ON-LINE PARTIAL DISCHARGE (OLPD) INSULATION CONDITION MONITORING OF COMPLETE HIGH VOLTAGE (HV) NETWORKS IN THE OIL & GAS INDUSTRY

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Abstract – The authors describe a new approach to on-line partial discharge (OLPD) insulation condition monitoring (CM) of complete high voltage (HV) networks (voltage range: 3.3 kV to 132 kV) in the oil & gas industry. The technique described is suitable for the condition monitoring of HV generators, switchgear, cables, motors and transformers. Comprehensive HV network OLPD condition monitoring coverage is achieved through the use of wideband, OLPD sensors and continuous monitors located at the central switchboards of the facility.

The complete HV network condition monitoring system described in this paper is an extension of a CM system originally developed by the authors for remote OLPD monitoring of the stator winding condition of Ex/ATEX HV motors operating in hazardous gas zones. This technique utilises wideband, high frequency current transformer (HFCT) OLPD sensors located at the central HV switchboards to detect partial discharge (PD) signals that originate in remotely-connected HV plant and have propagated down the cable feeder circuit to the switchgear.

This remote monitoring technique was presented by the lead author at the IEEE-PCIC 2012 [1] and IEEE-PCIC 2013 [2] for the application of OLPD condition monitoring of Ex/ATEX HV motors, whilst avoiding the need to install sensors in the hazardous gas zone. In this paper, the authors describe how this remote OLPD monitoring technique can be extended to include the insulation condition monitoring of other HV assets including; generators, switchgear, cables and transformers, using the same wideband HFCT sensors attached to the HV cable terminations located at the central switchboards.

The authors provide a number of case studies describing some past projects on the OLPD testing and monitoring of in-service HV generators, switchgear, cables, motors and transformers within the oil & gas industry. The applications knowledge obtained from these past projects on different plant types has been used by the authors in the development of this innovative, complete HV network condition monitoring solution.

Index Terms – partial discharge, PD, on-line partial discharge, OLPD, phase resolved partial discharge, insulation Diagnostics, Ex motors, ATEX motors, rotating HV machines, switchgear, transformers, hazardous gas zone, condition-based management, CBM.

I. INTRODUCTION TO ON-LINE PARTIAL DISCHARGE CONDITION MONITORING

On-line partial discharge (OLPD) monitoring refers to the diagnostics of high voltage (HV) insulation of in-service HV plant, including cables, switchgear, rotating machines and transformers, in their operational mode. The OLPD condition monitoring (CM) technique can be applied to all types of HV assets, with all components tested under both normal working conditions and abnormal variations related to changes in the associated thermal electrical, ambient and mechanical (‘TEAM’) operational stresses that the plant is subjected to.

The OLPD monitoring technique is complementary to the more traditional ‘off-line’ partial discharge test technique for the diagnostic assessment of the insulation condition of out-of-service assets. Off-line PD testing requires the HV cable or plant item to be de-energised and isolated from the network with a portable HV power source (Very Low Frequency, Resonant Test or 50/60 Hz Power Frequency) used to energise each phase of the asset. The off-line PD test technique is normally combined with a dielectric loss angle/tangent delta (TD) measurement and insulation resistance (IR) test to provide a combined, ‘holistic’ diagnostic assessment of the insulation.

The off-line test is useful as the test engineer has control over the applied voltage and can thus measure the partial discharge inception voltage (PDIV) during the test voltage ‘ramp-up’ (normally to 1.5–2.0 Uo, working voltage) and then the partial discharge extinction voltage (PDEV) during the voltage ‘ramp-down’. The techniques of on-line and off-line PD testing are very much complementary and symbiotic as the on-line technique can be used to pre-sort any cable/plant/machine that requires an outage for further off-line diagnostic testing and repair. For example, to get the exact location of the PD site(s) within the HV stator windings of motors and generators TVA probes and other ‘search coil’ type technologies can be used, as a prelude to the repair of the HV stator winding.

The focus of this paper is on the OLPD insulation condition assessment of in-service HV plant (including generators, switchgear, cables, motors and transformers) across entire HV networks. The application of the OLPD technology is now becoming more widely accepted in the worldwide petrochemical industry as a crucial condition monitoring (CM) diagnostic aid to support condition based maintenance (CBM) regimes and to avoid unplanned outages. The application and uptake of the technology has increased significantly over the past five years as operators recognise the main benefits that the technology...
can provides, namely the ability to provide an ‘early warning’ against ‘incipient’ HV insulation faults, to direct maintenance interventions and to avoid unplanned, costly outages. An incipient insulation fault is one that is yet to occur but which manifests itself through high PD activity. OLPD detection and monitoring is now commonly regarded as the best early-stage indicator of insulation degradation of in-service plant.

There is a wide range of technology available for OLPD testing and monitoring of in-service HV generators, switchgear, cables, motors and transformers. These range from simple-to-use, handheld OLPD ‘screening’ test units (for screening a large numbers of assets quickly) to continuous, 24/7 OLPD monitoring technology. By combining OLPD ‘screening’ tests with off-line PD test data (Phase 1), OLPD diagnostic spot-test data (Phase 2) and then extended, continuous OLPD monitoring (Phase 3) technology, it is possible to carry out a comprehensive, step-by-step condition based assessment of the health and the risk of failure of the insulation in the HV asset as shown in Fig. 1 below.

A strong argument for continuous OLPD monitoring is that it allows for the measurement of PD activity in normal and abnormal operating conditions. This is a much better diagnostic solution than the more traditional, periodic (typically 6- or 12-monthly) on-line PD ‘spot-tests’ as it is known that such PD ‘spot tests’ can miss sporadic, time-varying and environmentally-driven PD activity in the HV plant and can thus miss the ‘early warning’ of HV insulation degradation.

PD activity in HV equipment can initiate under normal working conditions where the insulation condition has deteriorated with age, has been aged prematurely by thermal or electrical over-stressing and/or due to improper installation (leading to infant mortality). Premature ageing of the insulation system can be accelerated by several factors/stresses, including: thermal, electrical, ambient and mechanical. Fig. 2 provides an overview of these ‘TEAM’ stress factors for the case of rotating HV machines. To take into account these variable stresses and how they can impinge on the reliability of a rotating HV machine, continuous electrical and mechanical condition monitoring (CM) is now becoming more widely applied in the oil and gas industry.

When it comes to monitoring complete HV networks, it is only through the application of continuous OLPD monitoring technology that the correct level of CM data required for the diagnostic detection of ‘trends to failure’ can be achieved.

**THERMAL**

- Loading / duty cycle thermo-mechanical effects and variations.

**ELECTRICAL**

- Localised electrical stresses at the end windings and voids or delaminations in groundwall insulation.

**AMBIENT**

- Temperature and relative humidity, surface discharges can occur with high humidity.

**MECHANICAL**

- Wedge tightness, rotor alignment/concentricity, vibration effects, short-circuit fault forces.

Fig. 2 The ‘TEAM’ stresses for rotating HV machines

II. **ON-LINE CONDITION MONITORING IN THE WORLDWIDE OIL & GAS INDUSTRY**

In the worldwide oil and gas industries, it is estimated that OLPD electrical condition monitoring (CM) technology is presently applied to only around 10% of the large (>2 MVA) HV motors and generators in operation. It is interesting to compare this 10% estimate to the percentage of large rotating HV machines in the industry that have mechanical, vibration condition monitoring technology fitted, where it is estimated that around 80% have some form of vibration CM monitoring technology deployed. This 10:1 disproportion can be partly explained due to the fact that historically it has been mainly mechanical engineers who had been responsible for the design, build and condition monitoring of the rotating HV machines. This naturally has resulted into a corresponding focus on mechanical condition monitoring in the past. However, this is set to change as the vast majority of HV motors that are now being deployed in the industry are variable/adjustable speed driven (VSD/ASD) machines that use electrical power conversion in the drives to control their operating speed. Oil and gas operators are also now beginning to see the benefit in combining the existing vibration (mechanical) technology with the OLPD (electrical) technology in order to provide a combined, ‘holistic’ condition monitoring solution.

In the case of HV motors, cause-of-failure studies carried out in the USA [3,4] show that HV stator winding failure contributes to around 37% of HV motor failures reported. The data from these studies is illustrated in Fig. 3 below and shows that 41% of all failures were due to bearing related failures. This data would suggest that a combined electrical and mechanical condition monitoring (CM) solution deployed to monitor bearing condition and stator winding could potentially detect up to 88% of faults in the HV motors. Whilst it is never possible to detect and/or remove 100% of the ‘incipient’ mechanical and electrical failures through the application of the CM technology with preventative maintenance interventions, a realistic target would be to detect and repair 50% of these (i.e. setting a target of trying to remove 44% of all faults based on the data from these two HV motor cause of failure studies).
The reliability of process critical HV assets within the petrochemical industry is crucial to maintaining production and refining output. With a large proportion of the critical HV pump motors in operation in the industry operating in Ex/ATEX hazardous gas zones, any complete HV network OLPD CM solution should include the assessment of the HV insulation condition of these motors. Continuous OLPD monitoring of HV assets is now gaining considerable acceptance as an effective CM technology in the industry with the appreciation that it can identify sites of localised insulation damage and degradation ahead of scheduled preventative maintenance outages.

While some discharges can be extremely dangerous to the health of the insulation system (e.g. discharges within polymeric cables and cable accessories), others can be relatively benign (e.g. such as corona into air from sharp, exposed points on HV overhead networks or on the outside surfaces of outdoor cable sealing ends). The key to diagnostic OLPD testing is to be able to differentiate between the dangerous and the benign; this differentiation often becomes more difficult as the voltage of the system increases, due to a corresponding increase in the background electromagnetic (E/M) noise levels.

III. THE DRIVERS BEHIND CONDITION MONITORING AND CONDITION-BASED MAINTENANCE

The main drivers for applying the OLPD test and monitoring technology to HV networks are to:

- Improve the reliability of the network by identifying high risk, worst performing assets before they fail.
- Collect diagnostic insulation CM data to provide an ‘early warning’ against ‘incipient’ faults.
- Provide plant condition data to support reliable life-extension programs of ageing networks.
- Avoid unplanned outages and minimise downtime.
- Provide qualitative information on the assets that facilitate condition-based maintenance (CBM) and a programmed ‘replacement and repair’ strategy.

Oil and gas operators worldwide are increasingly deploying OLPD technology to test, monitor and manage a wide range of assets including power cables, switchgear, transformers, and rotating HV machines. The business drivers for carrying out OLPD testing and monitoring of these HV networks include:

- Safety – many diagnostic OLPD test and monitoring projects are instigated further to insulation faults and equipment component failures. In this case there is an immediate requirement to carry out condition spot-tests on ‘sister’ plant to ensure that there is no immediate risk of further plant failures and thus danger to staff. Safety is of particularly relevance in the petrochemical industry due to the potential consequences of serious HV plant failure.

- Reliable life-extension – as many in-service HV machines are reaching the end of their ascribed ‘design-life’ (typically of 20 years), operators face an important asset management dilemma as to whether to extend the life of these existing assets (using CBM techniques) or to replace the machines with new units.

- Maximizing HV network availability and unplanned outages and downtime. As many petrochemical facilities are operated with minimal redundancy across their HV network, unplanned outages from HV insulation faults can have a dramatic effect on both production and therefore the ‘bottom line’ profit.

Studies on petrochemical both production and refining facility HV networks show that the main cost driver is to avoid any unplanned outages. This average plant downtime cost for unplanned outages in the oil & gas industry has been estimated at $220 200 per hour [5], this equates to $5.285 million per day. These potentially very large ‘loss of business costs’ due to unplanned outages means that operators have little difficulty in justifying the cost of implementing electrical and mechanical condition monitoring technology that can help to avoid them.

IV. PARTIAL DISCHARGE SENSORS OPTIONS

There are four (4) main OLPD sensor options available for the on-line detection of partial discharge in HV networks, as follows:

- High Voltage Coupling Capacitor (HVCC) sensors (these are also referred to as ‘PD Couplers’)
- Ferrite-based, High Frequency Current Transformer (HFCT) sensors
- Air-cored, Rogowski Coil (RC) sensors
- Transient Earth Voltage (TEV) probes

The most suitable OLPD sensor solution for any application will depend on the type of cable/plant/machine used and the cable earthing configuration employed. It is normal for the suitable points of attachment (POAs) for the sensors on the network to be identified through an engineering site survey project where technical data, drawings and photographs of HV switchgear, transformer and machine cable boxes are collected to ensure that the correct sensors are chosen. Also, and most importantly, it is essential that a full engineering assessment is made to ensure that any OLPD sensors can be installed safely without impinging on the minimum HV clearances required inside the HV cable boxes. Failure to do this may contravene the test certification for the switchgear/plant where the sensors are to be installed and in extreme cases can lead to flashovers in the cable boxes.

The HVCC sensor has been the most widely applied sensor to date for the OLPD monitoring of rotating HV machine stator windings and has now become the de facto sensor of choice for
the OLPD monitoring of large HV motors and generators (in the 2 MW+ class). The HVCC sensors are installed with an HV ‘jumper’ cable to make direct, galvanic contact to the HV terminals in the rotating machine’s HV cable-terminal box. A side-view of an HVCC installation in the terminal box of a bus-fed HV generator, is shown below in Fig. 4 below.

![Fig. 4 Side view of an HVCC installation in a bus-fed HV generator](image)

Whilst the HVCC sensor remains the most popular sensor for OLPD monitoring of rotating HV machines (since it was first applied over 40 years ago) in the case of HV cables it is the split-core, ferrite-based HFCT sensor that has become the de facto sensor of choice (after over 15 years of industrial application). The HFCT sensor works inductively to detect either the PD currents in the cable conductor, \( i_c \) (if the HFCT sensor is connected around the core and earth drain return as shown in Fig. 5, Left) or the PD current in the earth drain wire, \( i_e \) (if the HFCT sensor is connected on the earth drain wire only, see Fig. 5, Right).

![Fig. 5 Split-core HFCT sensor installations in HV cable boxes](image)

Left: HFCT sensor around core + earth return to measure \( i_c \) vs. \( i_e \)
Right: HFCT sensor on earth drain wire only to measure \( i_e \)

For the technique of remote OLPD monitoring of remotely connected HV plant (with HFCT sensors located at the central switchboards of the HV circuit) then it is recommended that the HFCT sensor is connected around the core and earth return, see Fig. 5, Left) as this connection ensures the highest sensitivity for the PD measurement through the detection of the conductor PD current, \( i_c \), this being typically around 2x greater than the earth PD current, \( i_e \). The difference in sensitivity between the two HFCT connection options is illustrated below.

In order to compare the relative sensitivity of the two options for HFCT connection (Option 1: around cable core + earth or Option 2: around earth drain wire only), low voltage (1.0 V) calibration pulses were injected between the earth screen and the conductive core of a 6.6 kV 3-core cable at the remote end of an HV motor feeder cable. HFCT sensors were placed around the cable ‘crutch’ (to detect the conductor PD current, \( i_c \)) and around the cable earth drain lead (to detect the PD current on the earth, \( i_e \)) as shown in Fig. 6 below.

![Fig. 6 Sensor Installation Set-up for comparison of the sensitivity of an HFCT detecting conductor PD current, \( i_c \) Vs earth screen PD current, \( i_e \)](image)

The results from this comparison are shown below in Fig. 7 and show that the HFCT output detecting \( i_c \) on the conductor was 30 mV compared to only 11 mV of \( i_e \) measured by the HFCT on the earth drain wire. Therefore, the conductor PD signal was around 2.7x higher than the PD signal in the earth drain wire in this case.

![Fig. 7 Sensitivity comparison between HFCT sensor attachments](image)

Blue Trace: HFCT around the cable crutch, to detect \( i_c \)
Orange Trace: HFCT around earth drain wire, to detect \( i_e \)

This is a typical result and confirms that the preferred HFCT sensor attachment of the sensor is around the cable core so that it can detect the stronger conductor PD signal, \( i_c \). Two examples of permanent HFCT sensor installations inside HV switchgear cable boxes to detect \( i_c \) in a 3-core cable and 3x single-core cables are shown below in Fig. 8. These examples show the HFCT sensor connections (1 per phase) for 3x single core cables (with the earth drain wire return through the middle of the sensor) and the HFCT sensor connection around the ‘crutch’ of a 3-core cable. Such installations are becoming more popular with HV plant owners for the application of remote OLPD monitoring of rotating machines and other remotely connected HV plant due to their ease of installation and lower cost compared to the more conventional HVCC sensors.
V. PARTIAL DISCHARGE SENSORS IN EX/ATEX HV MOTORS IN HAZARDOUS GAS ZONES

With reference to the special case of the installation of OLPD sensors in the HV cable boxes of Ex/ATEX HV motors located in hazardous gas zones, there are presently a number of vendors in the marketplace offering Ex/ATEX-rated PD sensors for this purpose. From discussions with a number of senior electrical engineers and electrical technical authorities (TAs) in the oil & gas industry it is clear that there remain some reservations about whether installing these sensors in the machine cable box contravenes the test certification of the Ex/ATEX motor. The reservations are due to concerns that as high voltage coupling capacitors (HVCCs) make direct, galvanic contact to the HV terminals of the machine in the cable box (via a jumper cable) and therefore, strictly, this should require a re-test and re-certification of the motor as the device has been materially changed. This problem can be removed using the inductively-coupled HFCT sensors at the switchboard end of the cables, outside the Ex/ATEX zone.

A second, more practical factor is the logistical and operational limitations in getting Ex/ATEX sensors installed including obtaining work permits for working in the Ex/ATEX hazardous gas zones. The third and final issue is the compact design of many Ex/ATEX HV motor terminal boxes which means that it is not always possible to install permanent HVCC sensors inside the cable box without contravening minimum HV safety clearances.

These technical and operational restrictions in the deployment of OLPD sensor technology in the Ex/ATEX zones were the main technical ‘drivers’ for the development of the new, remote OLPD testing and monitoring technique using inductive, wideband, high frequency current transformer (HFCT) sensors located remotely from the Ex/ATEX plant to be monitored at the switchgear end of the cable i.e. in a non-Ex/ATEX area.

VI. CENTRALISED OLPD MONITORING OF COMPLETE HV NETWORKS

The complete HV network OLPD monitoring solution that has been developed utilises the technique of remote PD monitoring of in-service switchgear, cables and remotely connected plant. The technique can be applied to all direct line-fed remote HV plant including motors, generators and transformers and was originally developed in 2011 by HVPD in conjunction with Chevron. This first application of the remote OLPD monitoring technique was used to monitor the HV stator winding condition of Ex/ATEX HV motors located in explosive atmospheres such as those within hazardous gas zones.

The wideband frequency response of the HFCT, as discussed in the previous section of this paper, means that the sensor can be located remotely from the HV asset under test while still being able to detect sufficient PD pulse energy to ensure that the PD pulse is represented accurately in the time and frequency domains at the switchgear end of the cable(s). This feature allows for the discrimination between PD types based on the PD pulse timing and pulse properties and waveform. This is illustrated below in Fig. 10 for the example of OLPD monitoring of a complete Ex/ATEX HV motor feeder.
circuit including the switchgear, cable and the remotely connected motor (located in the hazardous gas zone).

It should be noted, as discussed in the IEEE and IEC standards [7] and [8], there is always a risk of misinterpreting PD signals due to electromagnetic (E/M) interference exhibiting characteristics similar to the PD signals. The IEEE and IEC standards discuss time and frequency-domain methods for noise separation, the types of E/M interference that can be expected when OLPD testing, and the importance of distinguishing between the origins of and the different types of PD activity. The technique of remote OLPD monitoring described in this paper uses a combination of PD-classification knowledge rules using the technique of pulse waveshape analysis that uses both time-and frequency-domain parameters to distinguish between PD types and interference.

The basis for the remote OLPD monitoring technique was the development of innovative, high-current, ferrite-based HFCT sensors [6] by the authors in 2010. These split-core, high current inductive sensors were developed for the specific use of being attached around the cable cores of the HV cable at the switchgear end of the cables to detect the PD current in the conductor, i.e. the HFCT sensors can be used to test rotating HV machines of voltage rating: 3.3 kV to 30 kV and provide wideband (200 kHz to 30 MHz) OLPD measurements, up to a maximum phase cable conductor current of 1000 A.

The sensors are inductively coupled to each phase of the cable/motor feeder with the sensor connection dependent on whether the cable is single-core or 3-core (as shown previously in Fig. 8). This attachment location position for the HFCT sensors is crucial as it is necessary to detect the PD current on the conductor of each phase (i.e), this being a much stronger and more reliable signal than PD signal on the earth drain conductor (i.e) as shown previously in Fig. 7.

VII. PD PULSE PROPAGATION ALONG HV CABLES

An important part of making remote OLPD measurements on remotely-connected HV plant is to take into account the attenuation of the PD pulses as they travel along the HV cable from their source. By measuring this pulse attenuation along the cable it is possible to produce a PD Pulse Retention Factor (PPRF) for the cable that can be used to multiply remote OLPD measurements to produce the ‘at machine’ or ‘at plant’ equivalent PD levels. It is known that attenuation is a function of pulse frequency [1], which, for a PD pulse, is directly related to the distance propagated from its original source. The HV cable acts as a low-pass filter to the transient PD pulses that pass along them and the attenuation of the PD signal along the cable depends upon the cable length from the remotely-connected HV plant to the switchboard and the type of HV cable insulation (XLPE, PILC, EPR and PVC are the most common types).

As each cable is different it is essential that a calibration pulse injection test is carried out on every cable in order to get an accurate measurement of the PD Pulse Retention Factor (PPRF) for the cable that is used to convert remote OLPD measurements made at the switchgear end of the cable to the ‘At Machine’ or ‘At Remote Plant’ PD levels.

The authors have developed a multiple reflection technique to accurately measure the PD Pulse Retention Factor (PPRF) for an HV cable. This involves injecting a large calibration pulse (of between 5000 pC and 10 000 pC) onto the cable using an inductive, pulse injection HFCT and then measuring a minimum of three (3) reflections of this pulse as it travels up and down the HV cable. The HFCT sensor connections for injection procedure are shown in Fig. 11 below.

The results from a PPRF cable calibration test are illustrated below in Fig. 12 from a test on a 270-m long, 6.6 kV XLPE motor feeder cable. In order to calculate the PPRF of a cable circuit that is connected to both the switchgear at one end and the remote HV plant at the other, it is necessary to inject a large calibration pulse and to obtain a minimum of three (3) pulse reflections. This is required in order to take into account the losses at each end of the cable, MLoss at the remote plant and SLoss at the switchgear.
Fig. 12 PPRF Calibration Test for a 270-m long 6.6 kV motor feeder cable

Injected Calibration Pulse (A) = 6645 pC
1st Reflected pulse (B) = 4803 pC
2nd Reflected pulse (C) = 4150 pC
3rd Reflected pulse (D) = 3659 pC

- First Pulse (A) – Calibration pulse injected on-line via the pulse injection HFCT at switchgear end.
- 1st Reflected Pulse (B) – Pulse which has propagated down the HV cable towards the remote end and is then reflected back, with some of the pulse energy was dissipated into the remote plant (MLoss).
- 2nd Reflected Pulse (C) – Incoming Pulse B which reflected from switchgear end, travels towards the remote end and is reflected again. Some pulse energy is dissipated into the switchgear (SLoss) and again at the remote plant (MLoss).
- 3rd Reflected Pulse (D) - Pulse C which reflected from the switchgear end, travels towards the remote end again and is reflected again. At this point the pulse has been reflected three (3) times from the machine end and two (2) times from the switchgear end. Some pulse energy has been dissipated into the switchgear (SLoss) and the remote plant (MLoss) at each reflection.

As the multiple (3) reflections produce multiple (3) quadratic equations it is possible to remove the unknowns (SLoss and MLoss) through solving the following equations:

\[ B = A \times \text{PPRF}^2 \times \text{MLoss} \]
\[ C = B \times \text{PPRF}^2 \times \text{MLoss} \times \text{SLoss} \]
\[ D = C \times \text{PPRF}^2 \times \text{MLoss} \times \text{SLoss} \]

The PD Pulse Retention Factor (PPRF), for the cable can now be calculated using the injected pulse value – A, the 2nd reflected pulse value – C and the 3rd reflected pulse value – D, using the following equation:

\[ \text{PPRF} = \sqrt{\frac{C^2}{AD}} = 0.8416 \]

For this cable the PPRF is 0.8416 and so the PD Multiplier for remote OLPD monitoring is the reciprocal, i.e. 1.188.

VIII. OLPD CONDITION MONITORING DATABASE

It is proposed that complete HV network OLPD monitoring coverage can be achieved by pooling of the insulation CM data from multiple, distributed sensors and monitoring units into a central database for display on a single user interface at the control centre. A master server unit is used to provide real-time pooling of the condition data from multiple, distributed monitoring nodes located across all of the switchboards at the facility. All data is passed to a central database for the facility for logging, databasing, benchmarking and trending. The condition of individual plant items is displayed on a software user interface that includes a ‘mimic’ of the network’s single line diagram (SLD) with superimposed, colour-coded plant condition criticality data (rating from 0–100%).

This benchmarking condition monitoring (BCM) system means the operator can compare all of their plant on a ‘like-by-like’ basis with an ‘early warning system’ to identify any cable/plant/machine that has a significant risk of insulation failure. The condition of individual plant items is displayed in form of colour-coded plant condition indicators as shown below in Fig. 13 below (110 kV network at a large refining facility).

Fig. 13 OLPD monitoring database showing colour-coded condition criticality – example from a 110 kV network at a large refining facility
IX. CASE STUDIES FROM OLPD MONITORING

A. Case Study 1: OLPD Testing of a 20-year old 11 kV, 20 MVA Generator from a Norwegian Offshore Oil & Gas Platform

OLPD measurements were carried out on a 20-year old, 11 kV 20 MVA diesel generator on an offshore oil drilling facility in the Norwegian North-Sea. The OLPD testing showed very high levels of PD (of up to 200 nanocoulombs [nC]) with HFCT sensors. The diagnostic measurements suggested that the PD was originating from the stator slot section as the PD pulses were mainly phase-to-earth. Due to the high peak and activity levels measured in these on-line tests, the generator was replaced and removed from service for further, off-line PD testing (using a HV 50/60 Hz power source) and a visual inspection and/or repair of the stator windings at the rotating machine rewind factory. The results of this off-line testing corresponded with the on-line tests carried out with very high PD levels of 200 nC+ measured.

Upon removal of the generator’s rotor and out-of-service energisation at the machine rewind factory, the sites of the PD activity were confirmed to be where the slot section meets the end winding region. This is a location where significant electrical stresses can be present, particularly if there is insufficient clearances (in air) and/or HV insulation thicknesses.

Fig. 14 shows a photograph of the (very high) visible phase-to-earth PD activity (blue/purple sparks) occurring at the position where the windings exit the slot-section of the coils (the rotor has been removed for this off-line PD testing).

Fig. 14 Visible PD activity (200 nC+) occurring at the slot exit on a disassembled 11 kV, 20 MVA diesel generator

B. Case Study 2: On-line PD Testing of 110 kV XLPE Cables and Transformers at a European Oil Refinery Facility

In-service failures of two (2) 110 kV transformer cable terminations in two separate transformers at a European oil refining facility had occurred in short succession to each other and had resulted in significant operational disruption and loss of refinery production.

Due to concerns about the reliability of their network, OLPD measurements were carried out on all of the ‘sister’ 110 kV cable terminations at facility. This testing and monitoring of the cables showed some significant levels of PD activity, of around 400 pC (this being a high level for this type of HV XLPE cable termination as they should be completely PD free). Whilst the detection of this significant PD activity was considered as a cause for concern at the time of the OLPD tests, it was not possible to arrange an outage to carry out further investigation and/or repair due to the refinery’s production schedule and the client decided that this would only be carried out at the next full maintenance outage, in 15 months’ time.

At the time, whilst it was anticipated that the 110 kV termination would fail within the 15-month period, a ‘failure preparedness plan’ was put in place whereby should the termination fail, a quick repair could be instigated. It was therefore somewhat of a surprise that the discharging cable termination lasted for the full 15 months. On replacement a diagnostic assessment of the discharging cable termination...
revealed extensive tracking damage between the silicone stress control cone and the cable end, as shown below in Fig. 17.

Fig. 17 Tracking damage on 110 kV cable termination at the interface between the HV silicone stress cone and the XLPE cable – this cable had still not failed

The knowledge obtained in this 110 kV cable termination test project included that some ‘incipient’ HV cable faults can take longer to develop to a full insulation fault after inception of PD activity (12 months+) than was previously thought (up to 6 months). The OLPD testing in this case gave a very good ‘early warning’ of an ‘incipient’ fault in the HV termination with the discharging termination lasting a further 15 months after it was detected, and it had still not yet failed when it was taken out of service (although it looked very close to failure on diagnostic investigation with significant carbonisation observed on the cable). Whilst this discussion is of interest regarding the lead time to failure after the inception of PD activity, it would be the advice of the authors that if any significant levels of PD activity (>250 pC) are detected in HV XLPE cables then continuous OLPD monitoring should be considered and a cable repair preparedness plan brought together.

X. CONCLUSIONS

This paper has shown that it is possible to carry out reliable and effective OLPD condition monitoring of complete HV networks using wideband OLPD HFCT sensors and monitors located at the central switchboards of a facility. It has also been shown that it is possible to integrate the OLPD diagnostic monitoring data into a central database to enable benchmarking of condition levels and to support condition based maintenance (CBM) asset management regimes. For any such CBM scheme to be effective, the quality of the diagnostic condition data used in the CBM decision-making process must be of a high level in order to provide quantifiable and benchmarked asset condition data from which to make informed engineering decisions.

The authors have proposed a quantitative, condition-based ranking and benchmarking database approach that produces a condition criticality rating for the HV assets (from 0-100% based on comparison with a statistically significant OLPD measurements database. The solution can be used to identify and prioritize replacement candidates whilst also providing an early warning for the ordering and procurement of spares, replacements or repair services. The continuous OLPD monitoring technology also identifies any variations related to operational, environmental and seasonal variations to provide trends in data to further support the CBM asset management schemes.

It is proposed that significant cost and operational benefits can be gained from OLPD monitoring of complete HV networks in the petrochemical industry. The data from continuous CM technology can be used to provide an ‘early warning’ of ‘incipient’ insulation faults to support CBM schemes with direct preventative maintenance interventions to repair plant/cables ahead of insulation failure from PD activity. In this way, the petrochemical facility operator can avoid unplanned outages (these being reported to cost an average of $220k per hour [5]) caused by HV insulation faults across their HV network.

XI. REFERENCES


XII. VITAE

Lee A. Renforth (lee.renforth@hvpd.co.uk) studied Electrical and Electronic Engineering at the University of Manchester in the UK between 1986 and 1990. He was sponsored throughout this 4-year industrially-linked course by BICC cables where he received his first training in the partial discharge testing of HV cables. He graduated with a BSc, MEng degree in 1990 and went on to study for a PhD in the field of HV insulation breakdown under sponsorship by the National Grid Company, the transmission network operator for the UK. He was awarded his PhD in 1993 when his thesis on the topic of the breakdown of HV insulation was published, also at Manchester University. In 1994 he set-up a new technology start-up company, IPEC Ltd, with other members of Manchester University’s Power Systems Group. He was Managing Director at IPEC Ltd for 10 years from the company’s start-up before leaving to set-up HVPLD Ltd in 2004. He is currently Managing Director of HVPLD Ltd of Manchester, England, UK which has now established itself as one of the market leaders in the growing field of on-line partial discharge (OLPD) test and monitoring technology for high voltage plant, cables and rotating machines. He oversees the relationships with HVPLD’s customers and partners in more than 100 countries worldwide whilst remaining involved in the company’s R&D activities in conjunction with a number of universities in both the UK and internationally.

Marc J. Foxall (marc.foxall@hvpd.co.uk) received a First Class BEng (Hons) Degree from De Montfort University, Leicester in 2010 in Electronic Engineering, fully accredited by the IET. He was awarded the ‘IET Outstanding Achievement Award’ and ‘Department of Engineering Best Final Year Project’ which showed Marc’s research into High Frequency Current Transformers (HFCT’s) and their saturation currents. As the main author for a technical paper entitled on ‘Development of a new high current, Hybrid ‘Ferrite-Rogowski’, high frequency current transformer for partial discharge sensing in medium and high voltage cabling’, Marc presented his research at the 59th International Wire & Cable Symposium in November 2010, Rhode Island, USA. This paper included the R&D carried out in the development of HVPLD’s high-current HFCT sensor for application to rotating HV machines and is referenced [7] in this paper. Marc is a member of both the IEE and IET, currently working towards Chartered Engineer (C.Eng) status. Since joining HVPLD in 2009, Marc has completed the HVPLD accredited field test training course Marc is presently managing HVPLD’s test services team with an active role in HVPLD’s OLPD field and forensic test services as well as providing technical support to customers worldwide. Over the past five years Marc has carried out a wide variety of on-line and off-line PD test projects for the utility, industrial and marine sectors with over 60 projects now completed. Marc also continues to be an active member of HVPLD’s R&D team and helps in the development of new technologies for condition monitoring of in-service HV plant.

Andrew Burgess (andrew.burgess@hvpd.co.uk) received a B.Eng (Hons.) degree in Electrical and Electronic Engineering from The University of Manchester in 2010. Andrew joined HVPLD in June 2010. Prior to this Andrew worked for R&B Switchgear during his Industrial Year Placement as a Junior Project Manager. During this period, he worked extensively at Grand Bahamian Shipyard during the reinstatement of ‘The Mighty Servant 3’, a semi – submersible vessel which sank in 2007. Following the upring of the vessel, Andrew oversaw the replacement, installation and re-commissioning of all electrical services on board. Since joining HVPLD, Andrew is a multi-faceted member of the HVPLD engineering team and is a member of the IEEE. Andrew has completed the HVPLD accredited field test training course and has an active role in on-line PD field and forensic test services as well as providing technical support to worldwide customers. Over the past four years Andrew has carried out a wide variety of on-line and off-line PD test projects for clients in the petrochemical, utility, industrial and shipping industries. Andrew has recently set-up HVPLD’s new office in Houston where he is now based to provide local service and support to HVPLD’s clients in the USA.

Thomas Raczy (thomas.raczy@hvpd.co.uk) received an “Electronic Engineer and IT Specialist Diploma” from Technical Collage Nr 9 (ZSE-Zespol Szkol Energetycznych) in Cracow, Poland in 2004. He then went to work at Joy Computers in Poland where he worked as an electronics assembly engineer. He moved to the UK and joined HVPLD Ltd as a test technician in 2008 where he worked involved in final assembly and test of HVPLD’s sensors and measurement device products. In 2009 Thomas became a Trainee Field Test Engineer at HVPLD Ltd, receiving in-house training from HVPLD’s senior engineers for a 12-month period and was appointed as a Test Engineer in 2010 in this field. In 2013, after 3 years as a test engineer, Thomas was promoted to the position of HVPLD Senior Test Engineer and now manages and mentors a number of HVPLD Test Engineers and Engineering Apprentices. Over the past four years he has carried out over 60 OLPD test and training projects for the petrochemical, utility, industrial and shipping industries.