

A NEW TECHNIQUE FOR ‘HOLISTIC’ MONITORING OF HIGH VOLTAGE ROTATING MACHINES, COMBINING THERMAL, ELECTRICAL, AMBIENT AND MECHANICAL (TEAM) STRESS MONITORING

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INTRODUCTION

The use of on-line partial discharge (OLPD) insulation condition assessment of in-service high voltage (HV) motors and generators has been carried out for over 50 years and is now widely accepted as a very good diagnostic indicator of the HV stator winding’s insulation condition [1]. The mechanical condition monitoring of rotating HV machines using vibration technology has also been well established in the industry for a similar period [2].

It is interesting to note that whilst most in-service large (10MW+) HV motors and generators will have some form of vibration condition monitoring installed, the OLPD condition monitoring of the HV stator winding insulation has not, as yet, become as widely applied. Figure 1 below shows summary data from two studies, by the Institute of Electrical and Electronic Engineers (IEEE) [3] and the Electric Power Research Institute (EPRI) [4] in the USA, that show the main cause of HV motor failures reported in their studies were bearing related (at 41% and 50% respectively). However, it is also interesting to note that the next most likely cause of failure was HV stator related failures (these making up 37% of failures reported from both studies).

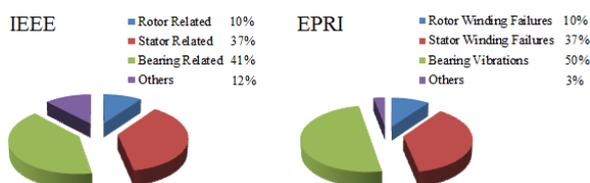


Figure 1 High voltage motor failure data analysis distribution studies [3,4]

It is interesting to note that the HV motor failure analysis studies above by the both IEEE and EPRI report that high voltage stator winding failure contributes to around 37% of the total motor failures. This statistic provides compelling evidence that the insulation condition of the stator windings should be monitored and that this should be done in conjunction with the mechanical/vibration monitoring already in place (to monitor bearing wear and rotor condition). The authors argue that it is only by combining both the mechanical and electrical monitoring of the rotating HV machines that a true, ‘holistic’ diagnostic condition assessment can be made. With reference to Figure 1, a combination of effective mechanical monitoring (to

monitor the causes of bearing and rotor failure) should be combined with OLPD (to provide an ‘early warning’ of impending HV stator insulation failure).

This paper presents a proposal for a ‘holistic’, combined rotating HV machine condition monitoring system that simultaneously monitors the electrical and mechanical parameters of the machine. Such a holistic condition monitoring approach should combine a number of condition monitoring modules (including on-line partial discharge – OLPD, vibration and current signature analysis (CSA) monitoring modules) to allow a more complete machine health diagnostic to be made to help improve maintenance decision-making. With reference to Figure 1, by combining monitoring technologies to provide an early warning against rotor, stator and bearing condition deterioration, (these three making up around 90% of all faults) it is proposed that many of these incipient mechanical and electrical faults can be detected and repaired ahead of catastrophic failure. The proposed holistic monitoring concept is discussed in this paper that also includes a review of some of the authors’ experiences of condition monitoring of rotating HV machines, including two case studies from OLPD monitoring of HV motors recently conducted.

THE COMBINED MONITORING APPROACH

A range of condition monitoring (CM) technologies are available in the marketplace to provide the necessary condition data for this combined, holistic machine rotating HV machine monitoring approach. The research carried out by the IEEE [3] and the EPRI [4] indicates that a significant proportion of rotating machine failures (up to 90%) can be attributed to one of three faults, bearings, stator-winding and rotor-related faults. To meet this CM requirement, the authors propose that a combined ‘holistic’ monitoring concept is applied. This should integrate up to 5 CM technologies including 1. Vibration, 2. Power Quality Monitoring (PQM), 3. On-line Partial Discharge (OLPD), 4. Cable Sheath Current Monitoring and 5. Current Signature Analysis (CSA). The monitoring of these key condition parameters (the Key Performance Indicators, *KPI*’s, of the machine) will enable the earlier detection, faster identification and more cost-effective resolution of both mechanical and electrical defects in the rotating HV machine to provide an ‘early warning’ of a developing problem, using continuous, on-line CM monitoring technology.

Such an integrated condition monitoring (CM) platform would provide an advanced ‘early warning system’ against potential stator, bearing or rotor-related faults, to enable the planning of preventive or corrective maintenance. In the process industries (including the petrochemical industry), the main cost driver is to avoid unplanned outages that can lead to large losses in revenue (many millions of \$’s in the case of some of the larger pump motors in the oil & gas sector). It is proposed that the CM platform necessary for an effective condition-based maintenance (CBM) scheme for rotating HV machines should include:

OLPD monitor module – for the detection of stator winding deterioration from partial discharge,
Vibration monitor module - for the detection of bearing wear, misalignment and other mechanical faults,
Current Signature Analysis (CSA) module – for the detection of broken rotor bars and rotor eccentricity,
Power Quality Module (PQM) – the measure of harmonics and transient overvoltages / overcurrents, &
Sheath Current Monitoring (SCM) module.

The application of combining continuous, on-line electrical and mechanical condition monitoring of rotating HV machines has been carried out recently by the authors with offshore oil & gas operator customers in the UK and Norwegian North Sea. In these projects, electrical OLPD and mechanical CSA monitoring measurements were combined with data from existing mechanical vibration monitoring technology. The application of the proposed holistic monitoring techniques to these high-priority motors and generators in the oil and gas industry is also applicable to other, ‘high-outage-cost’ industries such as the offshore wind farm (OWF) industry, particularly with the much larger (500MW-7GW) ‘Round 2’ and ‘Round 3’ UK OWF’s.

As per the Oil & Gas industry (where the unplanned outage costs of high criticality HV motor can run into several millions of \$’s per day), the large OWF’s can have significant outage costs with the main cost driver here being the high cost of carrying out emergency repairs. Such industries would also benefit from the advantages of a combined Vibration, OLPD, CSA, PQM & SCM monitor. A proposed application of the holistic monitoring concept to a new generation (5MW+) off-shore wind turbine is illustrated in Figure 2. It can be noted in the diagram that such a system would utilise what we have called wideband ‘Quadplex SMART’ sensors that are designed to detect a very wideband of signal frequencies (from DC to 200 MHz) to enable measurements to be made in the various frequency bands of interest (OLPD – high frequency 100kHz-100MHz, CSA– 50/60Hz and PQM/Transients – 50Hz –10kHz). These combined measurements are integrated into this ‘Quadplex’ sensor (one of these is used per phase) and the data is logged by a singular monitor control unit with remote uplink unit to provide real time access to the data and diagnostic analysis.

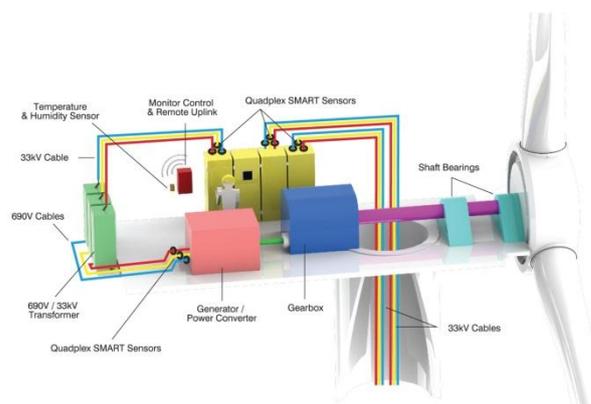


Figure 2 Large (5MW+) Offshore Wind Turbine holistic condition monitoring solution concept

Research documented in [3] has been applied by the authors to develop non-intrusive, wideband high-frequency current transformer (HFCT) sensors for on-line PD detection in rotating HV machines with phase currents of up to 1000 A (suitable for 11 kV machines of up to 20 MVA). Field test projects have shown that a combination of the HFCT’s, PQM sensors and Transient Earth Voltage (TEV) sensors, can detect partial discharge activity of different types and locations within the HV network. A description of the various condition monitoring parameters that could be incorporated into the holistic monitoring system are presented, along with a discussion of two case studies of OLPD measurements carried out on two high-priority Ex/ATEX motors, both operating within a hazardous (‘Ex/Atex’) gas zone.

THE ‘TEAM’ STRESSES ANALYSIS

Transient faults within insulation systems and accelerated ageing degradation mechanisms can have detrimental effects on the stator and rotor windings of a motor or generator. Stresses that can cause and sustain such issues for an insulation system may be summarised by the ‘TEAM’ acronym stresses [7]. This encompasses the four main stresses that can influence electrical and mechanical breakdowns, namely the Thermal, Electrical, Ambient and Mechanical stresses. Whilst some of these stresses are transient or intermittent in nature, such as electrical overvoltage transients, others are present all of the time, such as partial discharge activity in the stator windings. Continued on-line monitoring of the CM parameters along with the environmental (temperature, humidity) and operational state of the machine can assist in maintenance planning and the further understanding of rotating HV machine failure mechanisms.

Thermal stresses

Phase currents flowing within the conductor coils of the stator winding cause a build-up of heat within the winding, otherwise known as the I^2R losses. Combined with the heat generated from friction, bearing and eddy

current losses, these can gradually cause thermal deterioration of the insulation system. It is also known that the loading of the machine is directly related to the temperature variations experienced by the stator winding insulation. Advanced stages of thermal deterioration can lead to conductor delamination, and thermal run-away problems. An example of conductor delamination in a coil due to thermal ageing is shown in Figure 3 where it can be seen that the various layers of tape that make up the insulation have become separated (on the left hand side), probably due to the bonding agent becoming overheated, effectively letting go of the different layers of paper.

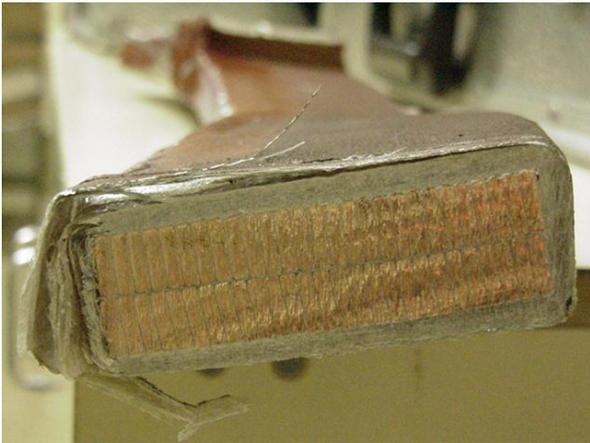


Figure 3 Mica Insulation Delamination of a stator winding coil

Ambient Stresses

Ambient types of stresses arise due to the type of environment that the rotating machine is operating within. Such conditions may include high humidity, the presence of sand, dirt or debris, a hazardous gas atmosphere (usually referred to as Ex - Explosive or ATEX – Atmospheres Explosive) or a location where onerous conditions are likely to be present, such as a coastal area where salt water is being pumped or processed or certain areas within nuclear power stations. Although it is not always possible, or necessary to monitor ambient temperature and humidity, these factors are known to have an effect on the PD activity within the stator winding, and would be trended along with PQM and PD measurement data.

Electrical Stresses

Partial discharges within the stator winding insulation, fast-fronted transients from switching/over-current surges and harmonics within the power system can all contribute to electrical stresses and insulation damage. Continuous on-line monitoring of these factors would be incorporated into the holistic monitoring concept. The main electrical stresses experienced by in-service rotating machines are briefly discussed here.

Partial Discharge Activity. Degradation of stator core semi-conductive coatings, insufficient end-winding clearances/stress relief tape, poor application of epoxy's in any vacuum pressure impregnation (VPI) process and third part damage are just some of the causes of PD activity within a rotating machine stator winding insulation system. Such defects can produce fast transient pulses within the insulation system, which can be detected at the machine terminals or at the switchgear-end of the power feeder cable (for a cable fed machine). Over time, PD activity will cause the eventual, complete breakdown of the insulation, often resulting in an unplanned failure of the machine. Continuous on-line monitoring of PD activity is generally accepted as being the most appropriate method to establish the stator winding insulation condition. Continuous monitoring of PD activity from two motors is presented in the section on Case Studies.

Cable sheath currents. 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. Poor cross-bonding of cable earths can produce high currents circulating in the sheath of a cable and have a detrimental effect on the current carrying capacity of the phase conductors. Sheath current measurements were carried out to assess the possibility of de-rating the cross-linked polyethylene (XLPE) 33 kV offshore wind-farm export cables and any thermal damage. High circulating currents were detected in the cable sheath which prompted re-evaluation of the earth bonding scheme. Measured load and sheath currents over a week long period are shown in Figure 4.

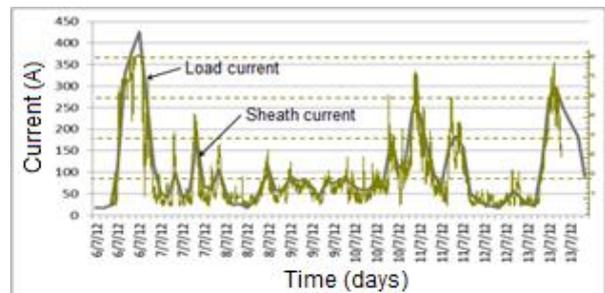


Figure 4 Measured cable sheath current and load current

Figure 4 shows the dependence of the cable sheath current on the load current within the power cable. Incorporating cable sheath current measurements into a holistic monitoring system can ensure that cross-bonding has been carried out correctly and that conductors are not operating near to their maximum current carrying capacity. A better approach would be to estimate the new current carrying capacity from the cable geometry, and the sheath current measurements.

Power quality. 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 terms of the effects upon stator winding insulation, the harmonic content of the power supply waveform can have an effect on the ageing of the insulation due to increased I²R losses or, dependent upon the harmonics present, can cause mechanical issues. For these reasons, it is proposed that the harmonic content of the supply waveform is monitored continuously.

To show how power frequency harmonic measurements could be used, tests were carried out on the XLPE 33 kV export feeders at a UK wind-farm. Measurements were made using permanently installed current transformer sensors, pre-installed within the cable termination boxes. The current waveforms were measured and the frequency response calculated using the fast Fourier transform (FFT).

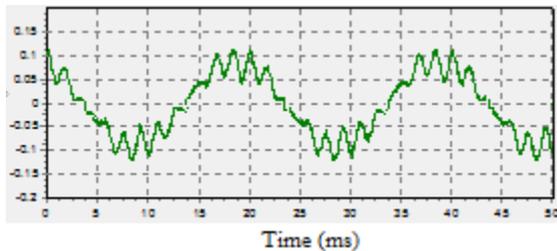


Figure 5 Feeder 1 red-phase 50 Hz current waveform

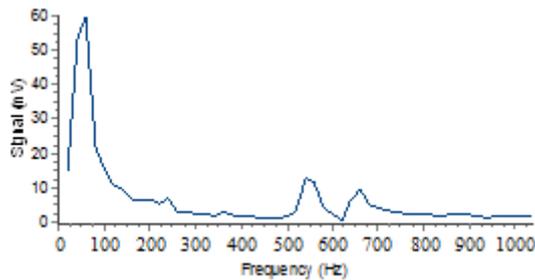


Figure 6 Feeder 1 red-phase current waveform frequency spectrum

Figures 5 and 6 show the current waveform and its frequency spectrum respectively, as measured by the current transformer sensor. Measurements showed that in all phases of feeder 1, dominant signals were present at the 11th and 13th harmonics (550 Hz and 660 Hz) with levels at around 15% of the 50 Hz value signal. It is proposed that a similar method could be used to measure and determine the harmonic content for operating motors and generators. From this analysis, it should be possible to determine the harmonics present within the power frequency waveform and assess the possible severity of such harmonics. Dominance of the third harmonic current is shown in Figure 7. This measurement was carried out on a 10 kV, 2.7 MW refrigerant compressor induction motor.

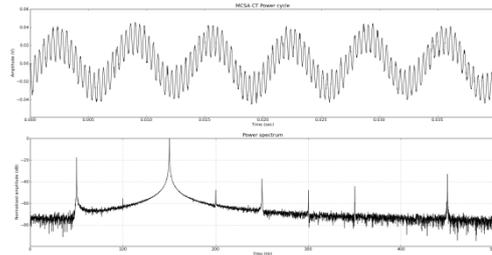


Figure 7 Measurements from a 10 kV, 2.7 MW refrigerant compressor induction motor

Although the cause of the enhanced third harmonic was not confirmed, it is known that the presence of such significant third harmonics can lead to increased copper losses and flux issues. These effects are not primary faults but form part of the overall assessment of the motor health.

Current signature analysis (CSA). Current signature analysis is a technique that is predominately used to identify possible faults associated with the rotor of a motor or generator. By analysing the machine current in the frequency-domain, it is possible to deduce if there are any problems with the rotor. The technique may be carried out on 3-phase machines and can be used to detect faults such as; eccentricity problems, bearing-related issues and broken/cracked rotor bars. Results from laboratory work carried out on a 3 kW, 2-pole induction motor operating at 2880 rpm are shown in Figure 8. The frequency-domain plots in Figure 8 show the motor operating with an induced rotor fault.

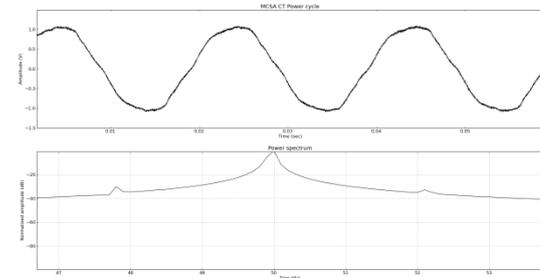


Figure 8 MDSA measurements from a 400 V, 3 kW induction motor

This is manifest in Figure 8 as sidebands to the main peak at 50 Hz near the slip frequency. With no induced fault, the upper sidebands would not exist for this motor.

Mechanical stresses

The mechanical stresses imposed on rotating HV machines can include those produced by short-circuit fault currents, the high speeds of angular revolution, oscillating magnetic forces and regular alteration of the rotor speed. All of these can exert large forces on a machines' HV insulation system. Mechanical stresses encompass a broad range of sources, including magnetic and centrifugal forces, vibrations caused by

bearing wear, overvoltage and overcurrent surges and finally, and most onerously, the very large mechanical forces induced by short-circuit fault currents. As part of the holistic monitoring concept, it is therefore important to include vibration monitoring to detect any problems associated with shaft misalignment, rotor imbalance or generally worn components.

CASE STUDIES

Two case studies are presented here where the technique of OLPD testing and continuous OLPD monitoring was carried out on in-service motors and generators for customers in the oil & gas industry. Case Study 1 is from an oil and gas drilling vessel in the North Sea whilst Case Study 2 is from an oil and gas processing facility in Kazakhstan.

Case Study 1 OLPD monitoring of 6.6 kV diesel generators on an O&G drilling vessel, North Sea.

Measurements were carried out on the 6.6 kV, 4.5 MW asynchronous, diesel generators on board an oil-drilling drilling vessel, over a period of two days. Slot section PD signals were detected in the W-phase of one of the two generators tested. From leaving port the electrical demand from the generators was gradually increased from 20% to 80% of full load, which allowed OLPD measurements to be carried out at 20%, 40% and 80% load, as shown below in Figure 9.

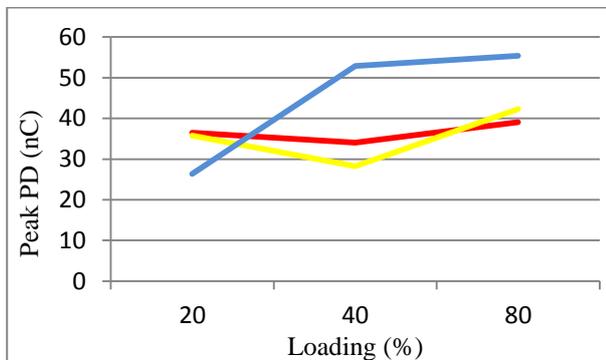


Figure 9 OLPD peak level vs generator loading

Figure 9 shows peak PD against the generator loading, as a percentage of the nominal load. Temperature and humidity readings were not available, although the increase in peak PD activity on the W-phase with the increased generator loading is suggestive of slot section discharges caused by the movement of coils within the stator slots. This diagnosis was supported by the wave-shape analysis [5].

Case Study 2 remote OLPD monitoring of 10 kV ‘Ex’ motors, O&G processing facility, Kazakhstan.

Development OLPD testing and monitoring over a 2-year period at an oil and gas processing facility in Kazakhstan has helped establish the validity of implementing a new, remote monitoring technique for

HV motors. This technique uses wideband HFCT sensors located at the central switchboard to monitor the PD activity in ‘Ex’ motors [7, 8]. This technique was developed due to a large proportion of the motors and generators at the facility operating in hazardous gas (‘Ex’) zones, where access to the motor cable box is not easy to arrange and where it is often difficult to install high voltage coupling capacitor (HVCC) sensors. High priority motors at the facility are being continuously monitored using this remote OLPD monitoring technique. These motors had recently completed 20 years of service; details of the motors are given below.

Motor Ref MF-AA this is a 4 MW, 10 kV motor that drives a gas compressor at the facility. It has a nominal line current of 267 A, and operates at 1500 rpm.

Motor ref M-BB is a 6.4 MW, 10 kV motor that also drives a (larger) gas compressor at the facility, with a nominal line current of 447 A operating at 1500 rpm.

TABLE 2 Measurements of peak and cumulative PD activity per phase

Circuit		Peak (nC)	Activity (nC/Cycle)
M-FF	U Phase	6.9	9.5
	V Phase	10.9	14.9
	W Phase	9.9	10.5

TABLE 2 Measurements of peak and cumulative PD activity per phase

Circuit		Peak (nC)	Activity (nC/Cycle)
M-BB	U Phase	36.3	1153
	V Phase	34.0	1135
	W Phase	35.6	1155

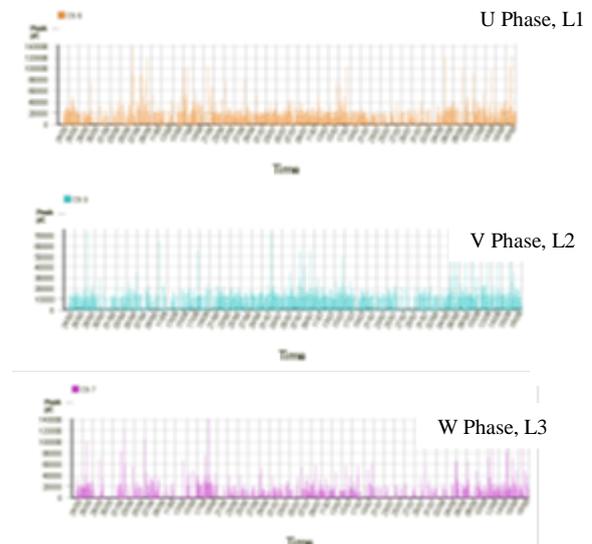


Figure 10 Motor Ref M-FF - 3-months of continuous OLPD monitoring data

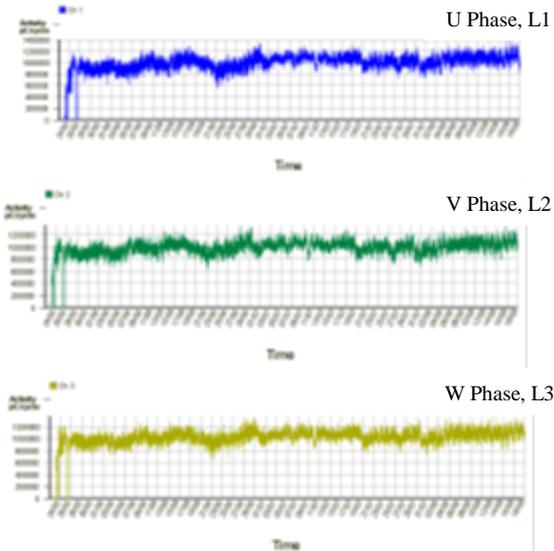


Figure 11 Motor Ref M-BB 3-months of continuous OLPD monitoring data

DISCUSSION

The 3-month (May-August 2012) OLPD monitoring trend plots in Figures 10 and 11 show low and stable PD activity on the M-FF and a high level and gradually increasing trend in PD on M-BB over the 3 months of continuous monitoring. In this case, motor ref M-BB has a significantly higher risk of stator insulation failure from PD than the M-FF one. It has been therefore recommended that a visual inspection of motor M-BB is carried out during the next planned maintenance intervention whilst the motor HV stator insulation of motor M-FF is suitable for further service. This example shows the importance of continuous OLPD monitoring of the stator winding PD activity to establish if there are any underlying trends in the PD activity. An increasing trend in stator winding PD activity over time indicates a developing problem within the insulation system, and could result in the eventual failure of the motor unless preventative maintenance is carried out.

CONCLUSION

The authors have proposed a new, ‘holistic’ combined electrical and condition monitoring approach for the continuous CM of rotating HV machines. It is the use of continuous on-line monitoring systems that will permit the detection of early-stage partial discharge activity, vibration from worn bearings, power quality and harmonic issues, sheath currents and overvoltage/overcurrent events. There are many, (relatively – when compared to the outage costs) low-cost monitoring modules capable of providing this holistic monitoring capability. It is argued that it will be the quality and range of any condition monitoring technology that will dictate the quality and effectiveness of any condition-based maintenance and/or preventative maintenance scheme employed by

the rotating HV machine operator. HVPD is continuing to carry out R&D in this field of combined electrical and monitoring of rotating machines with both our commercial clients and our academic partners (at The University of Manchester and Newcastle University). This work includes adapting the condition monitoring techniques and practices that are now established in the oil & gas industry into new developing markets such as the offshore wind farm industry mentioned in this paper.

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