Introduction to PD

October 2014

Presented by:
Dr Lee Renforth,
Managing Director
HVPD Ltd
CONTENTS

- PD detection theory
- PD test & monitoring equipment
- Cable PD – detection & location
- Local PD in switchgear
- PD in rotating machines
- Continuous PD monitoring
Introduction to HVPD Ltd

HVPD are experts in the growing industry of on-line partial discharge (OLPD) condition monitoring and condition based management (CBM) of high voltage networks.

We supply portable and permanent OLPD surveying, diagnostic test and continuous monitoring solutions, and a complimentary range of on-site services, monitoring services and training.

Over 350 customers in 100 countries trust our technology.
500+ test and monitoring projects completed over the past 20 years

OUR EXPERTISE

“Our Knowledge is Your Power”
Introduction to HVPD Ltd

Industry-Specific Condition Monitoring Solutions

Oil & Gas

Offshore Renewables

Transmission & Distribution

Power Generation

Shipping
**Introduction to Partial Discharge**

**What is partial discharge?**

“A localized electrical discharge that only partially bridges the insulation between conductors and which can or can not occur adjacent to a conductor”

*IEC60270 Definition*

**Why test for partial discharge?**

PD activity is an indication of an incipient fault in HV insulation and is widely regarded as the best ‘early warning’ indicator of the deterioration of high voltage insulation.
Common Applications of PD Testing

Power cables, joints/splices and terminations

Switchgear (Air, Solid, Gas-insulated)

Power transformers and bushings

Motors and generators

CT’s and VT’s
The Drivers for Applying OLPD Testing

- Safety – mostly with switchgear, outdoor HV plant and cable sealing ends
- Ageing population problem – life extension, delaying capital replacement
- Condition-Based Maintenance (CBM)
- Avoid unplanned outages and improve network reliability
Why and When to Perform PD Testing

New Equipment

At Manufacture

- Quality Assurance
- Type/routine tests, e.g. IEEE/IEC standards – test to less than 5 pC on the cables

At Commissioning

- To check for transport damage
- To ensure the installation of the cable accessories have made to a good standard (these are the weak points in the cable system)
• To get baseline PD readings
• To evaluate insulation quality
• To locate PD activity sites and target repair
• To avoid costly / unplanned outages
• To support Condition-Based Management (CBM) regime
Manufacturing → Transportation → Installation → Operation

Operation
Power frequency 50/60 Hz

Continuous Monitoring → Acceptance Testing → Factory Testing

Power frequency 50/60 Hz

Damage → Mistake → Aging → Repair

From ‘Cradle to Grave’ PD Testing and Monitoring Philosophy
OLPD DETECTION THEORY
7 Main Types of PD

**Internal**
- Void in insulation
- Sharp, irregular surface on conductor
- Tree growth in insulation

**External**
- 'Floating' metalwork near conductors
- Corona from sharp objects at high voltage
- Discharges from induced voltages onto sharp points at ground
- Surface discharges
PD Equivalent Capacitance Circuit – ABC Model

\[ C_a = \text{Bulk insulation capacitance} \]

\[ C_b = \text{Capacitance between discharging area and electrodes} \]

\[ C_c = \text{Cavity/surface area in which the PD occurs} \]

**Surface Discharge**

**Corona**

[Image of diagram showing the capacitance circuit with labels for \( C_a \), \( C_b \), and \( C_c \)]
Voltage Breakdown of Cavity of Surface Area (Cc)

$V_a$, $V_b$, $V_c$

Theoretical

Actual current pulses (stochastically occurring)

$V^+, V^- =$ PD inception voltages
Paschen Curve for Breakdown of Air in Uniform Field

Internal discharges can be caused by:

- Voids, cavities, delaminations in solid or liquid insulation
- Electrical trees form from these voids
PD Damage to Cables – Treeing on 66 kV Paper Cable
Insufficient Mastic Around 33 kV XLPE Connector
Surface Discharges on 24 kV Cable Elbow Termination
• Incepted from sharp points on HV conductors
• Also possible from sharp points on ground
**ENERGIES RELEASED**

- Electrical Charge
- Electromagnetic Wave
- Optical
- Acoustic Wave
- Gaseous by-products (such as white deposit oxides)
- Chemical by-products
- Ozone

**DETECTION METHODS**

- Capacitor/Inductive (HFCT)
- TEV, VHF/UHF Couplers
- Low-light/UV Cameras
- Contact/Airborne Acoustic
- Dissolved Gas Analysis
- Visual inspection
- Smell / Ozone Detector
Examples of OLPD Measurements / Results

- PD magnitude
- PD count (number of PD pulses per power cycle)
- Cumulative PD activity
- Phase Resolved PD (PRPD) Patterns
- PD monitoring over time
OLPD TEST & MONITORING EQUIPMENT
PD Testing Approach

SPOT-TEST

DETECTION

LOCATION

CONTINUOUS MONITORING

TEMPORARY/PERMANENT

Off-line / On-line

On-line
Phase 1 – Detection
  • Simple equipment
  • Initial indication of PD level/severity

Phase 2 – Diagnostics/Location
  • More advanced hardware/noise rejection
  • PD diagnosis and location within the cable/plant
  • Digital PD detector with PC for analysis and reporting
Continuous Monitoring Aspects

Phase 3 & 4 – Temporary/Permanent Monitoring

- Temporary or permanent hardware
- Trends PD over time and captures any trend to failure
- Web-based UI/SCADA alarms
- Simple and advanced options:
  - Simple hardware without diagnostic capabilities, generates alarm signals only
  - Advanced hardware with diagnostic capabilities
CABLE PD – DETECTION & LOCATION
- PDs are incepted by the high voltage applied to cable.
- PD pulses are short duration impulses (ns – µs) that propagate in both directions away from PD site between cable core and sheath.
- Signals can be detected on both the core and earth screen at terminations.
Example of PD Against Phase for Power Cables

**Single Core Cable**

Available Waveform Display

**Three Core Belted Cable with HFCT on Common Screen**

Available Waveform Display
PD Pulse Propagation Analysis

Distance of PD Pulse from Machine (Metres)
Direct pulse

Reflected pulse

$\Delta T = \text{Time difference between direct and reflected pulses.}$

$L = \text{Cable Return Time for cable}$

**PD Pulse Return Speed**: $V_{PD} = \frac{\text{Cable Length}}{\text{Return Time}}$

**PD Site Location**: 

$$PD\% = \left(1 - \left(\frac{\Delta T}{L}\right)\right) \times 100$$
In many on-line cases reflected PD pulses are often not visible:

- Attenuation is too large to measure reflected pulses from the far end (long cables)
- Waveforms too difficult to interpret (noisy signals)
- Teed or jointed cables
- Cables with many ring main units or switches
- Cables with no change in impedance at the far end
- Portable Transponder installed at remote cable end
- Compensates for lack of reflected pulse
- Detects PD pulse with Discharge Trigger Unit and re-injects large pulse back into cable with Pulse Generator
- Connects to cable with HFCTs
Example of Usage

**Measurement End**

- **Portable Transponder**

**Remote End**

- **Portable Transponder**

Reflection may not be clearly visible (e.g. due to noise)

The large transponder pulse removes any confusion

\[
\Delta T = \text{Time between direct and reflected PD pulses}
\]

\[
\Delta T_{tr} = \text{Transponder time delay}
\]
On-line PD Location on Power Cables

Example Results

Reflectogram showing PD and transponder pulses

PD location map for all PD pulses in cable section under test
LOCAL PD IN MV SWITCHGEAR
Example Use of Detection and Diagnostics
Transient Earth Voltage (TEV) Theory

- PD site within switchgear: Phase–Earth discharge
- EM signals radiate from PD site and couple onto metal-clad housing
- Signals emerge on the outer surface at openings in metal housing
Example Use of Detection and Diagnostics

Transient Earth Voltage (TEV) Theory
PD IN ROTATING MACHINES
Important to identify type of PD in machine for severity:

- slot section,
- delamination,
- end windings etc.

PD Sensors

HVPD Longshot™
Diagnostic Test Unit
- Signals captured synchronously from sensors on each phase.
- Identification of Phase-Earth PD and Phase-Phase PD.
- Phase Resolved PD (PRPD) patterns indicate the defect type.
CONTINUOUS OLPD MONITORING
• Important/high-value/critical plant items
• Plant with known PD variations in time – paper cables, rotating machines, AIS/GIS.
• Plant with high PD identified in spot-tests
Continuous Monitoring
PD Rise to Failure

PD rise to failure over 100 days

PD rise to failure over 20 days
PD burns in a hot cable: electrodes expand - possible movements inside accessories lead to increased field strengths in dielectrics – PD in accessories.
Remote OLPD Monitoring of Ex/ATEX HV Motors in Hazardous Gas Zones

PD activity within the MV switchgear

PD activity within the MV motor stator slot section

Safe Environment (no restrictions apply)

Ex Environment (restrictions apply)

MV Feeder Cables
Measurement Range:
- Up to 1.0 km for PVC / PILC
- Up to 2.0 km for XLPE cables

PD activity within the MV feeder cable

PD activity in the MV motor stator end windings
Case Study 1: On-line Cable PD Mapping, Excavation and Repair on an 11 kV PILC Cable (EDF Energy, London, UK)
Case Study: On-line Cable PD Mapping, Excavation and Repair on 11 kV PILC Cable

INCREASING PD ACTIVITY

STAGE 1: On-line monitoring

ON-LINE MAPPING

OFF-LINE MAPPING

Location of discharge

Location of discharge

Primary Sub

0m

OVERLAY

DISCHARGING AREA

NO DISCHARGES FOLLOWING RE-ENERGISATION

INCREASING PD ACTIVITY
Case Study 2: OLPD Testing, Location, Monitoring with Preventative Maintenance on a 33 kV Land-Sea Offshore Wind Farm Export Cable
Case Study: Circuit Details

- 1.7 km single core XLPE land cable
- 9.6/11.5 km 3 core XLPE subsea cable
High levels of PD (of up to 10,000 pC / 10 nC) measured on **Circuit B, Phase L3**.
Case Study: PDMap© Graph Showing PD Location

Switching Substation

Joint Pit 7

Land-sea Transition Joint

Location (meters)

1,600 1,400 1,200 1,000 800 600 400 200 0
Case Study: PD Signals Before and After Joint Replacement

**BEFORE**

High PD detected on L3

Joint 7 with PD removed and replacement cable section installed

**AFTER**

Lower-level sporadic PD signals from different site after joint replacement
Case Study: Circuit B – Evidence of Surface Degradation Due to Bad Fitting Heatshrink Stress Control
CONCLUSIONS
• OLPD testing is widely adopted for testing many types of MV & HV plant.

• The technologies enable the assessment of the health of MV/HV network with minimal disruption and cost.

• Equipment is tested under both normal (and abnormal) working conditions.

• PD can be detected, located and monitored, without the need to de-energise the plant.

• OLPD testing is an essential tool for the effective implementation of condition-based management (CBM) techniques to MV and HV power networks.
End of Presentation

Thank you for your time

Q&A?
Overview of On-line and Off-line PD Test Methods
CONTENTS

• On-line & off-line testing methods
• Overview of PD sensors
• MV/HV cable AC withstand voltage commissioning testing options
• Case studies
On-line

- In-service, under normal working conditions
- Various sensor options

Off-line

- Energised with external supply
- Usually HV Coupling Capacitor sensor used
<table>
<thead>
<tr>
<th>ON-LINE</th>
<th>OFF-LINE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td><strong>Advantages</strong></td>
</tr>
<tr>
<td>No need to isolate the circuit</td>
<td>Proven technology</td>
</tr>
<tr>
<td>Circuit loaded when tested</td>
<td>Better sensitivity</td>
</tr>
<tr>
<td>Economical &amp; non-invasive</td>
<td></td>
</tr>
<tr>
<td>Teed circuits can be tested</td>
<td>Circuit not loaded during testing</td>
</tr>
<tr>
<td><strong>Drawbacks</strong></td>
<td><strong>Outage required</strong></td>
</tr>
<tr>
<td>Data interpretation can be difficult</td>
<td>Expensive &amp; time-consuming</td>
</tr>
<tr>
<td>Earthing pre-requisites</td>
<td>Teed circuits cannot be tested easily</td>
</tr>
</tbody>
</table>
ON-LINE TESTING METHODS
High Frequency Current Transformers (HFCT)
Detects PD in cables and remote plant (e.g. transformers/rotating HV machines).

High Voltage Coupling Capacitor (HVCC)
Mainly applied to the PD monitoring of rotating HV machines.

Transient Earth Voltage (TEV)
Detects local PD within plant under test.

Airborne Acoustic (AA)
Detects airborne PD signals with direct line of sight to PD source.
<table>
<thead>
<tr>
<th>Plant</th>
<th>Power Cables</th>
<th>Cable Terminations</th>
<th>Metal-clad AIS</th>
<th>HV/EHV GIS</th>
<th>Rotating Machines</th>
<th>MV Transformers</th>
<th>HV Transformers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensors</td>
<td>HFCT</td>
<td>HFCT</td>
<td>TEV</td>
<td>UHF Coupler</td>
<td>HV Capacitor</td>
<td>Contact Acoustic</td>
<td>UHF Coupler</td>
</tr>
<tr>
<td></td>
<td>TEV</td>
<td>Airborne Acoustic</td>
<td>Contact Acoustic</td>
<td>HFCT</td>
<td>HFCT</td>
<td></td>
<td>Contact Acoustic</td>
</tr>
<tr>
<td></td>
<td>Airborne Acoustic</td>
<td>UHF Coupler</td>
<td></td>
<td>Rogowski Coil</td>
<td>TEV</td>
<td></td>
<td>Bushing Tap Adapters</td>
</tr>
<tr>
<td></td>
<td>Contact Acoustic</td>
<td>HV Capacitor</td>
<td></td>
<td>RTD Sensor</td>
<td></td>
<td></td>
<td>HFCT</td>
</tr>
<tr>
<td></td>
<td>HFCT</td>
<td></td>
<td></td>
<td>VHF Probes</td>
<td></td>
<td></td>
<td>TEV</td>
</tr>
</tbody>
</table>
High Frequency Current Transformer (HFCT) Sensors

• Detect PD in cables and connected plant
• Wide bandwidth (from 100 kHz to 20 MHz)
• Attach to power cables at terminations and earthing links of HV equipment
• Installation inside or outside of cable box
• Temporary or permanent
• Cable PD is measured in terms of charge.

• It is important to measure the number of PD pulses/power cycle (i.e. the cumulative PD activity).

The PD magnitude (in pC) is the area under the PD pulse.

This can be calculated from the output voltage of the HFCT using the HFCT’s Transfer Impedance, $Z_{TR}$

$$Q_{app} = \frac{1}{Z_{TR}} \int_{pulsestart}^{pulseend} V_{out} \, dt$$
The HFCT sensor should be attached to intercept either the conductor PD current \((i^+)\) or the earth PD current \((i^-)\).
Solidly bonded - lead plumbed

Solidly bonded - No insulated gland

Shorting links

Cable Terminations Not Suitable for PD Testing due to Solid Bonding
• Short outage to attach
• Permanent installation with external connection point
• Periodic testing/monitoring without subsequent outages
Local PD Detection with TEV Sensors

- Electromagnetic radiation from PD sites
- High frequency >5 MHz
- Main application: metal-clad AIS and SIS
- Sensitive to local (nearby) PD sites
- Also used at cable terminations and transformers
- Local PD magnitude is measured in dB
Example Use of Detection and Diagnostics
Time of Flight Measurements in MV Switchgear

Matched Length Co-axial Signal Cables

Measured Signals on 4x TEVs
High Voltage Coupling Capacitor (HVCC) Sensors

- Conventional sensor for factory/lab tests
- Placed in parallel with cable/plant under test
- Requires galvanic connection to the plant under test
- Common application for rotating machines/switchgear
Higher capacitance = higher bandwidth = higher sensitivity to PD deep in machine windings

Gain Vs. Frequency Plot for HVPD Sensors

- Standard 80 pF
- HVPD 500 pF
- HVPD 1000 pF
- PD Occurrence
Acoustic Detection

- Sensitive to local PD sites
- From 10 kHz to 1.2 MHz (≈40 kHz common)
  - Airborne – line of sight
  - Corona
  - Surface discharge
- Contact
  - Vibration of equipment housing
  - Internal PD
  - Surface discharge
Useful for identifying surface discharges/corona – coincident signals in:

- Outdoor equipment
- Air-insulated switchgear
Combined Acoustic and Electromagnetic Detection Across Power Cycle

Delay due to difference between speed of light and speed of sound
OFF-LINE TESTING METHODS
• New cable systems require AC withstand acceptance tests at commissioning.

• PD testing is now included as part of the field acceptance tests for HV and EHV cables.

• Some test specifications reference acceptance criteria from conventional, laboratory PD testing (5/10 pC).

• Whilst factory PD tests are performed at power frequency, field tests are often not.

Off-line power supplies must be dimensioned for the charging current of the plant under test.

\[ I = j\omega CV \]

\( I = \)Charging current, \( \omega = \)Test Frequency, 
\( C = \)Cable Capacitance, \( V = \)Test voltage
1. VLF (Very Low Frequency) (0.01–0.1 Hz)
   example supplier: Baur (Austria), B2HV (Germany)

2. Resonant Test Systems (RTS)
   example supplier: High-Volt (Germany)

3. 24-Hour Soak Test (at $U_0$)
   No external power supply is required but extended, 24-hour PD monitoring is necessary.

4. Damped AC / Oscillating Wave (OWTS)
   example suppliers: Seitz, SEBAkmt (Germany)
Option 1: VLF (Very Low Frequency) PD + Tan Delta (TD) Testing

**Pros**
- Inexpensive, *portable* equipment
- Effective in finding water-treed cables for shorter lengths.
- Easy to perform, non-expert test
- IEEE Standard 400.2.

**Cons**
- PD at VLF not directly comparable to PD at AC power frequency.
- ‘Noisy’ test sets, filtering required.
- Concerns about trapped charges at frequencies less than 0.1 Hz.
Option 2: Variable Frequency Resonant Test System (RTS)

83 A/260 kV (1650 nF) AC Resonant Test System (for 132–220 kV cables)
Option 2: RTS (Variable Frequency Resonant Test System)

**Pros**
- Allows direct comparison of factory PD tests to the field tests.
- Provides continuous, near power frequency AC withstand voltage.

**Cons**
- Large, expensive test equipment (for HV/EHV cables) although more compact RTS technology is available for MV cables.
**Commissioning Testing (Off-Line)**

- Measure PDIV, PDEV.
- Measure PD Level & Intensity.
- Identify PD pattern.
- Identify location of PD source.

⇒ Guiding criterion is that the cable system should be **PD free** (<5 pC) at the specified test voltage (1.7U₀) for the HV cable systems.

⇒ Less then 10 pC for MV systems using conventional test systems.

**Maintenance Testing (On-Line)**

- Assess individual PD sources separately.
- Measure PD level & intensity.
- Identify the location of the PD source(s) by PD mapping.
- Assess impact of individual PD sources against cable design (i.e. insulation materials, experience, etc).

⇒ Develop individual assessment and ranking of cable joints, terminations and cable sections.
Option 3: Damped AC – OWTS (Commissioning)

Pros

- Can energise long lengths of cable with smaller power supply.
- Easy to perform, non-expert test.

Cons

- Only limited number of over voltage cycles (2–3) applied.
- Difficult to do PD reading reliably (distributed PD).
- Tan Delta / Loss factor measurements are derived, not measured.
Option 3: Damped AC - OWTS

- 50 shots of individual discharges.
- Not continuous AC.

Wide variation of test voltage parameters:

- DC charging time: 0.25–62.5 s
- DAC frequency: 38–368 Hz
- DAC damping: 3.7–20.4%

The different scales of the DC charging and the DAC oscillation create a wrong impression!
Option 4: 24-Hour Soak Test (at $U_0$)

**Pros**

- Inexpensive as they do not require an external power supply
- Energised at line voltage $U_0$ only.
- Low risk of failure during test.
- Can perform extended PD testing and monitoring over the entire 24-hour soak test.

**Cons**

- May not find incipient insulation defects at $U_0$
- Not fully diagnostic or predictive as there is no overvoltage.
CASE STUDY 1: RESONANT TEST SYSTEM (RTS) TESTING
The distance from RTS to cable under test could be tens of metres.

Exposed HV connections pickup noise and generate corona.

Length of exposed HV connections (and interference) minimised with test cable.

**PD signals were measured using:**

- HFCT sensors placed around the earth jumper cable between the cable termination and GIS housing.
- 8.3 nF coupling capacitor placed on the feeding end of the resonant test set to discriminate any noise or interference from the test set.
Case Study: Typical Test Set-Up

- 3 Phase LV Supply
- Resonant Test Set and Control
- HV
- Blocking Impedance
- Wire Loom (2m)
- Test Cable (30m) (Three in parallel)
- Single Phase GIS Cable Test Adapter (Three in parallel)
- Transformer Cable Terminations
- GIS
- Cable Under Test (Three in parallel)
- Sync Signal
- HVPD-Longshot

Diagram showing the test set-up with various components connected in a series.
Case Study: Typical Test Set-Up

- Resonant Test Set
- Blocking Impedance
- Test Cables (3 in parallel)
Case Study: Wire Loom Connection from RTS to Cable Under Test
Case Study: Wire Loom Connection from RTS to Cable Under Test
Case Study: Noise

- Noise generated by RTS frequency convertor.
- Blocking impedance helps with filtering.
- Can be gated out with dedicated channel.
- PD event recognition or high pass filters often more effective.
- PD measurements made at various voltage steps.
- Ensure cables are PD-free.

<table>
<thead>
<tr>
<th>Test Date:</th>
<th>13/05/10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Voltage (kV)</td>
<td>Current (A)</td>
</tr>
<tr>
<td>76</td>
<td>3.4</td>
</tr>
<tr>
<td>114</td>
<td>5.1</td>
</tr>
<tr>
<td>132</td>
<td>5.8</td>
</tr>
<tr>
<td>76</td>
<td>3.4</td>
</tr>
<tr>
<td>114</td>
<td>5.1</td>
</tr>
</tbody>
</table>
• PD measurements were made at 76 kV, 114 kV and during the 132 kV HVAC withstand test.

• No PD signals were detected.

• Corona interference was detected in some cases and remedial action was taken to remove this so that this did not confuse measurements.

• The background noise levels on the HFCT sensors were relatively low in all tests, allowing good sensitivities of down to 20pC to be achieved.

• Noise interference from the resonant test set was detected with two 150 μs pulses at the zero crossing points of the voltage waveform.

• The HVPD PDGold© ‘EventRecogniser’ software was able to classify and discount these signals as noise.
CASE STUDY 2: OFF-LINE PD TESTING OF 11 KV METAL-CLAD AIS SWITCHGEAR
• Off-line PD testing of the newly installed 11 kV Air-Insulated Switchgear following a failure.

• Measurements made to determine insulation was in good condition prior to putting it into service.

• Portable power supply used to energise the busbar to $1.1 U_0$ (13.2 kV).
Case Study: Off-line Test Set-up

- The off-line test equipment and HVPD Longshot™.
- Voltage was applied (as per IEC 62271-200:2012) to each individual phase in turn with other phases isolated.
• Low levels of PD with peaks up to 54 pC were detected at 1.1 $U_0$ (13.2 kV phase to ground)

• Concluded the PD was not originating in the breaker sections (Breaker open and closed). PD was isolated within the Bushing and visual inspection was recommended (dirt, moisture or signs or tracking).

• The PD levels detected were considered to be low however maximum permissible partial discharge quantity at 1.1 $U_0$ shall be ultimately agreed between the manufacturer and the end user as per IEC 62271-200:2012.
CONCLUSIONS
**On-line PD Testing**
- Provides good data.
- Quick compared to off-line PD testing.
- Test under normal working conditions.
- Allows continuous monitoring.
- Does not require any HV power supply.

**Off-line PD Testing**
- Useful for factory and commissioning tests.
- Allows easy isolation of plant under test.
- Offers better sensitivity than on-line PD testing.
- Has a longer history.
- Allows testing at elevated voltages.
End of Presentation

Thank you for your time

Q&A?
On-line PD Testing & Diagnostics for MV and HV Equipment – Case Studies
CONTENTS

• Reliability centred maintenance
• Application-specific examples of OLPD testing
• Insulation condition monitoring strategies
Reliability Centred Maintenance (RCM) Bathtub Curve

- **Infant Mortality Phase**: the initial ‘bedding in’ period
- **Steady State Failure Phase**: the ‘normal’ operating lifetime up to the ‘Design Life’ of the asset
- **End of Life ‘Wear-out’**: up to the manufacturer’s recommended replacement time of the asset
CASE STUDY 1: OLPD TESTING OF 6.6 KV DIESEL GENERATORS ON CRUISE LINER
### Case Study: League Table of OLPD Test Results

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Generator</th>
<th>PD Level 1&lt;sup&gt;st&lt;/sup&gt; Test</th>
<th>PD Level 2&lt;sup&gt;nd&lt;/sup&gt; Test</th>
<th>PD Level 3&lt;sup&gt;rd&lt;/sup&gt; Test</th>
<th>PD Level 4&lt;sup&gt;th&lt;/sup&gt; Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel 1</td>
<td>1</td>
<td>-</td>
<td>18,412</td>
<td>-</td>
<td>5,239</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>17,416</td>
<td>-</td>
<td>-</td>
<td>4,259</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>15,854</td>
<td>-</td>
<td>-</td>
<td>7,866</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>29,248</td>
<td>21,637</td>
<td>5,800</td>
<td>9,466</td>
</tr>
<tr>
<td>Vessel 2</td>
<td>1</td>
<td>2,162</td>
<td>5,891</td>
<td>7,340</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>16,696</td>
<td>2,094</td>
<td>1,474</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-</td>
<td>520</td>
<td>3,790</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>12,986</td>
<td>4,557</td>
<td>6,644</td>
<td></td>
</tr>
<tr>
<td>Vessel 3</td>
<td>1</td>
<td>1,969</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3,470</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3,833</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2,251</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>5,001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vessel 4</td>
<td>1</td>
<td>439</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>542</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1,610</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2,643</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>510</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Case Study: Visual Inspection of the Stator Windings

- White oxide deposits at the end windings of the stator: a by-product of surface discharge activity
- The problem caused by a coolant leak.
- Recommendations: clean the end windings, fix the coolant leak and re-seal access hatches.
Case Study: PD Trending Results Before and After Maintenance to Generator

- Tests performed over 12 months to trend PD data.
- Low-cost, simple maintenance performed on generators in 2008 to remove dust, dirt and oil mist observed.
- PD levels after maintenance reduced from ‘Red = Unreliable’ to ‘Green = OK’.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel 1</td>
<td>1</td>
<td>-</td>
<td>18,412 pC</td>
<td>-</td>
<td>5,239 pC</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>17,416 pC</td>
<td>-</td>
<td>-</td>
<td>4,259 pC</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>15,854 pC</td>
<td>-</td>
<td>-</td>
<td>7,866 pC</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>29,248 pC</td>
<td>21,637 pC</td>
<td>5,800 pC</td>
<td>9,466 pC</td>
</tr>
<tr>
<td>Vessel 2</td>
<td>1</td>
<td>2,162 pC</td>
<td>-</td>
<td>5,981 pC</td>
<td>7,340 pC</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>16,696 pC</td>
<td>-</td>
<td>2,094 pC</td>
<td>1,474 pC</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>520 pC</td>
<td>3,790 pC</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>12,986 pC</td>
<td>-</td>
<td>4,557 pC</td>
<td>6,644 pC</td>
</tr>
</tbody>
</table>
CASE STUDY 2: IN-SERVICE, ON-LINE PD TESTING OF 34.5/5 KV 10 MVA TRANSFORMER (U.S. VIRGIN ISLANDS)
Following a failure of a 34.5/5 kV 10 MVA transformer, it was decided to carry out OLPD testing on the ‘sister’ transformer.

Tests were carried out on-line, measurements made at both transformer and 34.5 kV Substation – takes into account possible radiation of PD signals from other items of plant (i.e. connecting cables & switchgear).
Case Study: PD Propagation from Transformer on to Network

GIS Switchgear

Power Transformer
10 MVA 34.5/4.160 kV
Case Study: Sensor Connection

Legend

- 34.5 kV Bushing
- 5 kV Bushing
- TEV PD Sensor
- HFCT PD Sensor

Substation 44 (~700 ft, 213 m)
Substation 48 (~66 ft, 20 m)

HVPD Longshot On-line PD Test Unit
Case Study: HFCT and TEV Sensor Connection on 34.5 kV Cable Cores

Sensor Connections at Substation End

Sensor Connections at Transformer
• PD activity was found on the circuit and isolated to the transformer side of the cable.

• Further tests at the transformer revealed the likely source of the PD was in the *Phase B* of the 34.5 kV cable termination, transformer bushing or end winding.

• To isolate the PD source to either the cable or transformer components, the 34.5 kV cables on phases A, B and C were disconnected from the transformer and tested under working voltage supplied from the substation.

• No PD was detected on this test and thus through process of elimination it was concluded that the PD pulses originate from the transformer.
Case Study: OLPD Test Results

![Graph showing PD and Noise data](image)

**PD Waveform**

Segment Waveform

**Noise Waveform**

Segment Waveform
Case Study: OLPD Test Results

Separated PD and Noise against Power Cycle

Waveform Measured at Transformer HFCT B Phase with HFCT on LV Neutral
Case Study: Comparison of Pulse Rise Time Distribution at Both Cable Ends

GIS Switchgear

Power Transformer
10 MVA 34.5/4.160 kV

No of pulses in Risetime range

Substation End

Transformer End
Case Study: OLPD Testing of 34.5/5 kV 10 MVA Transformer

B Phase PD Data from Online Test (Purple Colour)

PD Across 60Hz Power Cycle

PD Waveform Shape (expanded trace below)

Pulse Risetime Graph
The peak levels of PD detected were 500 pC which is a reasonably moderate level for MV cable accessories and transformer bushings.

The PD detected was not thought to be an imminent threat but should have definitely been regularly monitored/tested.

The presence of PD, even at relatively moderate levels, does make the risk of failure higher than that on a discharge free component.

Regular on-line testing and monitoring of PD activity was recommended to ensure the PD in Phase B does not escalate to an unacceptable level.
CASE STUDY 3: OLPD TESTING OF 6.6 KV MOTORS AT GAS POWER STATION (UK)
HFCT Sensors located at HV Switchboard Cable End

Rotating HV Machine End

Range:
Up to 1 km for PVC
Up to 2 km for XLPE
## Case Study: Summary of Initial OLPD Test Results

<table>
<thead>
<tr>
<th>Motor Ref</th>
<th>PD Level [pC]</th>
<th>PD Activity [nC/Cycle]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer A – Motor 1</td>
<td>12,152</td>
<td>95</td>
</tr>
<tr>
<td>Manufacturer A – Motor 2</td>
<td>3,123</td>
<td>12</td>
</tr>
<tr>
<td>Manufacturer A – Motor 3</td>
<td>3,165</td>
<td>4</td>
</tr>
<tr>
<td>Manufacturer B – Motor 1</td>
<td>52,589</td>
<td>296</td>
</tr>
<tr>
<td>Manufacturer B – Motor 2</td>
<td>33,135</td>
<td>370</td>
</tr>
<tr>
<td>Manufacturer B – Motor 3</td>
<td>68,071</td>
<td>85</td>
</tr>
</tbody>
</table>
### Case Study: Off-line PD Test Results Circulating Water Pumps

<table>
<thead>
<tr>
<th>Motor</th>
<th>U Phase</th>
<th>V Phase</th>
<th>W Phase</th>
<th>All Phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor 1</td>
<td>10,530</td>
<td>30,260</td>
<td>12,870</td>
<td>24,960</td>
</tr>
<tr>
<td>Motor 2</td>
<td>14,920</td>
<td>30,620</td>
<td>17,730</td>
<td>27,070</td>
</tr>
<tr>
<td>Motor 3</td>
<td>15,140</td>
<td>30,890</td>
<td>16,920</td>
<td>31,040</td>
</tr>
</tbody>
</table>

All off-line PD measurements showed an increasing trend from the 2010 tests to the 2011 tests with an average increase in PD levels across all 3 motors of around 100% i.e. the PD levels **had doubled over the 12 months between these tests.**
Case Study: Visual Inspection after Off-line PD Tests

Image of Neutral Terminal Box. The Glass Cover (arrowed) was removed to inspect the windings

Image of winding connections. Neutral Cables and internal connections not spaced apart (arrowed)
Case Study: Visual Inspection after Off-line PD Tests

Image of connections not adequately spaced (arrowed) = design issue

Image of coil – coil connections touching a neutral cable (arrowed) = design issue
Customer’s feedback:

‘Thanks for your support throughout the whole process, your equipment and advice has played a big role in a fairly complicated warranty claim that enabled us to successfully identify and rectify a defect, which with PD was always going to be a difficult one to secure.’
CASE STUDY 4: OLPD TESTING AND MAPPING OF 34.5 KV XLPE CABLES FOR A PROCESS INDUSTRY CLIENT (SAUDI ARABIA)
• OLPD tests on a number of cable circuits where recent cable joint failures had occurred.

• Four cable circuits that were known to have been subjected to heavy circulating currents in the earth screen & armour (in excess of 80 Amps) which had led to catastrophic in-service failures.

• The previously failed joints showed evidence of tracking.
• OLPD tests on a number of cable circuits where recent cable joint failures had occurred.

• Four cable circuits that were known to have been subjected to heavy circulating currents in the earth screen & armour (in excess of 80 Amps) which had led to catastrophic in-service failures.

• The previously failed joints showed evidence of tracking.
Severely Damaged 34.5 kV XLPE Failed Cable Joint
The 1.9 km long, 34 kV XLPE cable circuit had 5 jointed sections with only one cross-bond point.
The HVPD PDSurveyor™ was used to detect any Local PD in the cable terminations / joints and switchgear panels.
The HVPD Longshot™ unit was used to test and locate the discharging joints.
Case Study: Sensor Attachment at Seawater Pump Transformers
Case Study: Sensor Attachment at GIS Switchgear Terminations
The measured **Cable Return Time** for the pulse injected at the switchgear to travel to the far end of the seawater feeders and back was 20.4 μsec.

Given that the seawater feeder cable is 1956 metres in length, this gives a **return speed** for the 34.5 kV XLPE cable of **95.9 m/μsec**.
• PDMap© software was used to create a map of the 1956 m cable.

• The source of PD activity was located within the Red Phase cable of seawater pump Tx302 at 1770 metres out from the 34.5 kV main substation (or 185 metres out from the Seawater Pump Transformers).

• This corresponds with the location of Joint No.3 on this cable as shown below.
The cable joint was replaced, re-tested and found to be discharge-free.
CASE STUDY 5: ON-LINE PD TESTING OF 34.5 KV INDUSTRIAL CABLE NETWORK (USA)
• OLPD tests were conducted within the 34.5 kV XLPE cable terminations at the padmount transformers in follow up to recent in-service failures of cable terminations.

• 21 cable circuit terminations were tested with 42 points of attachment (POA) with the PDSurveyor™, HVPD Longshot™, and temporarily installed HFCT sensors.
Case Study: OLPD Measurement Results across Network Diagram

- Considerable cross-coupling of the PD signals at each padmount.
- PD signals propagate far into the cable network from source.
- Four sources of this type of activity located.
Case Study: Targeted Investigation Locates Probable Cause

- **Poor workmanship** was the main contributing factor to the surface PD activity detected.
- **Signs of PD activity** on the cable terminations
- The rubber stress cone termination had been completely eroded.
• Re-termination of the cables into the six ‘RED PD Level’ padmounts.
• Further OLPD tests showed no PD activity and confirmed the rework had been effective.
• The customer was advised that regular, periodic OLPD ‘screening’ tests should be carried out.
CASE STUDY 6: OLPD TESTING AND LOCATION ON OFFSHORE WIND TURBINE TO OIL & GAS PLATFORM 33 KV CABLE FEEDER
• Two deep-water wind turbines supply power exclusively to an oil production platform 2km away.

• Two on-line PD tests were performed to assess the condition of the turbine feeder cables.
Case Study: Test 1 – OLPD Test of 33 kV Switchgear on Platform
• PD on Turbine A Feeder was detected and was considered to be remote source based on pulse properties.

• Analysis predicted the location to be near the far end of the Turbine A feeder cable. Mapping recommended.
Case Study: Test 2 – PD Location at Wind Turbine 33 kV Feeder RMU
Case Study: PD Location at Wind Turbine 33 kV Feeder RMU

- High PD magnitudes in excess of 6,000 pC, with average levels of 1,871 pC detected on Yellow phase.
- Test identified the PD source was the Yφ local turbine 33 kV transformer/cable joint.
- Measurement of PD pulses on wind turbine cable feeder show clear direct & indirect reflected pulses.
- Joint location was confirmed at 52 metres from the RMU.
CONCLUSIONS
• Insulation Condition Monitoring (CM) using OLPD requires **a continuous evaluation** of the HV insulation’s dielectric integrity throughout the service life of the asset.

• **Continuous OLPD monitoring** should be carried out throughout the first 3 years of service - the ‘bedding in’ period.

• **Test and monitor after any repairs to faults** – to ensure the repair has worked!

• **Continuous OLPD monitoring is recommended throughout the service design life** (of 20–25 years+).
End of Presentation

Thank you for your time

Q&A?
Deployment of OLPD Testing in Asset Management Systems
CONTENTS

• HVPD 4-Phase approach for OLPD monitoring of MV networks
• PD trending
• Plant condition analysis
• OLPD league tables
• Examples of deployment of PD testing in asset management systems
A complete solution for the OLPD screening, diagnostic testing and extended monitoring.

Identify, locate and monitor PD activity in the ‘**Worst 5%**’ of the customer’s network.

A range of portable and permanent OLPD test and monitoring technology can be applied to achieve this.
The HVPD Integrated OLPD Test and Monitoring Solution For Medium Voltage (MV) Networks (Voltage Range: 3.3–36 kV)

**Phase 1**
- 100% of the network
- OLPD ‘Pre-screening’ with Handheld OLPD Surveying Technology
- ‘Look-see’ tests, only requiring 10–30 second test per plant item
- PDS Air™ with TEV, HFCT and Acoustic Sensors

**Phase 2**
- ~20% of the network (as identified in Phase 1)
- Diagnostic OLPD Testing & PD Site Location with Cable Mapping
- PD Testing: 5–10 minutes
- PD Mapping – 10 minutes to 1 hour
- HVPD Longshot™ 4-channel Diagnostic OLPD Spot Tester

**Phase 3**
- ~10% of MV plant (as identified in Phases 1 and 2)
- Temporary OLPD Monitoring with Portable OLPD Monitors
- Periods from 1 day up to 3 months
- HVPD Multi™ Portable & HVPD Mini™ Portable OLPD Monitors

**Phase 4**
- ~1–5% of MV Plant (as identified in Phases 1, 2 and 3)
- Continuous OLPD Monitoring with Permanent OLPD Monitors
- 3 months+
- HVPD Multi™ Permanent Monitor (16 to 96 Channels)

12 Month Iterative Process

Our Knowledge is Your Power
• Used for initial, quick screening of large numbers of MV plant items.

• The MV cable/plant can be tested in-service under normal operating conditions, no outage required!

• Easy to read, 7-level, colour-coded PD level indication panel.
PDAir™

On-site OLPD Screening
Why Use the PDS Air™

- Combines HFCT, TEV and AA sensors to enable OLPD testing of both cables and switchgear.
- A look-see OLPD scan, indicating the plant which requires further diagnostic testing.
- Low cost, lightweight & portable, easy to use.
- Test the insulation condition of the plant in seconds.
• LED 1 – Green (Plant OK)

• LED 2 & 3 – Yellow (Moderate PD – Monitor)

• LED 4 & 5 – Orange (Moderate To High PD – Investigate Source Of PD)

• LED 6 & 7 – RED (High PD – Test & Restrict Access)

NB: It should be noted that the PD levels & actions recommended are guideline levels only and are based on HVPD’s experience in testing MV Plant
Example Use of Detection and Diagnostics

MV Switchgear with TEV

Very High Level Local PD Activity >48 dB (Panel 006)
Further Investigation Recommended
- 4-Channel, synchronous OLPD test unit
- Captures PD activity using very high speed data acquisition capability (100–500 MS/s)
- Diagnostic PDGold© v7 software with unique ‘Event Recogniser©’ software modules differentiates between PD activity and any electrical noise and RF interference.
- An automatic, detailed analysis of pulse frequency, waveshape and other signal waveform characteristics.
HVPD Longshot™
On-line PD Testing of an 11kV Motor
• Impulsive events **extracted** and **categorised by software** as cable PD, local PD and noise.

• Even amongst noise interference, **PD data can still be extracted**.
24/7 diagnostic portable OLPD monitoring technology for MV and HV Plant

- Measures, analyses and logs Cable PD, Local PD and Noise
- 'Knowledge-Rule' based PD criticality measurement (0–100)
- Remote access connection via LAN/Modem
- 16-Channel (HFCT/TEV/HVCC) with optional add-on 32x channel AA sensor modules
- Criticality league table
- Highlights most critical circuits
- Updated every 24 hours
- Link to data graphs
- Criticality algorithm, specific to plant

### Cable PD
- Peak Level = 1549pC
- PD Activity = 20,000pC/cycle

### Local PD
- Peak Level = 25dB
- PD Activity = 100mV/cycle
- Criticality league table
- Highlights most critical circuits
- Updated every 24 hours
- Link to data graphs
- Criticality algorithm, specific to plant

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Sensor</th>
<th>PD Peak (pC)</th>
<th>PD Activity (pC/cycle)</th>
<th>Criticality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Police Dog Training</td>
<td>HFCT</td>
<td>2671</td>
<td>4523</td>
<td></td>
</tr>
<tr>
<td>Haggs Rd Local No 1 Transformer</td>
<td>HFCT</td>
<td>5375</td>
<td>9119</td>
<td></td>
</tr>
<tr>
<td>Shawhom Crescent</td>
<td>HFCT</td>
<td>2546</td>
<td>2647</td>
<td></td>
</tr>
<tr>
<td>Pollockshaws commercial centre</td>
<td>HFCT</td>
<td>1994</td>
<td>4924</td>
<td></td>
</tr>
<tr>
<td>Rossendale Rd South</td>
<td>HFCT</td>
<td>1977</td>
<td>11990</td>
<td></td>
</tr>
<tr>
<td>Green Park</td>
<td>HFCT</td>
<td>2286</td>
<td>3873</td>
<td></td>
</tr>
<tr>
<td>145 Shawhill Rd tee Shawhill Rd</td>
<td>HFCT</td>
<td>2837</td>
<td>5202</td>
<td></td>
</tr>
<tr>
<td>Craigholme School</td>
<td>HFCT</td>
<td>2046</td>
<td>2120</td>
<td></td>
</tr>
<tr>
<td>Haggs Rd Local No 2 Transformer</td>
<td>HFCT</td>
<td>4200</td>
<td>4333</td>
<td></td>
</tr>
<tr>
<td>Millwood Street</td>
<td>HFCT</td>
<td>4898</td>
<td>4898</td>
<td></td>
</tr>
<tr>
<td>Shawmoss Rd</td>
<td>HFCT</td>
<td>697.4</td>
<td>922.9</td>
<td></td>
</tr>
<tr>
<td>Wellgreen Court</td>
<td>HFCT</td>
<td>1094</td>
<td>1285</td>
<td></td>
</tr>
<tr>
<td>Shawbridge Street South</td>
<td>HFCT</td>
<td>740.6</td>
<td>858.1</td>
<td></td>
</tr>
<tr>
<td>Shawbridge Street</td>
<td>HFCT</td>
<td>1338</td>
<td>1455</td>
<td></td>
</tr>
<tr>
<td>Rossendale Rd</td>
<td>HFCT</td>
<td>491</td>
<td>688.1</td>
<td></td>
</tr>
</tbody>
</table>

- Small PD-activity
- Moderate PD-activity
- Intensive PD-activity
- Critical PD-activity
Phase 3 – Temporary Monitoring HVPD Mini™ Portable 4-Channel OLPD Monitor

- Low-cost 24/7 PD monitoring technology for MV cables, switchgear & other plant
- Incorporates up to 4x portable PD sensors
- Measures and logs both cable PD and local PD (PD magnitude & ‘count’ – no. of pulses)
- Stores up to 12 months of data on local flash memory
- Uploads PD data to server every 24 hours via GSM/GPRS Modem
- Compact, lightweight and easy to set up unit for portable installations
HVPD Mini™ Monitor
Distributed TEV Sensors
• Provides an early warning against incipient faults to be indicated through changes in PD activity over time.

• PD activity can vary in relation to load, local temperature and humidity.

• Distributed temperature and humidity modules monitor these variations in the substation.
Range of Detection for Primary PD Monitor:
either up to 2.5 km or up to 3x Ring Main Units

Extended range from HVPD Mini™:
either 2 km or 2 RMU’s
Precedence Detection using the HVPD Mini™ OLPD Monitor
Phase 4 – Permanent Monitoring - HVPD Multi™ Permanent
16-Channel OLPD Monitor

- 24/7 monitoring of PD in switchgear, cables and rotating HV machines
- Non-intrusive, inductive sensors
- Remotely accessible with GPRS/3G modem
- Onboard automatic analysis software provides differentiation of all PD pulses from noise
- Can monitor up to 4x rotating HV machines
HVPD Multi™ Permanent Monitor
• The HVPD-Multi™ Monitor does not provide automated alarms but provide ‘flags’ for further engineer investigation.
• These ‘flags’ can signal an increase in either PD level or PD activity but can also be caused as a result of network switching.
• Each ‘flag’ is investigated by HVPD engineers before a diagnostic decision is made regarding preventative maintenance interventions.
HVPD Multi™ Monitor
30-day monitoring training period

INSTALLATION
DATA ANALYSIS
ADJUSTMENT

DAY 1
DAILY DATA ANALYSIS
DAY 30
Phase 3 – Remote Access

User Desktop PC with LPD Connect Software and Web Browser
Outbound traffic on port 22 allowed by firewall

LAN or 3G/GPRS
EXAMPLE OF HV NETWORK OLPD MONITORING SYSTEM USER INTERFACE BASED ON THE CLIENT’S HV NETWORK SINGLE-LINE DIAGRAM (SLD)
Complete Network Monitoring Database Interface

Presents data hierarchically using a 3-level interface:

- 1st level: all sites/vessels
- 2nd level: one site/vessel (entire SLD)
- 3rd level: one switchroom
Complete Network Monitoring Database Interface

HVPD OLPD Monitoring Database © 2014 – HV Switchboard Monitor

Analysis / Reports

Substation : HV SWBD 1

Local Area Network Criticality
League Table

Locations

Criticality (0-100)

Cable

Local

THRUSTER 1 HV PANEL

75 - 99

GENERATOR 1

51 - 75

HV SWBD 3 BUS TIE PANEL

41 - 60

TOPSIDE HV Tx 1 (HPU & LV)

31 - 40

GENERATOR 2

21 - 30

HV SWBD 3 FEEDER

10 - 20

EMCY HV SWBD INCOMER 1

0 - 10

THRUSTER 1 TR

20 - 30

Condition/Action
Guideline

Criticality (0-100)

High PD / Diagnostic

75 - 100

Moderate to High PD / Investigate

51 - 75

Moderate PD / Monitor

26 - 50

Plant OK / No Action

0 - 25

Key

Cable / Machine PD Activity

Local PD Activity

Monitoring Period

Last Hour

Last 24 Hours

Last Week

Last Month

Network Options

View Level

GEO : Overview

SLD : Overview

Substation : HV SWBD 1

Location : select

Overview Substations

Distribution Network

33 kV O&D Turbine Array

11 kV O&D Drilling Vessel

10 kV O&D Network

Sensor Configuration

Manual Configuration

PD Measurements

© Copyright High Voltage Partial Discharge Ltd.
EXAMPLES OF DEPLOYMENT OF PD TESTING IN ASSET MANAGEMENT SYSTEMS
CASE STUDY 2: OLPD TEST AND MONITORING PROJECT ON 11 KV AND 33 KV ‘WORST PERFORMING CIRCUITS’
• ‘Worst Performing Circuits List’ focuses on replacing cable sections with the highest number of faults.

• Due to budget, it is only possible to replace a small percentage of circuits a year.

• Limited monitoring budgets need to be used on circuits with the highest risk of failure.
Case Study: Average Number of Faults per 100 km per Annum

- Network A 11 kV: 6.91 faults per 100 km per annum
- Network B 11 kV: 13.66 faults per 100 km per annum
- Network A & Network B 33 kV: 11.5 faults per 100 km per annum


<table>
<thead>
<tr>
<th>No. of Circuits</th>
<th>Total Length</th>
<th>Average Circuit Length</th>
<th>Average faults per annum (Av. 5 years 2004 to 2008)</th>
<th>Faults per 100 km p.a.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network B - 86</td>
<td>530 km</td>
<td>6.160 km</td>
<td>72.4</td>
<td>13.66</td>
</tr>
<tr>
<td>Network A -122</td>
<td>970 km</td>
<td>7.950 km</td>
<td>67.0</td>
<td>6.91</td>
</tr>
<tr>
<td><strong>Total - 208</strong></td>
<td><strong>1500 km</strong></td>
<td><strong>7.210 km</strong></td>
<td><strong>139.4</strong></td>
<td><strong>9.30</strong></td>
</tr>
</tbody>
</table>

### Summary Data of 33 kV Worst Performing Circuits in Networks A & B (2002-2008)

<table>
<thead>
<tr>
<th>No. of Circuits</th>
<th>Total Length (est.)</th>
<th>Average Circuit Length (est.)</th>
<th>Average faults per annum (Av. 7 years 2002 to 2008)</th>
<th>Faults per 100 km p.a.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network B– 51</td>
<td>357 km</td>
<td>7.000 km</td>
<td>42.1</td>
<td>11.80</td>
</tr>
<tr>
<td>Network A – 62</td>
<td>434 km</td>
<td>7.000 km</td>
<td>48.6</td>
<td>11.19</td>
</tr>
<tr>
<td><strong>Total – 113</strong></td>
<td><strong>791 km</strong></td>
<td><strong>7.000 km</strong></td>
<td><strong>90.7</strong></td>
<td><strong>11.47</strong></td>
</tr>
</tbody>
</table>
The suitability of cable terminations for the attachment of the HFCT sensors is the main restriction on the widespread application of the OLPD technology.

- Only around 40% of the terminations on the customer’s networks can be considered as ‘suitable’.

- For future testing, it has been suggested that the customer modify solidly bonded terminations.
• OLPD tests were carried out at substations with worst historical failure rates.

• HVPD Mini™ Portable was installed at a number of substations.

• The spot testing was carried out using HVPD’s OLPD test technology.
10% of all of 39x 33kV cable circuits tested are in the **Red Condition Category**.

<table>
<thead>
<tr>
<th>No. of Circuits</th>
<th>Condition</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>Discharge within acceptable limits</td>
<td>66</td>
</tr>
<tr>
<td>7</td>
<td>Some concern, monitoring recommended</td>
<td>18</td>
</tr>
<tr>
<td>2</td>
<td>Some concern, regular monitoring recommended</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Major concern, locate PD and then repair or replace</td>
<td>10</td>
</tr>
</tbody>
</table>

4% of all 25x 11kV circuits tested in this project are in the **Red Condition Category**.

<table>
<thead>
<tr>
<th>No. of Circuits</th>
<th>Condition</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>Discharge within acceptable limits</td>
<td>72</td>
</tr>
<tr>
<td>4</td>
<td>Some concern, monitoring recommended</td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td>Some concern, regular monitoring recommended</td>
<td>8</td>
</tr>
<tr>
<td>1</td>
<td>Major concern, locate PD and then repair or replace</td>
<td>4</td>
</tr>
</tbody>
</table>
# Case Study: Worst Performing Circuits

## Test Results: 11kV and 33kV Combined ‘OLPD League Table’ – ‘Top 20’

<table>
<thead>
<tr>
<th>Criticality Number</th>
<th>Circuit</th>
<th>Comments</th>
<th>Peak PD Value</th>
<th>Cumulative PD Level</th>
<th>OLPD Criticality (%)</th>
<th>Maintenance Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Circuit 18</td>
<td>Large PD on this circuit</td>
<td>3600pC</td>
<td>195 nC/Cycle</td>
<td>83.2</td>
<td>Major concern, locate PD and then repair or replace.</td>
</tr>
<tr>
<td>2.</td>
<td>Circuit 62</td>
<td>Large cable PD</td>
<td>4000pC</td>
<td>62nC/Cycle</td>
<td>79.7</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Circuit 28</td>
<td>No cable PD</td>
<td>36dB</td>
<td>1.1 V/Cycle</td>
<td>78.3</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Circuit 26</td>
<td>No cable PD</td>
<td>35dB</td>
<td>1.4 V/Cycle</td>
<td>76.4</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Circuit 14</td>
<td>Some outdoor PD</td>
<td>25dB Local PD</td>
<td>24.6 V/Cycle</td>
<td><em>Outdoor Survey</em></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Circuit 32</td>
<td>No Cable PD</td>
<td>34dB</td>
<td>1.0 V/Cycle</td>
<td>73.3</td>
<td>Some concern, repeat test and regular monitoring recommended.</td>
</tr>
<tr>
<td>7.</td>
<td>Circuit 50</td>
<td>Cable box PD &amp; TEV levels at 35dB</td>
<td>1600pC &amp; 35dB</td>
<td>4.2 nC/Cycle 0.7 V/Cycle</td>
<td>70.1</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>Circuit 63</td>
<td>Cable PD &amp; Cable Box, 30dB</td>
<td>1200pC 30dB Cable Box</td>
<td>&lt;10 nC/Cycle 1.5 V/Cycle</td>
<td>62.2</td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>Circuit 36</td>
<td>No Cable PD</td>
<td>27dB</td>
<td>1.6 V/Cycle</td>
<td>57.7</td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>Circuit 21</td>
<td>Large PD on this circuit</td>
<td>3800pC</td>
<td>21 nC/Cycle</td>
<td>56.3</td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>Circuit 61</td>
<td>Low-Medium Level Cable PD</td>
<td>1600pC</td>
<td>52nC/cycle</td>
<td>55.8</td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td>Circuit 40</td>
<td>Medium-High Cable PD</td>
<td>4000pC</td>
<td>&lt;10 nC/Cycle</td>
<td>55.5</td>
<td></td>
</tr>
<tr>
<td>13.</td>
<td>Circuit 37</td>
<td>No Cable PD</td>
<td>23dB</td>
<td>1.1 V/Cycle</td>
<td>46.6</td>
<td></td>
</tr>
<tr>
<td>14.</td>
<td>Circuit 31</td>
<td>No Cable PD</td>
<td>25dB</td>
<td>0.6 V/Cycle</td>
<td>45.7</td>
<td></td>
</tr>
<tr>
<td>15.</td>
<td>Circuit 46</td>
<td>Medium Cable PD</td>
<td>2500pC</td>
<td>&lt;10 nC/Cycle</td>
<td>38.2</td>
<td></td>
</tr>
<tr>
<td>16.</td>
<td>Circuit 27</td>
<td>No cable PD</td>
<td>20dB</td>
<td>0.8 V/Cycle</td>
<td>37.4</td>
<td></td>
</tr>
<tr>
<td>17.</td>
<td>Circuit 43</td>
<td>Medium-High Cable PD</td>
<td>3500pC</td>
<td>&lt;10 nC/Cycle</td>
<td>37.1</td>
<td></td>
</tr>
<tr>
<td>19.</td>
<td>Circuit 11</td>
<td>PD on circuit, no location</td>
<td>1000pC</td>
<td>40.4 nC/Cycle</td>
<td>28.0</td>
<td></td>
</tr>
<tr>
<td>20.</td>
<td>Circuit 23</td>
<td>Red phase is the source</td>
<td>1400pC</td>
<td>&lt;10 nC/Cycle</td>
<td>25.2</td>
<td></td>
</tr>
</tbody>
</table>
• Continuous OLPD monitoring of the medium and high PD sites (the highest risk of failure).

• Retesting of all of the ‘TOP 20’ circuits within the next 3-6 months.

• Deploy monitoring units at the worst performing substations over an initial 3-month monitoring period.

• For the 44x circuits which have lower, a repeat ‘spot’ test within 12 months would be prudent.

• A larger survey of a minimum 100x 11 kV and 100x 33 kV feeders should be carried out to provide a more statistically valid data set.
CASE STUDY 3: OLPD TESTING AND CABLE MAPPING OF 33 KV XLPE CABLES IN THE DUBAI METRO NETWORK
• OLPD testing was carried out in response to a number recent faults* of 33 kV cable joints within the customer’s network.

• The faults led to disruption of the power supply to the Metropolitan rail system.

• The purpose of the testing was to measure and locate any PD activity within the cables with particular focus on the cable joints.

* It should be noted that this was a newly installed cable system that had been in-service for just over 12 months before the faults started to occur.
On-line Cable PD Mapping using the HVPD Longshot™ test unit and Portable transponder.

Tests started with calibration testing with pulse injection HFCTs.
• Cable PD signals have been detected on Blue Phase with cross-talk (lower magnitude) on Red and Yellow phases.

• The source of PD was located to Joint Number 2 (Jt2) using the on-line PD mapping technique.

• The faulty joint on this cable was replaced and re-tested using the HVPD Longshot™ test unit to verify the repair was good.
Case Study: Test Results

<table>
<thead>
<tr>
<th>Yellow Phase HFCT</th>
<th>Red Phase HFCT</th>
<th>Blue Phase HFCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable PD</td>
<td>Cable PD</td>
<td>Cable PD</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phase of Power Cycle (deg)</th>
<th>PD Magnitude (pC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td>30</td>
<td>6</td>
</tr>
<tr>
<td>40</td>
<td>8</td>
</tr>
<tr>
<td>50</td>
<td>10</td>
</tr>
</tbody>
</table>

Synchronous Measurements

<table>
<thead>
<tr>
<th>Cable PD</th>
<th>Cable PD Segment Waveform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time usSec</td>
<td>Voltage (mV)</td>
</tr>
<tr>
<td>0</td>
<td>-5</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
</tr>
<tr>
<td>7</td>
<td>30</td>
</tr>
<tr>
<td>8</td>
<td>35</td>
</tr>
<tr>
<td>9</td>
<td>40</td>
</tr>
</tbody>
</table>

PD Site Location (PDMap)

<table>
<thead>
<tr>
<th>PD Map of Circuit</th>
<th>Joints</th>
</tr>
</thead>
<tbody>
<tr>
<td>QP1 to QS1 C2</td>
<td></td>
</tr>
<tr>
<td>Jt 1</td>
<td></td>
</tr>
</tbody>
</table>

PD located to joints on Red Phase
Out of the 50+ circuits tested, Major PD was detected within cable accessories on the three of the circuits (6%) as shown in RED in the Table below.

The levels of discharges detected put these 33 kV cables into RED category, “Major concern, locate PD and then repair or replace”.

### Case Study: Top 20 ‘Worst Performing Circuits’

<table>
<thead>
<tr>
<th>Criticality Number</th>
<th>Circuit</th>
<th>Comments</th>
<th>Peak Cable PD Level (pC)</th>
<th>Local PD Level (dB)</th>
<th>Cumulative Cable PD Level (nC/cycle)</th>
<th>OLPD Criticality (%)</th>
<th>Maintenance Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>DUB to MPS1 C2</td>
<td>B Phase</td>
<td>25888</td>
<td>&lt;10</td>
<td>247</td>
<td>97.4</td>
<td>Major concern, locate PD and then repair or replace.</td>
</tr>
<tr>
<td>2.</td>
<td>ABS to AH C2</td>
<td>B / Y Phase</td>
<td>9729</td>
<td>&lt;10</td>
<td>120</td>
<td>90.3</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>BUR to HCC C2</td>
<td>B / Y Phase</td>
<td>3781</td>
<td>&lt;10</td>
<td>12.3</td>
<td>78.7</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>BUR to HCC C1</td>
<td>B / Y Phase</td>
<td>3245</td>
<td>&lt;10</td>
<td>7.9</td>
<td>78.1</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>ABS to AH C1</td>
<td>B / Y Phase</td>
<td>2920</td>
<td>&lt;10</td>
<td>14.4</td>
<td>77.4</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>NHD to QYD C2</td>
<td>R Phase</td>
<td>2849</td>
<td>&lt;10</td>
<td>15.0</td>
<td>76.2</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>ALQ to AHS C2</td>
<td>B Phase</td>
<td>1733</td>
<td>&lt;10</td>
<td>4.6</td>
<td>70.6</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>MPS3 to BNS C2</td>
<td>R / B Phase</td>
<td>1337</td>
<td>&lt;10</td>
<td>6.4</td>
<td>65.5</td>
<td>Some concern, repeat test and regular monitoring recommended.</td>
</tr>
<tr>
<td>9.</td>
<td>NHD to QYD C1</td>
<td>R Phase</td>
<td>887</td>
<td>&lt;10</td>
<td>8.8</td>
<td>47.8</td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>HCC to CRK C1</td>
<td>Y / B Phase</td>
<td>759</td>
<td>&lt;10</td>
<td>2.5</td>
<td>39.2</td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>AHS to SLD</td>
<td>Y / R Phase</td>
<td>705</td>
<td>&lt;10</td>
<td>3.1</td>
<td>38.5</td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td>STD to ABH</td>
<td>Y Phase</td>
<td>238</td>
<td>&lt;10</td>
<td>1.0</td>
<td>24.1</td>
<td></td>
</tr>
<tr>
<td>13.</td>
<td>ALR to BNS C1</td>
<td>B Phase</td>
<td>184</td>
<td>&lt;10</td>
<td>0.9</td>
<td>18.6</td>
<td>Re-test in 12 months.</td>
</tr>
<tr>
<td>14.</td>
<td>ALR to BRJ</td>
<td>No PD detected</td>
<td>0</td>
<td>&lt;10</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>15.</td>
<td>ALG to PMD</td>
<td>No PD detected</td>
<td>0</td>
<td>&lt;10</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>16.</td>
<td>ALG to KBW</td>
<td>No PD detected</td>
<td>0</td>
<td>&lt;10</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>17.</td>
<td>AQD to AQ2</td>
<td>No PD detected</td>
<td>0</td>
<td>&lt;10</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>18.</td>
<td>JDD to CRK</td>
<td>No PD detected</td>
<td>0</td>
<td>&lt;10</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>19.</td>
<td>ODM to JDF C1</td>
<td>No PD detected</td>
<td>0</td>
<td>&lt;10</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>20.</td>
<td>ODM to JDF C2</td>
<td>No PD detected</td>
<td>0</td>
<td>&lt;10</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Conclusions

• A combination of both on-line and off-line partial discharge testing and OLPD monitoring systems for in-service plant helps produce 'risk-of-failure' indices that support condition-based asset management decisions.

• By replacing or repairing cables or plant that has high levels of OLPD activity (and therefore a higher risk of failure) the MV and HV plant owner can target their maintenance budgets to those assets in most need whilst simultaneously reducing the risk of HV insulation faults on their network.

• With the advent of recent developments in wideband OLPD monitoring, such as with the HVPD Complete HV Network Monitoring Solution, the entire installed HV network, including switchgear, cables and remotely connected HV plant can be assessed under normal working conditions, without the need for an outage.

• Real-time condition monitoring (CM) such as this, combined with a proactive, preventative maintenance intervention strategy can help reduce the risk of unplanned outages caused by HV insulation failure.
End of Presentation

Thank you for your time

Q&A?