Best Practice Guideline for the Complete Condition Monitoring (CM) of Offshore Wind Farm (OWF) Cable Networks

Riccardo **GIUSSANI** (1), Malcolm **SELTZER-GRANT** (1) and Lee **RENFORTH** (1)

(1) - HVPD Ltd, Manchester (UK), riccardo.giussani@hvpd.co.uk , Malcolm.Seltzer-Grant@hvpd.co.uk , Lee.Renforth@hvpd.co.uk

Ross **WILSON** (2)

(2) – RWE Innogy, (UK), ross.wilson@rwe.com

ABSTRACT

The paper presents an overview and 'best practice guidelines' for the condition monitoring of off-shore windfarm cables from installation and commissioning through to service life. Measurements of online partial discharge (OLPD), power quality (PQ) parameters, sheath current (SC) are combined to provide a 'holistic' condition monitoring technique to assess the online condition of export cables and inter-array network.

This work presents the experience and knowledge gained developing a holistic electrical condition system dedicated to offshore windfarms.

KEYWORDS

Online Partial Discharge Monitoring, OLPD, Sheath Current Monitoring, Offshore Wind Farm, Inter-Array Network, Power Quality, Condition Monitoring,

INTRODUCTION

Offshore wind farm (OWF) operators need accurate, detailed (real-time) information on the state, condition and performance of offshore high voltage (HV) networks. This diagnostic intelligence is essential to maintain high reliability and availability and achieve the significant reductions in operating/maintenance costs required into the future. This paper reports the results and knowledge gained during an 18 month project to develop an integrated offshore high voltage network management system (OHVMS) for windfarms through a collaboration led by HVPD Ltd including several industrial and accademic partners.

The drive is to support condition-based management (CBM) schemes to help improving maintenance practice and drastically reduce operational costs since:

- The UK offshore wind farm industry has (to date) suffered a higher-than-expected number of medium voltage (MV) and high voltage (HV) cable faults.
- The Insurance Industry has reported that MV/HV cable faults presently make up over 80% of UK offshore wind farm insurance claims with many faults occurring during the construction and commissioning phase [1].
- The UK Government (DECC) have stated that they require the (presently high) Levelised Cost of Electricity (LCOE) over the 20-year lifetime of the asset to fall by 25% by 2020 to make offshore renewables electricity more affordable[2] [3] [4].

It is argued that a radical rethink of existing offshore MV and HV cable network asset management practices is needed to achieve this through the use of better, diagnostic commissioning testing and 'holistic' condition monitoring (CM) solutions for in-service cables.

Initially the drives behind the use of CM will be explained introducing the needs for a multi-parameters CM system developed specifically for OWF. The paper then summarises some of the parameters to be monitored and presents the proposed 'Best Practice Guidelines'. Finally the OHVMS system developed is presented with a case study.

The OHVMS is a highly innovative system, that combines online partial discharge (OLPD) condition monitoring (CM) technology, with additional sheath current (SC) and power quality (PQ) CM technologies.

CONDITION MONITORING OVERVIEW

Good equipment maintenance consists of identifying any issues 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, see Fig. 1. Bedding in phase: good quality control could reduce the failures related to the defects introduced during the manufacturing process of the assets and their installation.
- Steady State phase: commissioning/acceptance tests could reduce the failures related to the defects that would occur during the normal life of the asset, but earlier than can be reasonably be expected.
- End of life phase: spot testing/continuous monitoring could reduce unplanned faults 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.

It should be noted that it is largely assumed failure rates on off-shore windfarm cables will follow this path as cables have not yet been left installed for their predicted service life.

This theory can also be visually reassumed by Fig. 1.

Fig. 1 The bath-tube curve

There are several techniques that can be used to asses the insulation condition of the OWF networks; this project has focussed on electrical detection methods, mainly online partial discharge (OLPD), power quality (PQ) parameters and sheath current (SC).

Partial Discharge (PD)

Partial discharges occur due to voids or imperfections in the insulation system. PD will eventually lead to electrical treeing or surface tracking and is thus a good indicator of incipient insulation faults. As most new subsea MV and HV installations use XLPE cable, the most likely source of any PDs are at the accessories as shown in Fig 2. For inter-array cables interconnecting wind turbine towers this is generally only the terminations. On export feeder cables this can be the terminations and also any joints on the land cable section, land-subsea transition joints, factory joints in the subsea cable and any subsea joints in the circuits [5].

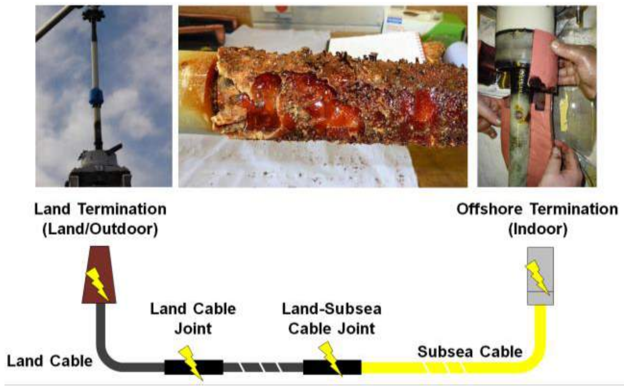

Fig. 2 Most likely sites of PD activity on subsea cables [6]

PD testing is performed on the cables in the factory as part of the quality assurance tests, PD testing at the commissioning of cable circuits should also be carried out although this is still not always the case and often the first PD measurements on the installed cable system are the OLPD tests made once it is in service.

For testing of in-service cables, measurements can be made as a spot-test and as continuous monitoring on a temporary or permanent basis, in order to detect, locate and trend any PD activity over time. Often a test strategy is developed for large wind farms in which permanent monitors are installed on the main export feeders (most critical circuits) and then inter-array cables tested routinely either with OLPD 'spot' measurements using portable temporary monitoring technology and sensors permanently installed.

Online PD (OLPD) testing has the advantage that it can be employed on in-service equipment to give an indication of insulation condition and is widely used in condition based maintenance (CBM) programs. Online PD also tests equipment under normal operating conditions. An in-service test continuously monitoring the assets can be performed to detect intermittent PD activity or changes in PD which can indicate the condition worsening (e.g. a rise in OLPD level).

Power Quality (PQ)

Power quality incorporates a number of different aspects of electricity supply and generation, including; voltage stability, frequency, power factor, total harmonic distortion and balancing of phases. Given the range of possible measurements under the general heading of PQ, it may not be possible or necessary to continuously monitor them all.

In each turbine within an off-shore windfarm the generators are operating at different speeds (depending on the wind speed). The generators are connected to the inter-array cables (typically 33kV) through a power convertor (to regulate the frequency at which the energy is supplied to the network). As consequence each power converter introduces some level of harmonic pollution into the system, and the higher the number of turbines within the system the higher the total harmonic distortion present within the system. This high presence of harmonics can create several problems to the generator including, the protection and all the components, moreover it increase the likelihood of build-up of high sheath currents within the subsea cables yeilding to a reduction of the lifetime of the cable insulation. In terms of the effects, the harmonic content of the power supply waveform can have an effect on the ageing of the insulation due to increased I^2R losses moreover determinate harmonics have been shown to promote PD activity. What is relevant to measure to assess the condition of the dielectrics system for offshore wind farm is the presence and the magnitude of the harmonic pollution within the OWF network.Measurements can be carried out using permanently installed current transformer sensors, pre-installed within the cable termination boxes.

Sheath Current (SC)

For single-core, HV power cables, the voltage induced in the metallic sheath of the cable can cause a current to flow within the sheath (SC) [7]. Lack of use of special bonding of cable earths can produce high currents circulating in the sheath of a cable and have a detrimental effect on the ampacity of the phase conductors. The main issues have been observed on the subsea export cabes in particular in the cable section between the onshore substation and the transition joint. Sheath current measurements should be carried out to assess the possibility of de-rating the cables due to thermal stresses. If high SC are detected within the cables then aprompt re-evaluation of the earth bonding scheme should be consider alongside a dynamic rating of the cables' current carrying capacity.

Distributed temperature sensing (DTS)

Distributed temperature sensing (DTS) system use optical fibres as temperature probes and are used to monitor the thermal profile of cables. The accuracy of the DTS is related to the cable length and the fibre properties.

This paper so far has presented electrical technique for the assessment of subsea cables however thermal issues can often arrise from such issues such as hot spots due to PD, harmonics or elevated sheath currents could be detected with the use of DTS. Consequently DTS is a complimentary technique and development work is ongoing to integrate the DTS system within the holistic OHVMS system in order to produce an even more accurate CM system.

BEST PRACTICE GUIDELINES

Consideration must be given to performing diagnostic testing at all stages in the life time of cable circuits, starting with the commissioning and then during its service life as part of condition-based maintenance programs. This section outlines some best practice guidelines for this.

Commissioning Testing

The minimum requirement for cable testing is for no-load soak testing, however there are clear benefits to testing at voltages above U_0 to put more electrical stress on the cable and detect defects that may manifest after energisation. PD testing is of particular interest at commissioning as cables are assembled at site with the installation of cable joints and terminations which is a point at which defects can be introduced.

It should be noted that not all defects in a cable will fail upon energisation and thus there are cases where a defect in the cable insulation can survive the withstand test but fail after being put into service. Hence the importance of performing PD testing during commissioning is to identify these weak points in the insulation and identify where remedial action should be taken. This can then be done prior to putting the cable into service and whilst the cable installation and jointing team are still at site.

It is also recommended to perform TDR finger-printing as part of the commissioning program. This involves injecting a low voltage (<100V) impulse into the de-energised cable and measuring the time for the pulse to propagate to the end of the cable and back to the pulse injection cable end. This information is then available for fault location and also location of PD events on the cable.

Testing at End of Warranty Periods

It is prudent to perform PD testing towards the end of the warranty period of the cable, joints and terminations. This provides reassurance that the cable has remained in good health and is not likely to fail soon after the warranty expires. The testing can be performed online as a short duration spot test or continuous monitoring session in the absence of a permanent monitoring system.

Testing and Monitoring During Service Life

In order to identify any problems in the insulation that manifest over time due to aging and operating stresses on the cable, holistic monitoring can be deployed. Mainly this involves monitoring for PD with power quality and sheath current, to provide a more in depth assessment of the electrical stresses on the cables. Testing can be performed on a short duration spot measurement or with temporary or permanent monitoring. The most comprehensive use involves permanent monitoring at all cable terminations. However more optimised installations can be achieved monitoring at export cables and the points where load is highest. Portable equipment and/or service contracts can also be utilised, for example to test on an annual basis as opposed to continuously.

THE OFFSHORE HV NETWORK MANAGEMENT SYSTEM

System Requirements

There are some key requirements for CM equipment for use in OWF that have been used in the specification of the OHVMS.

- Ability to be installed non-intruselvely with minimum disruption, ideally without any outage.
- Ability to monitor multiple parameters with one system to reduce the amount of instrumentation needed.
- Noise reduction on PD measurements for power convertor noise. It has been observed that in most WT noise signals were observed from the power conversion. The noise interference can vary between sites and is mostly an issue for inter-array cables and old generation of export cables operating at 33kV which are connected directly to inter-array as opposed to via a transformer.
- Pre-location of PD based on pulse shape. Analysis of the pulse wave shapes can give a good indication of the likely source of PD which can be used to plan further diagnostic testing on the network. Particularly to differentiate cable issues, switchgear or transformer issues either at the WG or the off-shore substations.
- Remote communications for data access/diagnostics and alarming.
- Low weight to allow installation on turbines without electrical lifting equipment.

System Overview

The OHVMS is multi-parameter system able to monitor OLPD, PQ and SC parameters as reported in Table 1 while Fig. 3 shows the basic schematic of the system.

The OHVMS can be used to monitor all the MV and HV network components of the offshore windfarm and its onshore substation (transformers, switchgear, cables), however the main focus is on the subsea HV export cable and inter-array system (cables and switchgear).

Table 1 The parameters monitored by the OHVMS.

Parameter	Units of measurement	Data/parameters recorded and/or calculated
PD	mV, pC, dB	Cable PD: peak value (pC), count/repetition rate, cumulative activity (pC/cycle) Local PD: peak value (dB), count/repetition rate, cumulative activity (mV/cycle)
PQ	V,A, %of Uo and %of Io	Vpeak and % of harmonics Ipeak and % of harmonics
SC	A	RMS of sheath current and relative load current for each line

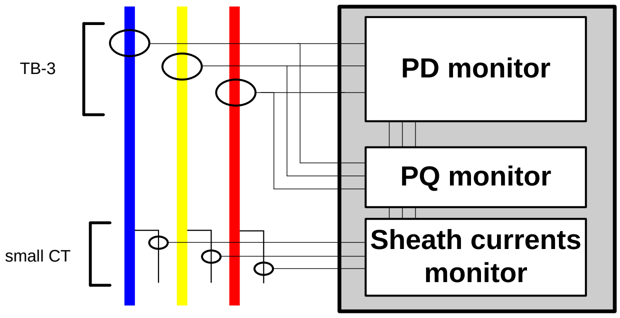

Fig. 3 HVPD OHVMS schematic of the funtionalities and the use of TB-3 sensor7

Tri-band sensor

HFCT sensors due to their low-profile design split-ferrite core and wide bandwidth (0.1 – 20 MHz) are one of the most widely used sensors for the OLPD testing of in-service MV and HV cables.

On the base of the HFCT, a novel wideband Three-band (TB-3) inductive sensor has been developed (bandwidth 1Hz – 30 MHz, see Fig. 4). The incorporation of multiple bandwidth measurements allows one sensor to target several condition monitoring parameters, notably OLPD, PQ and other transient events on the system [8]. An installed prototype of the sensor is shown in Fig. 5.

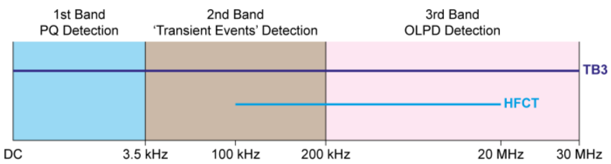

Fig. 4: The three (3) bands monitored by the TB-3 in comparison with the bandwidth of HFCT.

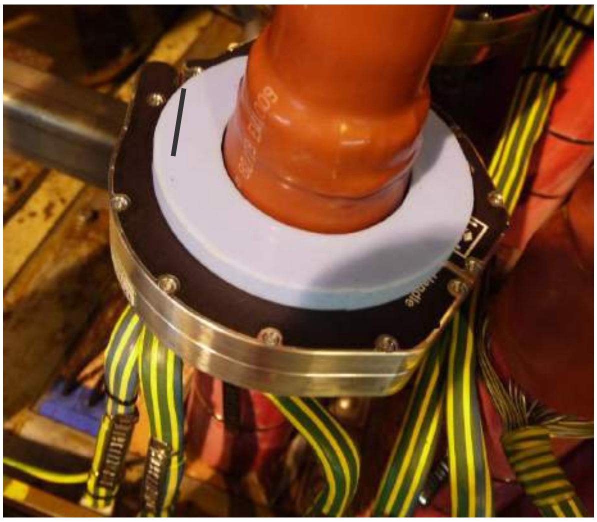

Fig. 5 An installed TB-3 sensor

Deployment on Wind Farm Network

The OHVMS system is usually deployed on strategic locations, within the network, such as the onshore and offshore substation and on the turbines located at the beginning of each strings. This choice is based on focusing on the cables which are carrying the highest load and thus most critical to transmitting the generated power to shore.

Where budget is limited, a solution based on permanent sensor installation and portable OHVMS systems can also be used to perform periodic monitoring.

User Interface & CM Database

A comprehensive view of the MV and HV cables monitored can be achieved by pooling data from multiple sensors and monitoring units to a central database. This serves the function of benchmarking the data across the network, generating criticality league tables of the equipment insulation condition and presenting results on a user interface. An overview is shown in Fig. 6.

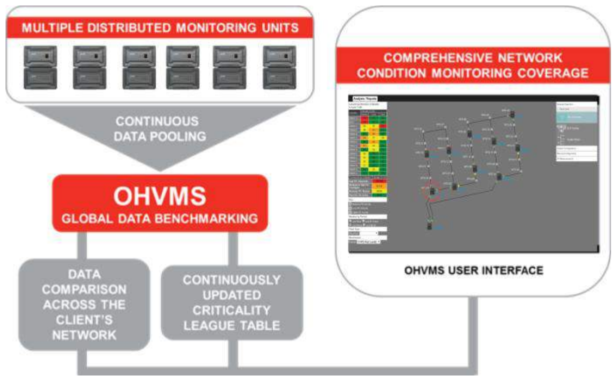

Fig. 6 OHVMS database on wind farm network.

The processed data can be viewed via a user interface containing colour-coded plant condition data superimposed onto a 'mimic' of the MV network's single-line diagram (SLD). Logging, comparison and trending of the CM data provides real-time insulation condition status of the MV and HV network.

The top-level of the user interface shown in Fig. 7 is based on the SLD and allows individual assets to be selected and viewed.

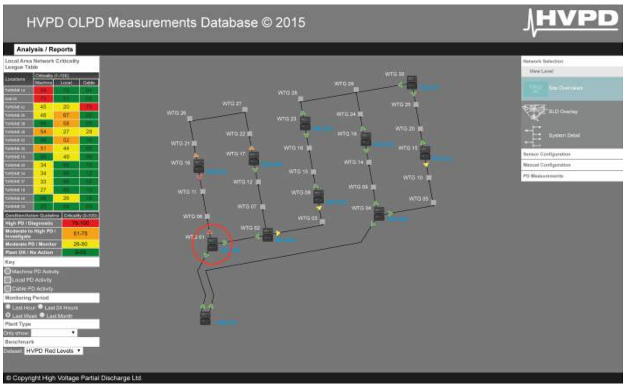

Fig. 7 Top level overview – substations and turbines can be selected and viewed from central layouts

Within the second-tier asset layer, the operator can access detailed asset condition data (based on OLPD activity) with alert levels and trends, as shown in Fig. 8. Further tiers allow viewing the trends for the parameters monitored.

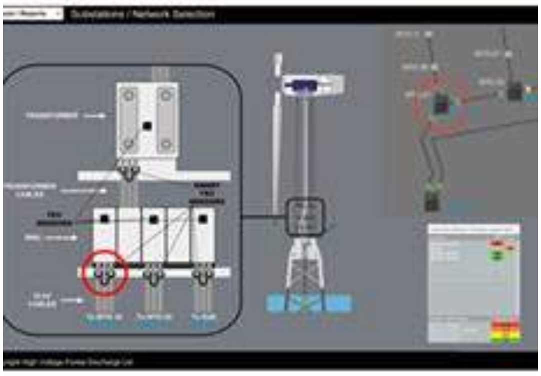

Fig. 8 Turbine view – detailed PD, PQ and SC information is provided by Turbine, with alert levels.

The data from continuous monitoring can then be used to support CBM schemes and to direct preventative maintenance interventions to repair plant/cables ahead of insulation failure.

CASE STUDIES – OHVMS & TB-3

The case study presents the use of the OHVMS system to perform permanent PD and PQ monitoring of an offshore Inter array network through the use of the TB-3 sensor. Fig. 9 shows the schematic of the system and the points of installation of the sensors on the 33kV main ring unit at the wind turbine. The sensors were installed as part of a permanent CM system specifically developed for OWF [9].

During the tests intermittent PD activity was detected, as visible in Fig. 10. Subsequent diagnostics OLPD 'spot' test were performed to pinpoint the source of the PD and guide remedial action.

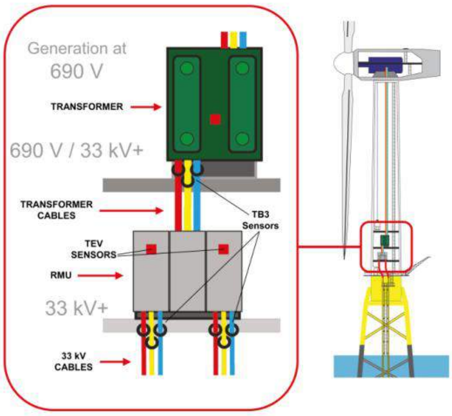

Fig. 9: Installation of TB-3 sensors in an OWT

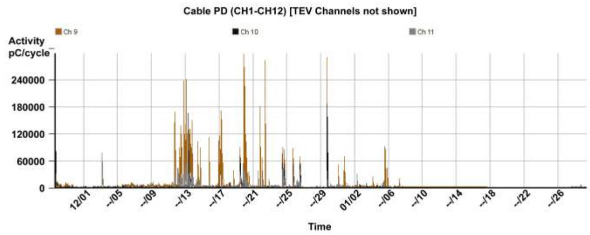

Fig. 10: Intermittent PD activity (pC/cycle) detected over a 2-month period. Ch9: R Phase, Ch10: Y Phase, Ch11: B Phase

Fig. 11 shows the waveform of the PD pulses detected on the yellow phase; the reflection of the PD is clearly visible as is the crosstalk of the PD on the blue phase. Analysing the return time of the PD and the PRPD pattern (see Fig. 12) it was possible to pinpoint the source of the PD in one of the GIS switchgear installed in the nearby turbine

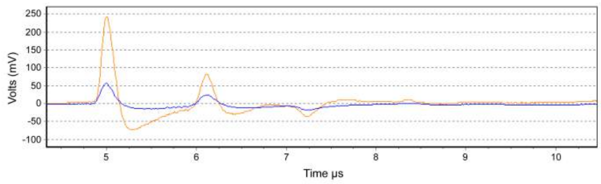

Fig. 11: Partial Discharge pulse and the PD reflection (yellow phase) and the crosstalk on the blue phase

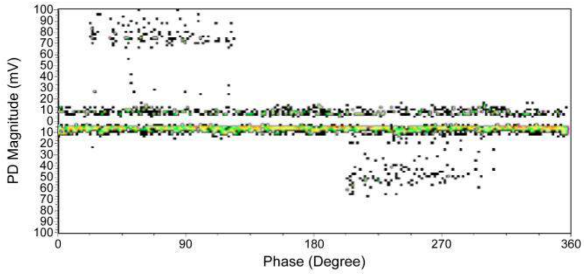

Fig. 12: the PRPD pattern of the PD activity measured.

This case study showed how the use of the TB-3 sensors in conjunction with the OHVMS system has helped to detect PD activity that may had led to degeneration of the insulation and finally to an unplanned outage and to implement corrective maintenance.

CONCLUSION

This paper has given an overview of the condition monitoring techniques available for the export and inter-array cables used in off-shore windfarms.

More in-depth testing at commissioning including elevated test voltages and PD measurements clearly has its benefits, in particular to identify any damage or installation errors during installation that could manifest into failures after being put into service.

The merits of holistic monitoring systems have been shown with a view to reducing the amount of monitoring hardware to be installed and identify different issues that can arise in service life. Monitoring can performed on a continuous basis or periodic with temporarily installed equipment, with the main focus placed on the export cables and inter-array cables carrying the highest loads.

Whilst condition monitoring is often not deployed at point of wind farm installation, some care can still be taken at the specification and design stages of offshore windfarms to ease the deployment of such systems in the future. The following measures are recommended to ease the retrofitting of such equipment during service life:

- Cable termination styles chosen to allow attachment of sensors. Particularly terminating cable earths in unenclosed areas such that PD, PQ and SC sensors can be attached to power cables without an outage. Alternatively including permanent sensors in the specification of the site such that they are installed from the outset.
- Spare mains outlets in turbines/substations for CM equipment
- Spare fibre optic cables in export and inter-array cables for communcations to CM equipment and monitoring temperature and strain.
- Penetrators/cable entry on nacelle towers for placement of data communication antennas outside.
- Consideration given to accessibility of earth link boxes on land joints and land-subsea transition joints for attachment of OLPD sensors along with power source.

Acknowledgments

This work has been carried out with innovation grant support from the UK Government Department of Energy and Climate Change and a number of offshore park operators.

REFERENCES

[1] J. McKenna, “Experience is key to reduce cable claims,” 2012. [Online]. Available: http://www.windpowermonthly.com/article/1133682/experience-key-reduce-cable-claims.

[2] DECC, “UK Renewable energy road map.” 2011.

[3] Offshore Wind Cost Reduction Task Force, “Offshore wind cost reduction task force report.” 2012.

[4] L. Renforth, M. Seltzer-Grant, S. Goodfellow, and M. Foxall, “Combined Power Quality and Condition Monitoring of Offshore MV and HV Cable Networks,” in EWEA, 2013.

[5] M. Seltzer-Grant, L. Renforth, S. Djokic, and P. McKeever, “Combined Power Quality and Condition Monitoring of Offshore Networks,” in C I R E D 22nd International Conference on Electricity Distribution, 2013, no. 1334, pp. 1334–1337.

[6] R. Giussani, M. Seltzer-Grant, L. Renforth, D. Clark, and R. Shuttleworth, “Insulation Condition Assessment of Offshore Wind Farm Export and Inter-array Cables,” in EWEA OFFSHORE, 2013.

[7] “IEEE Guide for the Application of Sheath-Bonding Methods for Single-Conductor Cables and the Calculation of Induced Voltages and Currents in Cable Sheaths,” 1988.

[8] R. Giussani, C. Zachariades, M. Foxall, L. Renforth, and M. Seltzer-Grant, “A Novel Electrical Sensor for Combined Online Measurement of Partial Discharge (PD) and Power Quality (PQ),” submitted to International Symposium on High Voltage Engineering, 2015.

[9] R. Giussani, M. Seltzer-Grant, L. Renforth, and W. Waugh, “The Adoption of Best Practices for Insulation Condition Assessment and Condition Monitoring of OWF HVAC Export and MVAC Inter-array Cables: Preliminary Field Trial Results,” in EWEA Spain, 2014.