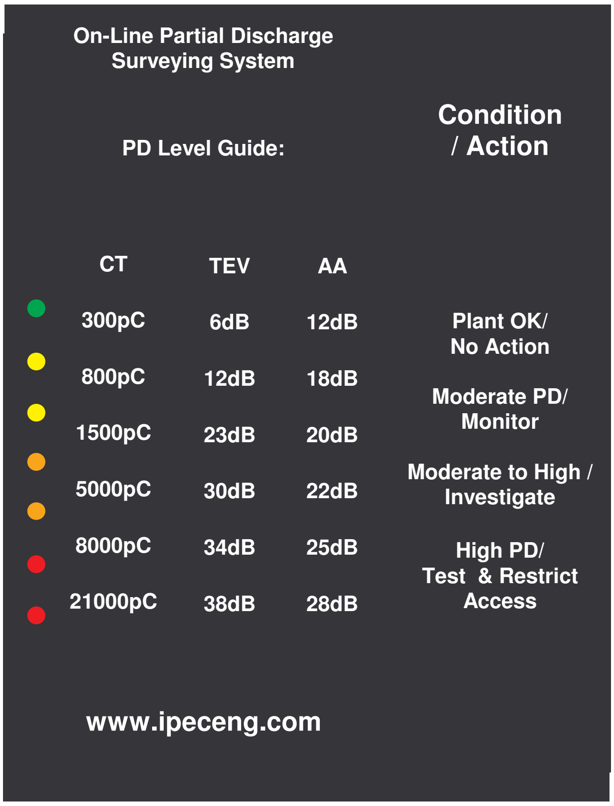

Figure 19: PDSurveyor© Guide: LED Indication vs Signal Level with Condition/Action

11. CONCLUSIONS

This Review Paper is intended to provide the reader with an introduction to the relatively new techniques of On-Line Partial Discharge Testing of MV and HV plant. This application is now well established for testing a wide range of indoor, MV plant in the voltage range of 6.6kV to 66kV with much of this testing now having been fully automated.

Ongoing research and development in the field of On-line PD measurements for HV plant (110kV+) is being geared towards the twin goals of noise reduction and then separating noise from real PD activity. As this development work remains ongoing, the On-line PD Testing of HV plant remains the preserve of only a few measurement experts around the world. It is however only a matter of time before these HV test techniques are perfected.

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