On-Line and Off-line PD monitoring: The Experiences in testing MV and HV apparatus from an Industrial Point of View

Lee Renforth, Riccardo Giussani, Malcolm Seltzer-Grant, Marco Marcarelli and Marc Foxall
HVPD Ltd.
Contact author: riccardo.giussani@hvpd.co.uk

***Abstract*— In recent years, an increasing demand for partial discharge (PD) testing on medium and high voltages apparatus has been observed. This includes cables, switchgear, transformers and rotating machines, both with on-line (in-service) and off-line (out-of-service) testing/monitoring practices to increase reliability and reduce financial losses due to plant downtime, unplanned outages and expensive maintenance regimes.**

This paper firstly presents an up-to-date overview of the on-line and off-line PD techniques used in the modern industries and how these techniques can be used to test for PD on the MV and HV assets.

In the second part of the paper, several case studies are reported to highlight differences, advantages and disadvantages of the two different PD monitoring approaches (on-line vs off-line). Finally, recommendations are made for how more effective condition monitoring (CM) of MV and HV networks can be achieved by focusing on the 'Worst 5%' of assets in a network based on the on-line PD testing and monitoring data.

***Index Terms*— On-line PD test, condition monitoring, VLF PD test, RTS PD test, OWTS PD test, PD monitoring**

I. List of Abbreviations and Acronyms

50/60Hz	50/60 Hz PD test
AAS	acoustic airborne sensor
AV	Alternate voltage
CAS	contact acoustic sensor
CBM	condition base maintenance
CM	condition monitoring
DC	direct current
DGA	dissolved gas analysis
HV DC	high voltage direct current
GIS	gas insulated switchgear
HFCT	high frequency current transformer
HV	high voltage
HVCC	high voltage coupling capacitor
MV	medium voltage
O&M	operation and maintenance
OLPD	on-line PD testing
OWTS	oscillating wave test system
pC	picocoulomb
PD	partial discharge
PRPD	phase resolved PD plot
RCM	reliability centered maintenance
RTD	resistance temperature detector
RTS	resonant test set
TBM	time base maintenance
TDR	time domain reflectometry
TEV	transient earth volt
UHV	ultra high frequency
VHF	very high frequency
VLF	very low frequency
XLPE	cross-linked polyethylene

II. Introduction

PD measurements are diagnostic tests that could be performed on virtually all the electrical assets (such as cables, generators, motors, transformers, switchgear, etc.) in order to assess the health status of the assets' insulation. These measurements detect the presence of localised points of degradation, which can do lead to tracking in the insulation system throughout the asset's service life.

Through the reliability centered maintenance (RCM) theory we can identify 3 main phases of the life of any equipment. Plotting the failure rate of an asset against time on a graph produces the classic "bathtub curve" [1], [2], see Figure 1 below.

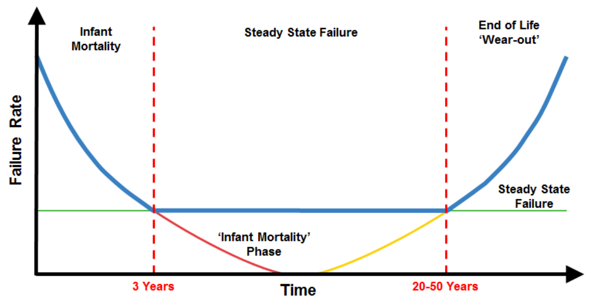


Figure 1 The "bathtub curve" base of the RCM [3].

Good equipment maintenance consisting of nursing the equipment through the "bedding in" phase and then overhauling (or replacing) it before it reaches the wear-out phase. An extended and more conscious maintenance strategy could be focusing on extending the life of the equipment.

This is accomplished by monitoring and detecting degrading conditions in each phase of the bathtub curve:

- Bedding in phase: good quality control could reduce the failures related to the defects introduced during the manufacturing process of the assets.
- Steady State phase: commissioning/acceptance tests could reduce the failures related to the defects introduced during the transportation/installation of the assets.
- End of life phase: spot testing/continuous monitoring could reduce the unplanned fault related to the degradation of the insulation itself. Diagnosing any incipient faults and coordinating and directing repair actions could extend the life of the assets.

This theory can also be visually reassumed by Figure 2 below.

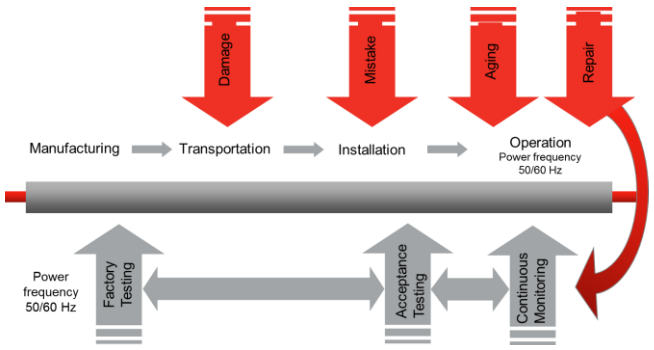


Figure 2 PD Testing and Monitoring Philosophy.

III. Up-to-date Overview of On-line and Off-line PD Measurement Techniques

PD measurements are mainly divided into two categories: off-line and on-line. The advantages and disadvantages of these two kinds of measurement are summarised in Table 1 below.

Table 1 Comparison of On-Line and Off-line PD testing.

ON-LINE	OFF-LINE
Advantages	**Advantages**
No need to isolate the circuit	Proven technology
Circuit loaded when tested	Better sensitivity
Economical & non-invasive	**Drawbacks**
Teed circuits can be tested	Circuit not loaded during testing
Drawbacks	Outage required
Data interpretation can be difficult	Expensive & time-consuming
Earthing pre-requisites	Teed circuits cannot be tested easily

PD measurements can be performed at different stage of the life of the assets:

- Factory testing
- Acceptance testing (installation and commissioning)
- On-line/Off-line spot-testing
- On-line permanent monitoring

Whilst factory PD tests are usually performed at power frequency, acceptance/field tests are often not. This is due to the large power absorption of large assets like: long cables and transformers. The power source required for the energisation of such assets is often difficult or even impossible to be transported to the field.

Different type of tests could be chosen for different assets, see Table 2 and Table 3 below.

Table 2 Off-line PD test techniques and applications.

Off-Line test	Rotating Machines	Cables	Switchgear	GIS	Transformers
50-60 Hz	x	x	x	x	x
VLF	x	x			
RTS	x	x	x	x	x
OWTS	x	x			

Table 3 PD sensors and applications.

	Rotating Machines	Cables	Switchgear	GIS	Transformer
HFCT	x^1	x	x	x^2	x^1
HVCC	x				
AAS and CAS			x	x	x
UHF coupler				x	x
TEV		x^2	x		x
Rogowski Coil	x				
RTD sensor	x				
VHF probe	x				

1) Limited to machines feed by cables.
2) Limited by the configuration of the cable termination.

A. Principles of Electrical Discharge Detection

Partial discharge (PD) is a form of non-disruptive electrical discharges which exist within the dielectrics of high voltage system (HVS) which manifest itself in the surrounding medium in several forms. Consequently there are several techniques to detect PD [4] This paper will concentrate on 'Electrical discharge detection'.

Figure 3 below shows the principle of this measurement. The details of this technique can be found in the IEC 60270 which describes how to test PD in *"electrical apparatus, component or system when tested with alternating voltages up to 400 Hz or with direct voltage."* [5].

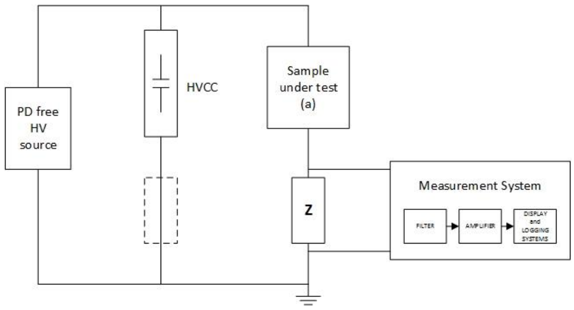


Figure 3 Basic diagram for electrical discharge detection [6]. In figure are clearly visible the HV PD-free source, the HV coupling capacitor, the sample under test (a) and the detection impedance Z; on the figure the alternative location for the Z is indicated with dashed lines.

Referring to Figure 3 the sample under test (a) is energised at the required test voltage by a PD-free generator. PD pulses (if present) will travel across the measuring impedance Z where the measuring system detects the PD pulses as voltages.

B. 50-60 Hz AC PD testing

This test is probably the most dated and it is based on the principle shown in Figure 3. The test is performed energising the sample with a 50-60 Hz HV source.

Typically the results of the PD test are reported using the PRPD plot. This way of representing the acquired PD data can be seen in Figure 4.

C. Very Low Frequency (VLF) PD

The 50-60 Hz PD test set-up is a proven and renowned method, however it presents some limitations when the test object has an high capacitive load (e.g. cables) this is mainly due to the onerous power consumption that consequently influence the dimension and weight (hence costs) of the 50-60 Hz power supply that would be required.

To overcome this limitation PD testing in cables was firstly performed with DC power (no reactive power required), however research showed that the results were not representative of the real PD activity in the cables and furthermore the DC PD testing was harmful to the insulation of the modern cables (XLPE) [8].

As a solution VLF HV source for PD testing has been developed. [9], [10] report that the VLF method produce PD test results that are comparable to the 50-60 Hz PD test while requiring power consumption that are of the order of one hundred times smaller than the power required by the comparable 50-60 Hz PD test kit [11]. This allows to easy testing even in-field on long cables and big rotating machines.

Figure 5 shows the VLF source as described in [12] and for further information on VLF testing for cables the authors suggest to consult the "IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency" [13].

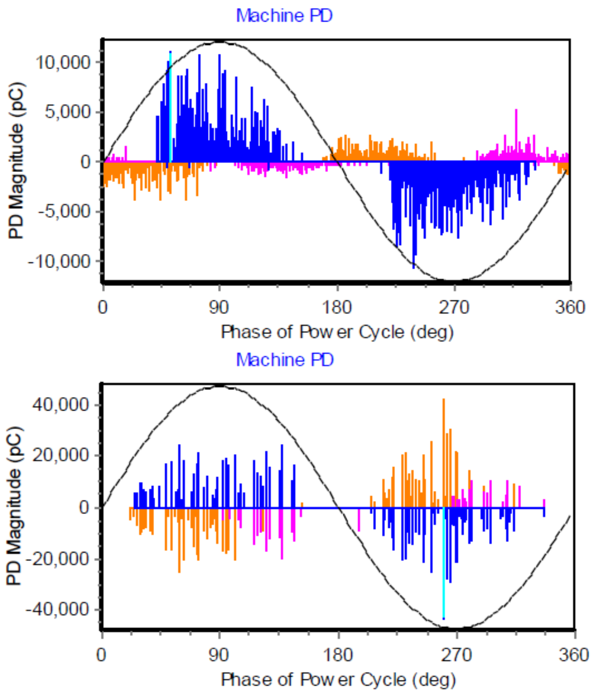


Figure 4 PRPD plots from PD measurements of rotating machines (motors). The figure on the top shows the Phase-to-Earth PD activity while the bottom one reports the Phase-to-Phase PD activity [7].

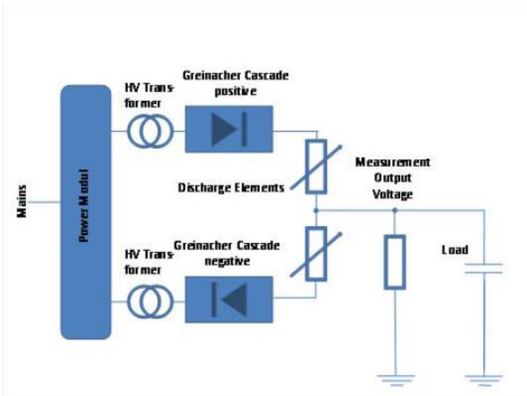


Figure 5 VLF voltage generation by controlled DC charging and discharging circuit [12].

D. Resonant Test Set for PD test

The resonant test set (RTS) is another method to test PD based on continuous alternating voltage (AV); the system is basically composed of a frequency converter usually providing a frequency output between 10-400 Hz placed before an LV/HV transformer to energise the test object. Figure 6 shows the diagram of a RTS test and Figure 7 shows how several RTS sets are used to energise and test a very long cable (400 kV, 16 km long).

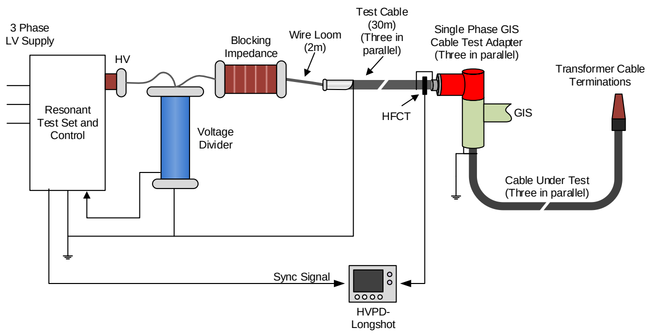


Figure 6 RTS test diagram.

Figure 7 RTS to test a 400 kV line, 16 km long.

E. On-Line PD testing and monitoring

On-line PD (OLPD) testing and monitoring is the most powerful tool to prevent unexpected/unplanned failure/outage and enable to manage the asset from the perspective of a condition based maintenance (CBM), minimising cost and the unreliability of the MV and HV systems.

The main advantages of the OLPD are that it is possible to test the assets under its normal operating conditions without requiring an outage and to be able to detect intermittent PD activity (in the case where the PD activity is strongly related to the work-cycle of the asset or to a cyclic environmental factor).

Several monitoring techniques are available for OLPD monitoring however HVPD suggest the installation of permanent sensors, the selection of the adequate sensors can be aided through the use of Table 3.

F. OWTS for PD Cables Testing

The oscillating wave test system (OWTS) is another system that allows off-line PD testing of cables with a low input power requirement. The overview of the system can be seen in Figure 8. The system is based on an HV DC source that charges in a few seconds the cable. When the voltage reaches the test's ignition voltage the system discharges and the cable produces an oscillating voltage.

The OWTS' main advantage is its low power consumption that is reflected by a small and light test set.

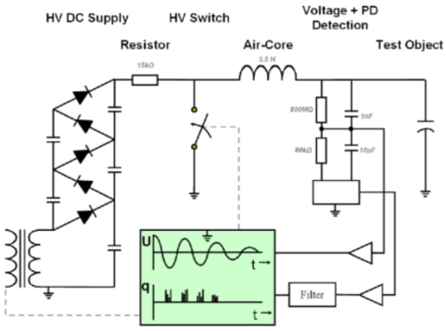


Figure 8 OWTS schematic [14].

G. Time Domain Reflectometry (TDR) for cables mapping

The time domain reflectometry (TDR) is a technique that allows location of a PD source in cables.

PD location technique is extremely important especially for the maintenance and repairing of buried cables. A precise location of the fault enables asset managers to reduce the cost and diminish the disruption caused by the repairs.

To perform the TDR a low-voltage signal is transmitted down a cable and any inhomogeneity on the cable's impedance (insulation degeneration, faults, etc.) generates a reflection that can be detected and used to locate the defect's location [15]. Figure 9 shows the transmission line model of a defect on a cable; this model is at the base of the TDR.

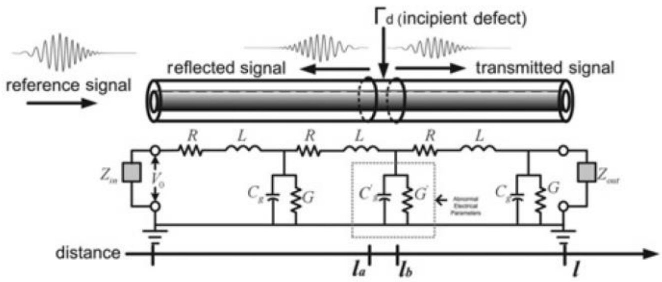


Figure 9 Transmission line model of a defect on a cable [15].

TDR can be performed either Off-line with a galvanic connection to the cable or termination and On-line using a HFCT to inject and signal and study the cable's TDR.

TDR, in particularly critical circumstances (e.g. long subsea connections), can be used as a preventive tool. The connection is TDR-mapped at regular intervals to constantly monitor the condition of the cable and ensure damage has not occurred (e.g. damage to the cable sheath by a fishing vessel anchor or fishing equipment).

IV. Case Studies

This section reports 6 case studies which present real application of on-line and off-line PD testing for:

- Rotating machine
- Power cables
- Switchgear
- Transformers
- Rotating Machines

Each case study presented will be preceded by a summarising chart to facilitate the access to the material.

A. Case Study 1

Test	OLPD Testing and Mapping of 33 kV Cable Network
Asset under test	33 kV power cables
Phase	Within the first 12 months of the asset operation
Testing outcome	Infant mortality of the asset was prevented

On-line PD testing was carried out in response to a number of recent faults of 33 kV cable joints within the network. 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.

The purpose of the testing was to measure and locate any PD activity within the cables as a pre-cursor to preventative maintenance.

On-line Cable PD Mapping was carried out using the HVPD Longshot™ PD Diagnostic unit and portable transponder. These tests started with calibration testing with pulse injection HFCTs safely attached around cable core and earths as shown in Figure 10.

Figure 10 Mapping of the 33 kV network of a metropolitan rail system.

The source of PD was located using the on-line PD mapping technique. The faulty joint on this cable was replaced and re-tested using the HVPD Longshot™ PD diagnostic system to verify the repair has been carried out correctly.

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 4. Figure 11 and Figure 12 show respectively the PD measurement and the location of the PD in one of the cables.

Table 4 Out of the 50+ circuits tested, major PD was detected within cable accessories on the three of the circuits (6%) as shown in RED.

Circuit	*Peak Cable PD Level (pC)*	*Cumulative PD Activity (pC/cycle)*
DUB to MPS1	*25.888*	*247.000*
BUR to HCC C2	*3.781*	*12.300*
BUR to HCC C1	*3.245*	*7.900*
NHD to QYD C2	*2.849*	*15.000*
NHD to QYD C1	*887*	*8.800*
ODM to JDF	*0*	*0*

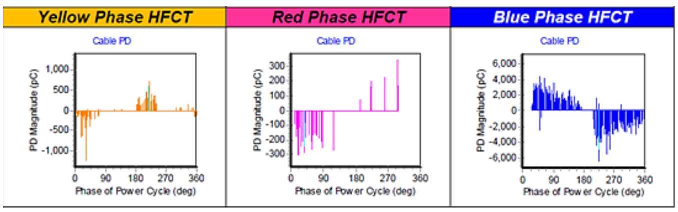


Figure 11 The on-line PD pattern detected within one of the cables.

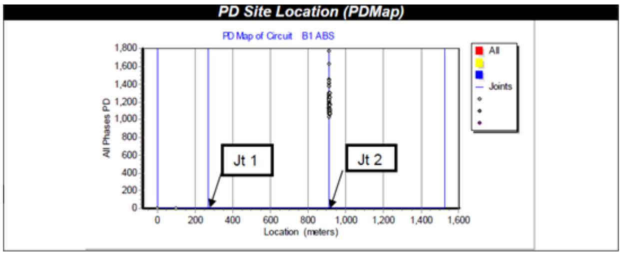


Figure 12 PD site location.

B. *Case Study 2*

Test	On-line PD Testing and Monitoring
Asset under test	6x 6.6 kV Feedwater Motors
Phase	Infant mortality
Testing outcome	Asset repaired under warranty

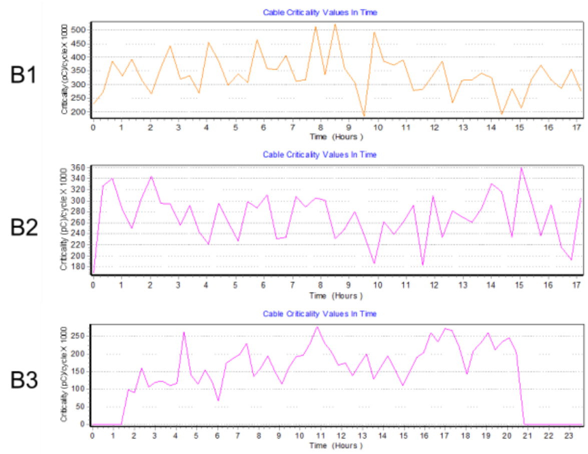
This case reports of the OLPD testing on six 6.6 kV motors supplied by two separate companies (respectively maker A and maker B). The tests were performed before the end of the 3-year manufacturers' warranty period as part of a CBM task.

The test were conducted with the equipment that HVPD developed to remotely OLPD monitor motors, switchgear and cables [7].

Table 5 shows the initial results where is as clearly visible a very high level of PD activity on the machines supplied by maker B (up to from 33.000 pC to 68.000pC).

Table 5 OLPD testing on 6x 6.6 kV rotating machines.

Motor Ref	*PD Level [pC]*	*PD Activity [nC/Cycle]*
Manufacturer A Motor 1	*12.152*	*95*
Manufacturer A Motor 2	*3.123*	*12*
Manufacturer A Motor 3	*3.165*	*4*
Manufacturer B Motor 1	*52.589*	*296*
Manufacturer B Motor 2	*33.135*	*370*
Manufacturer B Motor 3	*68.071*	*85*



As a result HVPD's Customer filed a Warranty Claim with maker B as the motors were under a 3-year manufacturer's warranty.

The machines after investigation were finally repaired with no cost for the customer. This case is a good example of how a well-planned CBM (Figure 13) has helped to avoid huge costs and unexpected asset's failure.

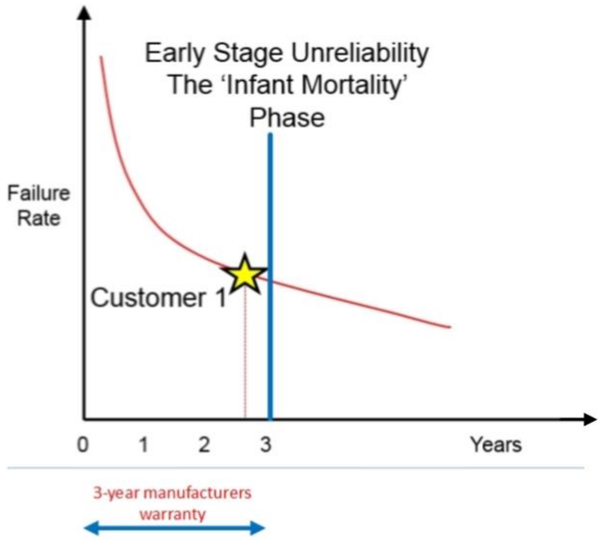


Figure 13 The ideal time for performing CM test of the assets in order to take full advantages of the manufacturer's warranty.

C. *Case Study 3*

Test	Off-line VLF Withstand/Partial Discharge
Asset under test	76x 30 kV Cables
Phase	Commissioning
Testing outcome	All 76x 30 kV cables passed VLF withstand at 43.3 kV (2.5 U0) and were PD-Free at 22 kV (1.27 U0)

This case reports on the VLF withstand and PD testing of 76x 30 kV cables of lengths between 19 and 625 meters. The testing was done at the commissioning phase. The PD testing allowed insulation defects in the installation to be detected which would not necessarily have caused the cable to trip during the withstand test and could manifest into a failure during operation

Figure 14 below shows the equipment set up for the testing. Tests were performed by increasing the voltage levels to 17.3 kV (1 U0) for five minutes followed by a minute at 22 kV (1.27 U0). During this time the cable was monitored for signs of PD as this was the cables' working voltage and just slightly above it. Partial discharge discovered at 17.3 kV (1 U0) would indicate that the cable would discharge as soon as being switched on. PD at 22kV (1.27 U0) indicates that the cable could start to discharge soon due to the PDIV lowering with age.

The test voltage was then increased to 43.3 kV as a withstand test and the cable monitored for an hour. All the cables were found to be PD free at 17.3 and 22 kV and all passed the 43.3 kV withstand test.

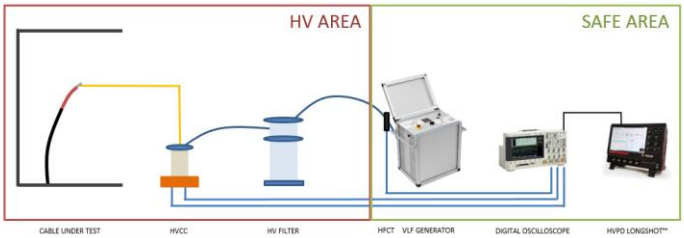


Figure 14 HVPD VLF test set.

The addition of PD diagnostic testing to the commissioning program gave the cable owner further comfort that the installation was of a high standard and the cables were good for continuous operation.

D. Case Study 4

Test	OLPD
Asset under test	4000 kVA transformers
Phase	normal operation
Testing outcome	high PD and DGA regular testing and monitoring recommended

HVPD conducted an On-line Partial Discharge (OLPD) testing on four 33 kV, 4000kVA transformers for an offshore wind farm.

The main purpose of the project was to assess the insulation condition of 4x 33 kV Transformer windings. Pressure alarms caused by excessive gassing in the transformer tank had been triggered in the past and high levels of Hydrogen (H_2), Methane (CH_4) and Ethane (C_2H_6) gas on all four transformers were confirmed by DGA oil analysis performed routinely by the site engineers.

Table 6 shows results from On-Line PD testing.

One of four of the transformers (Transformer 4) had been fitted with a free breather system to release some of the gas pressure (the other 3 transformers remained as hermetically sealed units). It should be noted that this transformer fitted with the free breather system still had very high measurements of PD levels (up to 9173 pC) and it would appear that this solution alone will unlikely solve the problem of high PD in the transformers tested.

Further comparative measurements with oil pumps active and inactive are recommended for all transformers affected by excessive gassing and subsequent pressure alarms to establish whether there is any correlation between the PD activity and oil pumps duty.

Further diagnostic PD spot-testing with the HVPD Longshot™ and/or long-term PD monitoring of these transformers (using portable or permanent, continuous PD monitoring technology) should now be considered to enable PD trending and to detect any underlying PD trends and/or clear trends-to-failure that may show up to provide an 'early warning' against insulation failure. This technology would be used in conjunction with the DGA analysis and trending that is presently being done to provide a 'holistic' condition assessment.

Table 6 Summary of Overall PD Levels for Offshore Wind Farm Transformers

Plant / Reference	Phase	Peak (pC)	Activity (nC/Cycle)	Local (dB)	Condition*	
Transformer 1	L1	572	6.17	0	Defective Condition	High levels of PD detected in Transformer tank.
	L2	668	11.17			
	L3	1191	2.92			
Transformer 2	L1	7143	1.63	45	Faulty (irreversible)	Very high levels of PD detected in Transformer tank. High Local PD detected on Tx tank.
	L2	699	8.31			
	L3	2208	4.44			
Transformer 3	L1	8605	0.68	46	Faulty (irreversible)	Very high levels of PD detected in Transformer tank. Activity on Phase L3 increased 3 fold.
	L2	800	0.87			
	L3	12564	13.15			
Transformer 4	L1	7111	6.82	53	Faulty (irreversible)	Very high levels of PD detected in Transformer tank. High Local PD detected on Tx tank.
	L2	9173	6.53			
	L3	6666	0.90			
Transformer 5	L1	3651	11.23	45	Faulty (irreversible)	Very high levels of PD detected in Transformer tank. High Local PD detected on Tx tank.
	L2	3246	9.89			
	L3	2652	9.50			

E. Case Study 5

Test	Off-Line TDR
Asset under test	90 kV subsea cable
Phase	maintenance
Testing outcome	TDR 'fingerprint' of the cable. Joints were located with an accuracy of 0.14% of the total cable length

This case report on the TDR testing of a 90 kV subsea cable connection of the length of approximately 109 Km. Due to the importance of the installation a preventive study to evaluate the use of TDR on such a long connection and map it was performed. The TDR was performed Off-line during an outage due to maintenance work using HVPD equipment.

Tests were performed injecting pulse with different width (1-10 µS), the results enabled the precise mapping of the cable and an accurate location of the cables' joints. Table 7 below shows the comparison of the data calculated with the data from the installation records while Figure 15 shows one of the TDR measurements.

Table 7 Comparison of TDR results with known lengths' data

Feature	Time, µs	Length, m		
		Calculated	From records	Difference
Start	0	0	0	0
Land joint	7.19	640	623	17
Land joint	14.72	1310	1270	40
Land/Subsea transition	21.6	1923	1940	-17
'10 km' BICC/ Pirelli Joint	131	11661	11508	153
'60 km' Pirelli/ BICC Joint	721	64178	64300	-122

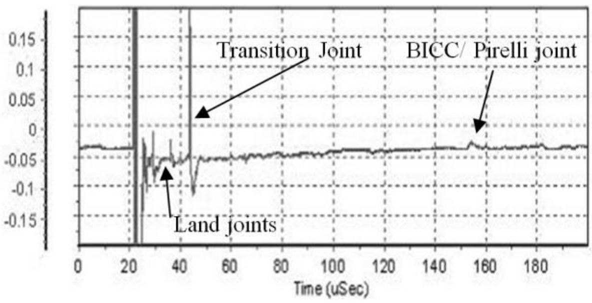


Figure 15 Details of the TDR measurement, in the picture are clearly visible the injected pulse and some of the reflected ones [16].

The results , fully reported on [16], proved that the TDR is achievable even on very long cables. This results are congruent also with other published studies [17].

F. *Case Study 6*

Test	On and off line tests
Asset under test	6.6kV, 4.6MVA Generators
Phase	Routine maintenance
Testing outcome	PD within a tolerable level detected on-line and off-line. PD trending recommended.

On-line and off-line PD testing was performed on two 6.6kV, 4.6MVA generators on board a cruise ship. The testing was performed as part of the routine maintenance.

Testing was carried out initially on Off-Line using a portable VLF test set. Following this, the generators were connected to the switchgear and an on-line PD test was made. The off-line and on-line test results are shown in Table 8 and Table 9.

The phase PD patterns detected on generator 2 off-line and on-line are shown in Figure 16 and Figure 17.

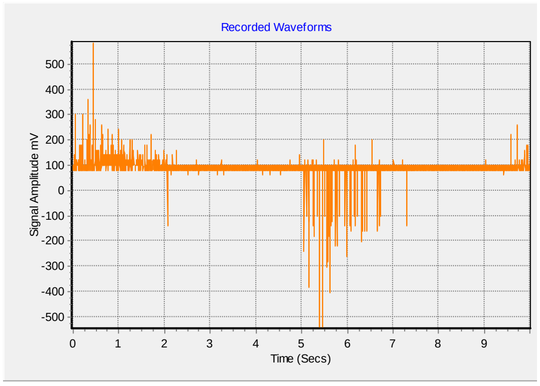


Figure 16 Generator 2 Line End 10kV PD phase pattern.

Table 8 Off-line PD Test Results

Generators Off-Line Partial Discharge Activity				
	No.1		*No.2*	
Phase	*Line end Peak (pC)*	*Neutral end Peak (pC)*	*Line end Peak (pC)*	*Neutral end Peak (pC)*
U	Max 4816 Avg 3899	Max 10547 Avg 8185	Max 7092 Avg 3014	Max 14927 Avg 7927
V	Max 628 Avg 482	Max 3956 Avg 1671	Max 2732 Avg 1304	Max 7621 Avg 6255
W	Max 1060 Avg 574	Max 5074 Avg 4469	Max 2690 Avg 1355	Max 8072 Avg 4709

Table 9 On-line PD Test Results

Generators On-Line Partial Discharge Activity				
	No.1		*No.2*	
Phase	*Peak (pC)*	*Activity (nC/Cycle)*	*Peak (pC)*	*Activity (nC/Cycle)*
U	3408	35.9	2643	8.78
V	3120	21.78	5561	16.27
W	2547	4.6	4569	25.37

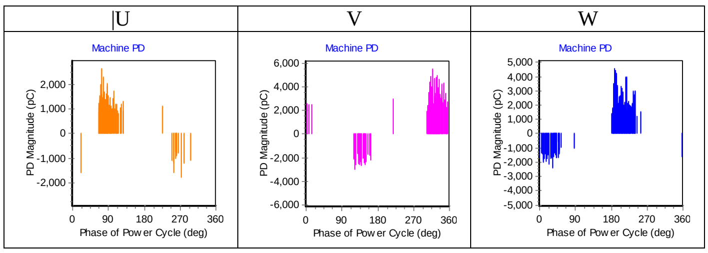


Figure 17 Generator 2 On-line PD phase pattern

Moderate levels of PD activity were measured on the two generators throughout the On-line and Off-line measurements. It is important to note that the high peaks measured off-line was generate on the neutral side which was thus with higher stress than during the normal working condition. Continued PD testing as part of the routine maintenance on the machine was recommended to trend the PD levels over time and detect any changes that could indicate a worsening insulation condition.

V. CONCLUSIONS

This paper has presented HVPD's experiences in on-line and off-line PD testing, and demonstrate how the testing can be implemented in condition-based maintenance (CBM) programs to lead to a reduction in O&M costs. This can be achieved through a continuous and systematic PD testing and monitoring of all the assets within all their life-cycle:

• Bedding in phase: commissioning and within first 12 months of operation	To reduce the failures related to defects introduced during installation and infant mortality.
• Steady State phase: spot testing or continuous monitoring	To guarantee the reliability of the assets and prevent unplanned failures
• End of life phase: spot testing or continuous monitoring	To assess the insulation condition and check if it is in a good state for plant to remain in service.

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