This document was prepared for the ETI by third parties under contract to the ETI. The ETI is making these documents and data available to the public to inform the debate on low carbon energy innovation and deployment.

Programme Area: Offshore Wind

Project: Condition Monitoring

Title: Final Report on an Holistic Approach to Wind Turbine Monitoring

Abstract:

The InFLOW project was initiated to develop an holistic, predictive condition monitoring system. This was seen to be distinct from conventional condition monitoring systems (CMS) in that it did not restrict itself to a single technology, but brought together a range of sensing technologies and available turbine data to generate holistic diagnostics and real-time damage modelling to provide prognostic information relating to the life used on various parts of the turbine. It was shown that there were significant savings to be made by optimising the inspection and maintenance regimes for off-shore turbines, in large part due to the expense of jack-up barges with weather defined access constraints.

Context:

The Condition Monitoring project was led by Moog Insensys and included Romax, SeeByte, the University of Strathclyde, E.ON and EDF. It looked towards developing an intelligent integrated, predictive, condition monitoring package for wind turbines, which improves reliability, increasing availability by reducing downtime by up to 20% and leading to potential savings of 6,000 per turbine.

Disclaimer:
The Energy Technologies Institute is making this document available to use under the Energy Technologies Institute Open Licence for Materials. Please refer to the Energy Technologies Institute website for the terms and conditions of this licence. The Information is licensed 'as is' and the Energy Technologies Institute excludes all representations, warranties, obligations and liabilities in relation to the Information to the maximum extent permitted by law. The Energy Technologies Institute is not liable for any errors or omissions in the Information and shall not be liable for any loss, injury or damage of any kind caused by its use. This exclusion of liability includes, but is not limited to, any direct, indirect, special, incidental, consequential, punitive, or exemplary damages in each case such as loss of revenue, data, anticipated profits, and lost business. The Energy Technologies Institute does not guarantee the continued supply of the Information. Notwithstanding any statement to the contrary contained on the face of this document, the Energy Technologies Institute confirms that the authors of the document have consented to its publication by the Energy Technologies Institute.

E.ON New Build & Technology

E.ON New Build & Technology Limited, Technology Centre, Ratcliffe on Soar, Nottinghamshire, NG11 0EE T+44 (0) 2476 192900 F+44 (0) 115 902 4012 entcommunications@eon.com www.eon.com/technology

UNRESTRICTED

ENT/13/TMR/CM/1138/R Revision 1
Job No: 2122.CA4066.001
May 2014

FINAL REPORT ON AN HOLISTIC APPROACH TO WIND TURBINE MONITORING

prepared for
ENERGY TECHNOLOGIES INSTITUTE
by
D N Futter (E.ON New Build & Technology)

The author also gratefully acknowledges contributions from: R Chevalier (EDF), D Gilbert (Moog Insensys), E Miguelanez (SeeByte), M Whittle (Romax) and D Infield (Strathclyde University)

EXECUTIVE SUMMARY

The InFLOW project was initiated to develop an holistic, predictive condition monitoring system. This was seen to be distinct from conventional condition monitoring systems (CMS) in that it did not restrict itself to a single technology, but brought together a range of sensing technologies and available turbine data to generate holistic diagnostics and real-time damage modelling to provide prognostic information relating to the life used on various parts of the turbine. It was shown that there were significant savings to be made by optimising the inspection and maintenance regimes for off-shore turbines, in large part due to the expense of jack-up barges with weather defined access constraints.

The Project developed prototype systems for testing on E.ON and EDF turbines, whilst simultaneously constructing the business case to understand the key value drivers and then validate that such a system could achieve the main project goal of a saving of 0.5 p/kWh in offshore wind power generation.

The improved financial modelling of fault detection on O&M costs during the project provided some key insights. The extended modelling brought together newly available onshore fault data by subsystem and applied to this to a UK Round 3 offshore farm. The model also split out what could be achieved by existing vibrational based CMS systems and what wider capabilities could deliver. Results showed that 0.7 p/kWh saving can be delivered using traditional vibrational based CMS on gearbox and generator faults alone. While improved diagnostics from an holistic approach and coverage of a wider set of faults seen in on-shore turbines could deliver an additional 0.8 p/kWh saving. In addition to these savings is the possibility of mitigating against damaging events to prolong the life of specific turbine components based upon damage modelling.

One of the barriers to the adoption of condition monitoring in the wind turbine industry has been the behaviour of the Original Equipment Manufacturers (OEMs). Historically contracts have been set up such that any data from a pre-fitted CMS is available only to the OEM, and that retro-fitting a CMS effectively invalidates the Warranty. In some cases CMS has been fitted after the warranty period, although this still requires the cooperation of the OEM in order to

obtain load, wind speed and generator speed signals, which are vital to a successful monitoring campaign. This significantly reduces the value available, but CMS can generally pay for itself well within the 5 year timeframe usually demanded. As a result OEMs are now widely applying CMS from new in larger turbines, but are not giving free access to the data. This restricts the information available to Operators and to alternative service providers. It results in holding back progress to reduce the overall cost of energy. Given that the industry is public/government supported, more openness should be required when awarding ROC or similar support mechanisms.

The wider application of CM in larger wind turbines, and therefore all future off-shore turbines potentially poses a problem with the expert skills required to support interpretation of data. The aim of the project was to provide a basis to integrate expert knowledge more efficiently.

The project developed a broad based prototype system with the expectation that this would be optimised in following stages, once performance and value had been demonstrated. The prototype comprised a modular set of subsystems which were connected back into a central hub where the data fusion occurs. Each subsystem dealt with a different area of monitoring: blades, drivetrain, generator, tower and SCADA. “Events” are defined by comparison of the parameters with a threshold level along with expert defined fault logic using correlations across parameters and time periods.

To provide improved diagnostics an holistic, or relational, model was developed. This provides a topographical link between the various components of the turbine. This operates by logging each event temporally and topographically. The component from which the event has been raised is checked on the relational model, along with any simultaneous events on other components. The relational model checks for the links with other components which may be associated with the event, and for simultaneous events on other components. The symptoms related to each event are compared to those stored in a pre-defined Failure Modes and Events Analysis (FMEA) table, giving a set of possible diagnoses as to the cause. Where there is no specific FMEA entry, but connections are apparent through the relational model, conclusions can be drawn about possible sources for the event, possibly including components for which there is no specific measurement.

Damage modelling was developed for the drivetrain and other subsystems to support improved prognostics. The drive-train modelling is based on meta-models of the gearbox from pre-processed numerical simulations across a range of load conditions. The measured multi-axis loads from the blades, transformed to the nacelle axis, allowed real-time damage to be calculated across the gearbox components. Fatigue damage on the blades was estimated by using stress cycle counting combined with glass composite material fatigue properties. Models for tower damage, generator brush wear and electrical pitting of bearings were also implemented.

The platform of condition monitoring capabilities created by the project is significantly wider than has previously been available to the industry and offers the possibility to enhance cross-turbine performance and fault understanding. However, the wide range of capabilities defined in the scope of work also resulted in many technical challenges. These included: reproducing a stable vibration based CMS, which included damage modelling; initial quality control issues with the rotor monitoring hardware; and debugging of the new relational models and associated GUI. These were compounded by network access and slower communications on older sites.

The project aim was to validate the potential of this new set of capabilities to support further development. Even without the longer development period it was recognised with only 4 turbines in the trial, and the known fault frequencies, this would result in limited real faults being seen during the agreed trial period. Therefore validation would necessarily also involve off-line aero-elastic modelling of faults, retrospective analysis of real failure data and simulations.

As expected there have been limited validation events captured on the 4 turbines. However, the project was able to use transitory events to demonstrate system sensitivity and the potential for holistic information to improve the interpretation of events. Along with off-line work these give reasonable confidence in the monitoring systems' fault detection capabilities across a range of potential fault types. The limited events meant detection rates could not be validated nor could the value in the application of a holistic relational model.

The system has shown that real-time damage modelling can be used in the wind industry but has identified a key challenge in validation. The damage values being produced refer to parts with a 20 year design life, so no detectable damage would be expected in the short term. It would be beneficial to estimate the uncertainty associated with the life usage parameters, to assist decision making based on the information. With this understanding there are potential savings through the optimisation of inspection and maintenance using this new information, but specialist drivetrain expertise is required to build and calibrate these models. Unfortunately the dependence on the supplier and the availability of detailed design information is a disadvantage.

The incorporation of real-time SCADA fault detection algorithms has shown the potential for this area of monitoring, in particular when associated with other forms of data as occurs here. The ability to cross correlate blade load information which may indicate a pitch or yaw error with SCADA data showing a real-time Power Curve deviation is very powerful. Even using simpler methods than developed here to check relationships within SCADA data has the potential to provide significant savings to operators, although the University of Strathclyde (UoS) work has provided a good platform to minimise false positives in such monitoring.

Given the development issues some aspects of the programme were not delivered to the extent that had been expected. These were a wider set of cross-turbine correlations between operating conditions and sensor responses and integration with an existing vibration CMS. Both capabilities were demonstrated but not enough resources remained to fully implement during the project.

The prototype systems at the end of the project were able to demonstrate a number of technologies and provided a number of learning points. However, even though cost savings of >0.5p/kWh could be possible; integration into a single platform was not considered a viable route for further development of a product. EDF and E.ON intend to continue to develop SCADA based fault logic.

EXECUTIVE SUMMARY OF CONCLUSIONS

The overall experience leads to the conclusion that holistic data analysis and associated relational models would be applied more successfully at a different place within the measurement chain. To act as the control function for multiple data collection activities proved to be too ambitious for a new system being developed from scratch, especially given the advanced state of development of the condition monitoring market. The niche for a holistic monitoring system is as a set of advanced data fusion tools, fault logic and cross farm analysis sitting at the fleet-wide central database. Individual monitoring systems should then send appropriate values back to such a database to allow the temporal and topological correlation that can be applied by data fusion. In this case the holistic system would provide the overview of condition, but any examination of the data by experts to verify the situation would need to be done on the appropriate individual condition monitoring system.

There is some work to reach this level of sophistication for central databases, but this is potentially a much more tractable problem than the development of multiple hardware interfaces in the hostile environment of an offshore turbine. Much of the work involves persuading OEMs to open pre-existing software interfaces to turbine data they are already collecting for themselves.

The on-turbine testing has provided limited opportunities for field validation but transitory events have demonstrated system sensitivity. Along with several off-turbine validation approaches, this suggests that the system has a wide range of fault detection capabilities. However, the dataset is far too limited to give any validation of failure detection rates.

The ability to support “event” conclusions from one sub-system with data from across the turbine potentially allows better diagnostic decisions by reducing false positives. Cross correlation of rotor and SCADA data and fault algorithms is particularly powerful. However, much greater configurability than delivered in the prototype would be necessary to realise this potential.

The application of holistic relational models has been applied for the first time in wind turbines across a wide dataset. This capability shows promise to codify expert knowledge but would require further development and validation.

The use of prognostic damage models provides additional information to support inspection and maintenance optimisation. However, there is a need to build more experience with these models.

The introduction of SCADA fault algorithms into the system reflects current thinking in wind turbine fleets, and the models produced represent advanced examples of what can be achieved. These real time algorithms can be implemented in the control system or a data historian.

EXECUTIVE SUMMARY OF RECOMMENDATIONS

Operators should adopt suitable data correlation techniques for monitoring condition as well as performance.

The development of prognostic damage modelling should be pursued, in particular using simplified inputs from wind solicitation to gain experience in its application.

Any holistic condition monitoring system should be based on established providers of condition monitoring systems feeding data to an off-site database along with data from the wind turbine control system. The holistic element should then be used for scrutiny of this database to identify links, trends and patterns.

The potential value in judicious use of condition monitoring systems is significant, and could make a direct impact on the affordability of off-shore wind power. Based on the insights gained during the O&M cost modelling, all operators should adopt a high level of condition assessment across a wide range of fault types. The cost modelling work undertaken in the project should be widely disseminated.

Condition monitoring and process data should be made available via a single platform. Data access restrictions imposed by the OEM should be considered unacceptable.

Purchasers of Wind Turbines should include the condition that any data generated from any system on the wind turbine is the property of the wind turbine owner from first commissioning.

OEMs and operators should provide open access information about reliability and component life, in order to facilitate improved maintenance regimes for all.

Prepared by	**Approved for publication**

Master copy signed by D N Futter & P Jeffreys (19/05/2014)

D N Futter	**P Jeffreys**
Technical Head	**Department Manager**
Condition Monitoring	**Gas Turbines and Condition Monitoring**

UNRESTRICTED

This document was prepared by E.ON New Build & Technology.

Telephone +44 (0) 2476 192900 (please ask for customer administration)
Fax +44 (0) 115 902 4001
E-mail entcustomeradmin@eon.com

CLIENT DISTRIBUTION LIST

EF	Mr M Smith	Energy Technologies Institute
EF	Mr S Swatton	Energy Technologies Institute
EF	Mr R Chevalier	EDF Energy
EF	Mr D Infield	Strathclyde University
EF	Mr D Gilbert	Moog Insensys
EF	Mr E Miguelanez	SeeByte
EF	Mr M Whittle	Romax

CONTENTS

1 INTRODUCTION AND BACKGROUND

The InFLOW project was initiated with the goal of developing a holistic, predictive condition monitoring system. The aim of the project was described as follows:

> “This project will produce a holistic condition monitoring system for offshore wind turbines that will predict damage to any type of turbine, by means of monitoring and analysis of all critical sub systems incorporated within that type of turbine. This will enable early detection of incipient faults, facilitating planned intervention and thus resulting in reduced intervention cost and avoidance of costly secondary damage.”

The project goals were stated as:

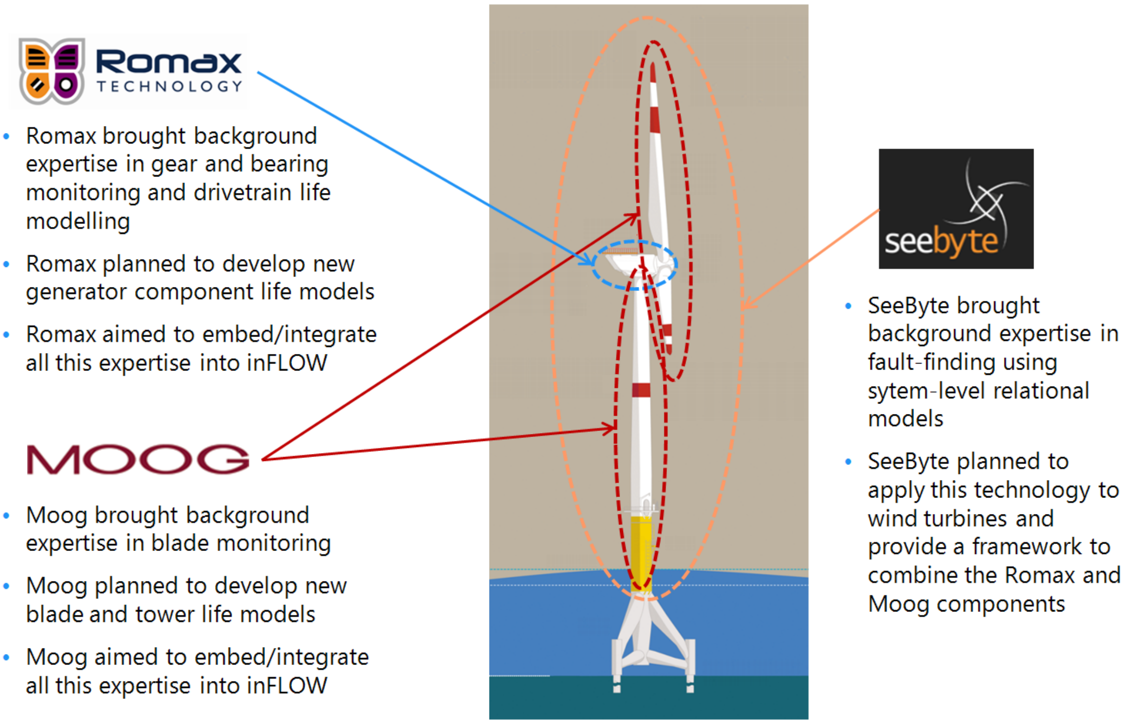
“1. The project will result in an estimated reduction in the cost of electricity produced by offshore wind farms of approximately 0.5p per kWh.”

“2. Based on consortium estimates, this project could increase average offshore turbine availability from around 90% to around 95%.”

“3. [To deliver] the ability to gather data from the entire turbine, in order to detect the CAUSES of problems, such that they can be corrected BEFORE expensive damage occurs in large components, such that the cost and downtime of replacing these large components is AVOIDED.”

“4. [To deliver] the ability to PREDICT an impending failure well in advance of its occurrence, such that the turbine can be operated in a way that extends the life of this component, giving time to arrange the relevant equipment and replacement parts BEFORE the failure occurs, thus preventing downtime, and further secondary damage.”

The following figure shows the project vision and the key technology the main developers brought to the project:



- Romax brought background expertise in gear and bearing monitoring and drivetrain life modelling
- Romax planned to develop new generator component life models
- Romax aimed to embed/integrate all this expertise into inFLOW

- Moog brought background expertise in blade monitoring
- Moog planned to develop new blade and tower life models
- Moog aimed to embed/integrate all this expertise into inFLOW

- SeeByte brought background expertise in fault-finding using sytem-level relational models
- SeeByte planned to apply this technology to wind turbines and provide a framework to combine the Romax and Moog components

EDF provided experience in the development and deployment of novel condition monitoring techniques, including prognostics.

E.ON brought experience of routine delivery of condition monitoring to large fleets, including wind turbines.

The University of Strathclyde (UoS) provided experience of SCADA analysis and cost modelling.

The data from the distinct monitoring technologies were brought together in a single system, along with SCADA information; information regarding physical connections between the different turbine components was captured in a relational model. The Seebyte Recovery system delivers all the functionality for the holistic aspects of the system, which underpins one of the key differentiators for the system; existing condition monitoring systems generally focus on one part of the system only.

The relational model is not a data correlation model. It is a way of correlating individual events that are detected by threshold crossings. These events are related back to a Failure Modes and Effects Analysis (FMEA), which provides a range of possible causes for the identified exception. Direct matches are identified as primary causes. A process of logical relationships is then used to rank possible sources for the “fault” including plant components which are not directly monitored, but which have a connection to the parts identified. These are identified as secondary or tertiary causes.

In order to compile a suitable FMEA and relational model, common anomalies and relationships first had to be defined in a consistent format that could be easily used by the recovery system. The resulting system does include an integration of all the data outputs onto a single monitoring output, but this in itself is not a major step forward - only the intransigence of manufacturers in releasing data-feeds has previously stood in the way of this, and the inFLOW consortium cannot easily influence that. It is the correlation of faults and/or events across the entire system which can deliver extra benefit.

It is also worth noting that the relational model does not produce a ‘normal model’ for a system and flag deviations, as would be the case for a classic condition monitoring system. Such systems are for expert users who have the capability to make the diagnosis without assistance from software. The intention of inFLOW was to support operators who have limited or no in-house expert CM resource. System experts supplied the knowledge to define the specific relationships and fault logic for all the subsystems; this information can then be played back to those with less knowledge. However, the limiting factor to this approach is the clarity and adaptability of the FMEA and relational model.

The project specified and delivered four prototype systems to test the concepts outlined above. The general feedback on the performance of these systems is that they have not reached their potential, and are not sufficiently developed to be the basis of a viable product in its present form.

2 SYSTEM SPECIFICATION

The project followed a typical system specification development process:

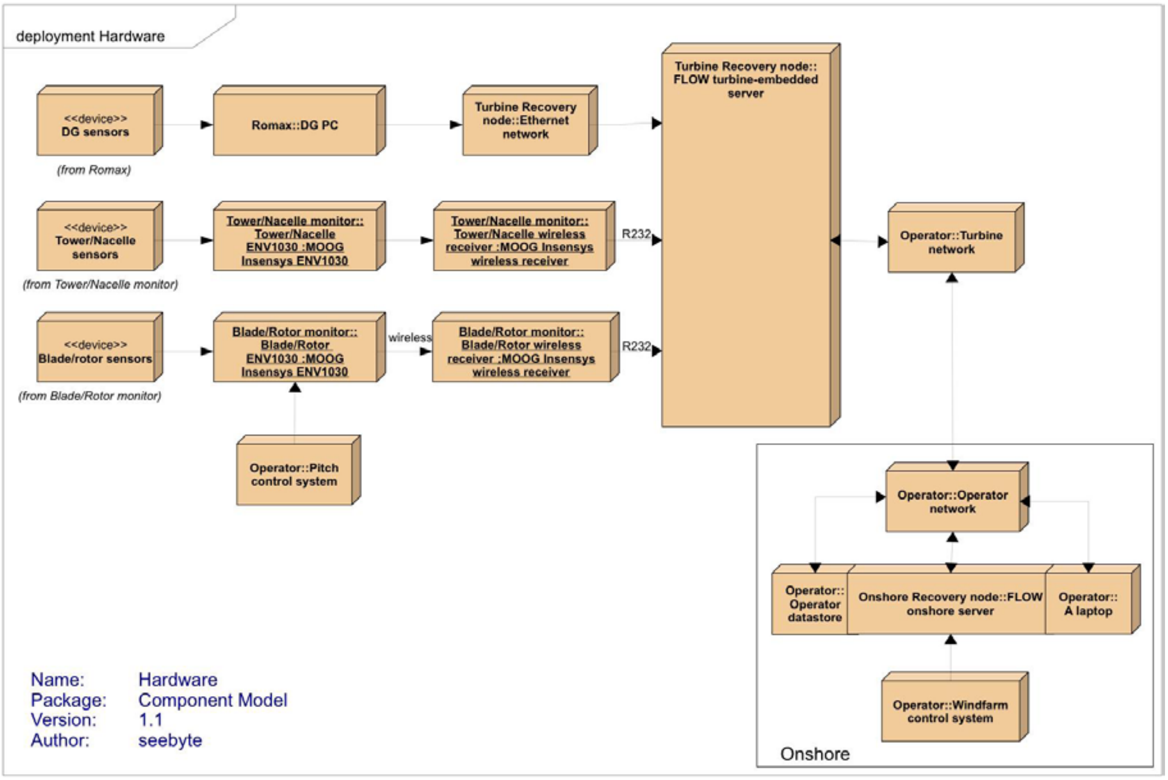
- User requirements were defined by E.ON & EDF operators and other technical experts through a structured workshop which produced a user requirements list, which was subsequently reviewed and agreed. In addition, a requirements analysis document was also produced to support this process;

- System requirements were then defined by developers and a design proposed.

Due to the later than planned start to the project, these requirements were developed in a shortened timescale. With hindsight more time should have been spent on this critical phase. In addition resources should have been planned to adapt systems once the benefits case had been better understood.

3 DESCRIPTION OF THE RESULTING INSTALLED SYSTEMS

The resulting prototype system comprises a modular set of subsystems which are connected back into the recovery box. This is summarised diagrammatically as below:



Implicit in this architecture is the principle that data will also be obtained from the SCADA system and any other relevant sources.

Each subsystem relates to a particular monitoring function, returning data to the recovery box to facilitate ongoing monitoring of the correlations between events on the various systems. All thresholding functions are performed within the recovery box, and related to events, with particular attention being paid to the correlation between events on different systems. There is also transfer of data between systems, in particular to allow the Romax life models to work with a combination of input torque, thrust and nod data from the blade monitoring systems.

The Recovery system works by comparing input data (either raw, derived values or from fault logic) to a series of thresholds. When a threshold is exceeded the system logs an “event” which is recorded in the alarm table. The variable that has triggered the event is then used to identify a possible cause from the failure modes and effects analysis, and the component from which the variable was measured is checked on the relational model to identify connected components, which may or may not be monitored with a sensor.

The Rotor Monitoring System (RMS) from Moog Insensys collects information from the blade strain sensors and reprocesses this to give information about the bending moments (and calculates mass) of each blade, and aggregated information relating to nod and twist forces, out of balance forces and aggregated torque transmitted to the input shaft. Life usage for the blades is estimated by rainflow counting of stresses seen on each blade.

The Romax box collects vibration data from sensors from a proprietary National Instruments Analog-digital convertor. The data is aggregated internally using band pass filters, demodulation techniques and statistical tests such as kurtosis. This requires prior knowledge of the kinematic data relating to the drivetrain, including bearing configurations, gear teeth numbers, shaft speeds, etc. The various individual damage indicators are then aggregated into a variety of “health indices” which is based on conventional techniques for monitoring multiple outputs from the standard signal processing techniques. This approach provides supporting data for vibration engineers to complete the diagnosis.

The Romax box also makes calculations of life usage, based upon a meta-model derived from a design model of the gearbox. This is a turbine specific model which has to be provided for each turbine design. Similar prognostic models are used to provide monitoring of the generator and the brush gear life usage. This new approach shows potential, due to its long term prognostic capability, but requires further work to raise its technology readiness level. Design codes are supposed to account for significant over-loads within the life calculation, but published reliability data show that many components fail before their expected design life [1-4]. The prognostic model should be seen as a tool which indicates trends, and gives some long term prognosis of asset health; this approach is complementary to conventional vibration based techniques as it enables the possibility of medium/long term asset management planning.

SCADA fault logic algorithms were developed by the University of Strathclyde (UoS) in the form of Matlab code which was then recoded in Recovery [5, 6]. These give real-time analysis of Power Curve deviations and in addition Pitch and Yaw fault analysis algorithms. This approach would work for other faults and a number of options were identified by the team including gearbox temperature analysis and cross-farm correlations.

The interface gives a first level view screen showing which turbines are in alarm, and is intended to providing a diagnosis of why this has occurred, based upon the FMEA. This is the limit of functionality for operators, but it should then be possible for expert users to rapidly interrogate each alarm to investigate the cause further, and adjust threshold levels if necessary. The recovery system also uses the relational model to distinguish topographical relationships between turbine parts identified as the source of the errors by the FMEA.

The holistic approach is delivered through the temporal and topographic correlation of faults, which should deliver greater insight into the source of any fault. Unfortunately the tuning of the FMEA and the limited validation data has not allowed this capability to be fully developed.

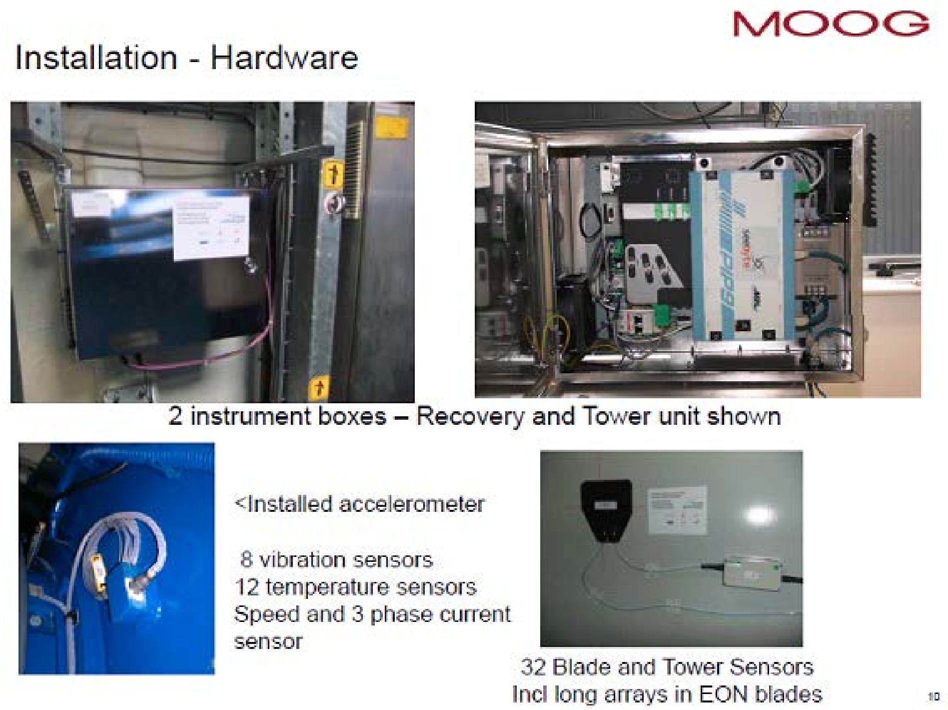
4 IMPLEMENTATIONS

On the EDF turbines it was possible to implement the full system:

- Gearbox, generator, blade and tower monitoring;
- SCADA data and fault logic;
- Damage models for gearbox, generator components, blade & tower;
- Distributed GUI interface.

On the E.ON turbines the installation comprised gearbox, generator, blade and tower monitoring. Plans to integrate to the SCADA could not be achieved due to the local network infrastructure and licensing limitations. In addition the use of the GUI was not compliant with the E.ON IT security policy regarding external connections; however, a full implementation of the GUI was possible via the ENT offices.

The following figure shows some of the key hardware from the installations:



Installation - Hardware

MOOG

2 instrument boxes – Recovery and Tower unit shown

<Installed accelerometer

8 vibration sensors
12 temperature sensors
Speed and 3 phase current sensor

32 Blade and Tower Sensors
Incl long arrays in EON blades

10

A full validation exercise was carried out by the project; a summary of key development gaps is as follows:

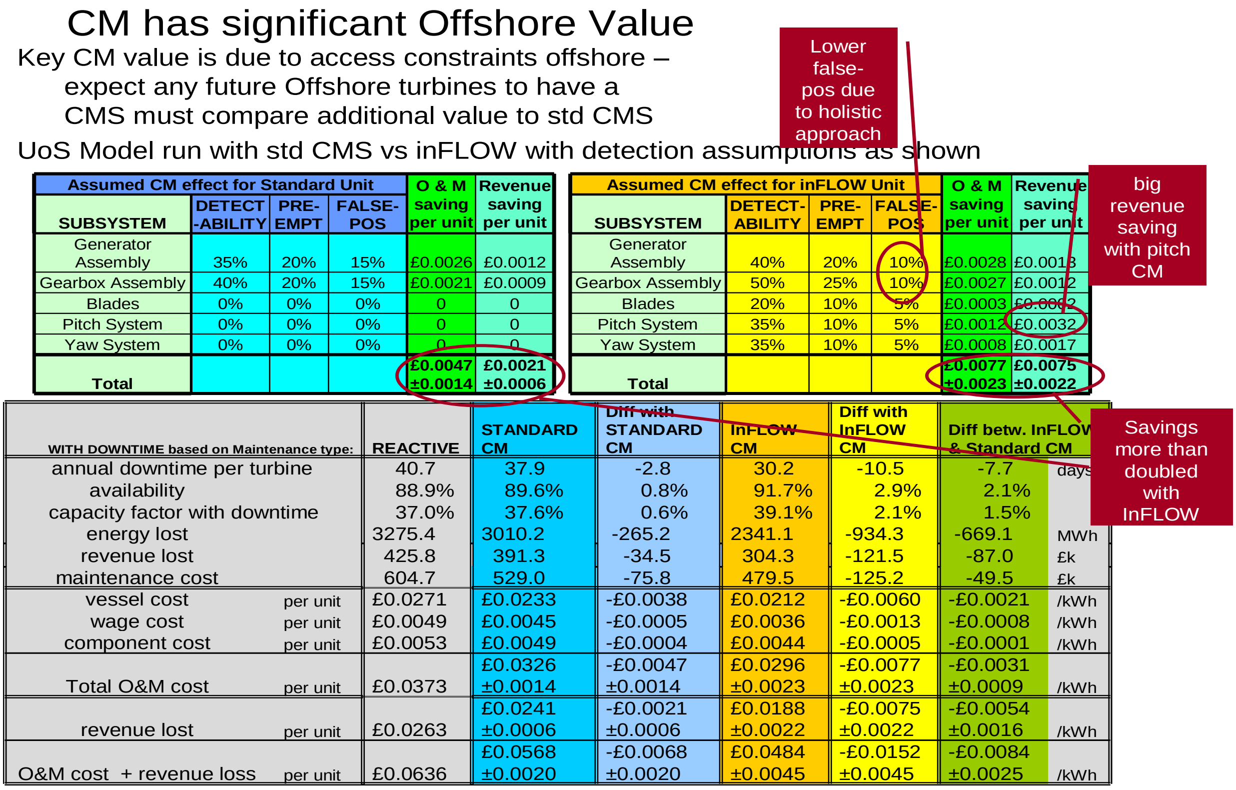
- Introduction of data-driven correlations to identify ‘events’;
- Improved user configuration (e.g. ability to switch off a failed channel);
- FMEA for drive-train fully tied in;
- Diagnostics support through Health Management panel to be demonstrated;
- Cumulative damage modelling experience to be developed.

It was recognised that compared to some off the shelf systems the following elements would need addressing:

- Addition of a configuration interface (measurement set up, alarms, descriptors, fault logic, kinematic data etc);
- Simple diagnostics against list of common faults to be displayed;
- Faster data display;
- Some changes to models to be accessible by users.

5 VALUE AND BENEFITS DEMONSTRATED BY THE PROJECT

A wide ranging cost benefit case was constructed by the University of Strathclyde, based on publicly available failure databases and some data from the operators. This was combined statistically to derive the likelihood of events being detected in sufficient time to mitigate the impending failure, concluding that the inFLOW system could save 0.8 p/kWh more than a conventional CMS system. The analysis can be subdivided into the systems on the turbine, and the effect of the holistic approach.



CM has significant Offshore Value

Key CM value is due to access constraints offshore –
expect any future Offshore turbines to have a
CMS must compare additional value to std CMS

UoS Model run with std CMS vs inFLOW with detection assumptions as shown

Lower false-pos due to holistic approach

SUBSYSTEM	Assumed CM effect for Standard Unit DETECT-ABILITY	PRE-EMPT	FALSE-POS	O & M saving per unit	Revenue saving per unit
Generator Assembly	35%	20%	15%	£0.0026	£0.0012
Gearbox Assembly	40%	20%	15%	£0.0021	£0.0009
Blades	0%	0%	0%	0	0
Pitch System	0%	0%	0%	0	0
Yaw System	0%	0%	0%	0	0
Total				**£0.0047 ±0.0014**	**£0.0021 ±0.0006**

SUBSYSTEM	Assumed CM effect for inFLOW Unit DETECT-ABILITY	PRE-EMPT	FALSE-POS	O & M saving per unit	Revenue saving per unit
Generator Assembly	40%	20%	10%	£0.0028	£0.0013
Gearbox Assembly	50%	25%	10%	£0.0027	£0.0012
Blades	20%	10%	5%	£0.0003	£0.0002
Pitch System	35%	10%	5%	£0.0012	£0.0032
Yaw System	35%	10%	5%	£0.0008	£0.0017
Total				**£0.0077 ±0.0023**	**£0.0075 ±0.0022**

big revenue saving with pitch CM

WITH DOWNTIME based on Maintenance type:		REACTIVE	STANDARD CM	Diff with STANDARD CM	InFLOW CM	Diff with InFLOW CM	Diff betw. InFLOW & Standard CM	
annual downtime per turbine		40.7	37.9	-2.8	30.2	-10.5	-7.7	days
availability		88.9%	89.6%	0.8%	91.7%	2.9%	2.1%	
capacity factor with downtime		37.0%	37.6%	0.6%	39.1%	2.1%	1.5%	
energy lost		3275.4	3010.2	-265.2	2341.1	-934.3	-669.1	MWh
revenue lost		425.8	391.3	-34.5	304.3	-121.5	-87.0	£k
maintenance cost		604.7	529.0	-75.8	479.5	-125.2	-49.5	£k
vessel cost	per unit	£0.0271	£0.0233	-£0.0038	£0.0212	-£0.0060	-£0.0021	/kWh
wage cost	per unit	£0.0049	£0.0045	-£0.0005	£0.0036	-£0.0013	-£0.0008	/kWh
component cost	per unit	£0.0053	£0.0049	-£0.0004	£0.0044	-£0.0005	-£0.0001	/kWh
Total O&M cost	per unit	£0.0373	£0.0326 ±0.0014	-£0.0047 ±0.0014	£0.0296 ±0.0023	-£0.0077 ±0.0023	-£0.0031 ±0.0009	/kWh
revenue lost	per unit	£0.0263	£0.0241 ±0.0006	-£0.0021 ±0.0006	£0.0188 ±0.0022	-£0.0075 ±0.0022	-£0.0054 ±0.0016	/kWh
O&M cost + revenue loss	per unit	£0.0636	£0.0568 ±0.0020	-£0.0068 ±0.0020	£0.0484 ±0.0045	-£0.0152 ±0.0045	-£0.0084 ±0.0025	/kWh

Savings more than doubled with InFLOW

5.1 Rotor

It has been shown that it is possible to fit an optical based strain measurement system inside the blades, and that the outputs show good correlation with wind and load conditions. Aeroelastic modelling has shown it should be possible to detect pitch faults via blade imbalance. At present a blade specialist is required to interpret the data, as might be expected. There have been limited actual specific events which have occurred on the EDF turbines; the events that have been observed have related to high wind speed or highly turbulent conditions showing good system sensitivity, some similar features were observed on preliminary data from E.ON turbines. Yaw events have also been seen suggesting the system can be used to detect persistent Yaw errors. In addition imbalance events were observed during some start-ups. Blade life models were implemented quite late in the project, so there will be no opportunity to validate the life usage models. The internal functioning of the algorithms was developed by Moog with a theoretical basis provided by external consultants. All details are fully documented and could be developed and used further by the industry.

5.2 Drivetrain

There is significant value in condition monitoring of the drivetrain, but this is already being realised on a large proportion of the wind turbine fleet through standard vibration analysis tools. This is of the order of 0.7±0.2 p/kWh. There is no additional benefit from using the basic vibration data analysis methodologies, which are widely available on the market. The Romax health indices are intended to provide a simplified event flag for use in the recovery system in response to complex vibration events, giving relevant diagnostic information via the FMEA table. In practice this “black-box” approach requires further supporting data to be available to the end user, than is the case with inFLOW, to allow experts to gain confidence in the generated outputs.

5.3 Electrical

There is some value in monitoring the condition of the electrical machines, based on relative failure rates, but differences in designs make it difficult to attribute a major value to this capability. The Romax brush wear model could potentially assist in planning inspections/ exchanges. In practice the models have not shown any significant capability.

A generator failure at one of the EDF sites occurred shortly after installation, but the failure mode was not within the scope of the FMEA with the available instrumentation, and not all the thresholds had been set. Retrospective analysis identified a clear change in the vibration spectra, but the vibration analysis experts at EDF and E.ON confirmed that the symptoms identified (rotor bar passing frequency with sidebands at line frequency at the DE bearing) were unlikely to correspond to the actual failure that had occurred (flashover between the winding tail and the slip-ring connection at NDE).

There have been no other alarms since all the thresholds have been set up, but nor have there been any other reported faults to date. The theoretical basis of these models has been made available, so it could be possible for further enhancement of the capabilities, based on the algorithms and further testing.

5.4 Tower

This capability was implemented using strain gauges as load data was required for fatigue modelling. This also gave a consistent value for natural frequency which gives a potential way to monitor for changes in tower/foundation strength. FE modelling was performed by TWI and showed that scour could be monitored using changes in natural frequency. Whilst there is value in this information, especially for offshore turbines, natural frequency can be measured in simpler ways. Fitting an array of strain gauges would generally only be considered worthwhile for intensive investigative campaigns or design studies.

5.5 SCADA

The consortium has developed an automated monitoring method using data from the SCADA to monitor yaw and power curve to detect deviations from the expected values. This has been implemented inside the recovery system logic, tested on the EDF turbines, and has shown to work. However, there has not been any opportunity to fully validate the technique, since there have been no significant faults on the EDF turbines (one minor power curve deviation has been seen). This capability would be valuable to operators to maintain turbines at optimum performance at all times, provided the sensitivity and reliability of the method are proved to be sufficient.

There is potential to widen this approach to carry out comparisons between turbines on the same farm, for example to detect wind direction anomalies, and to compare running temperatures of the drivetrains.

5.6 Damage Modelling

Real time damage models are a new industry capability. Damage modelling is separate to the relational model or specific fault indicators within data from the sensors, but it is built from load sensor data to generate extra information available to operators and engineers to support decision making. High damage rates can then be used as a flag of anomalous behaviour to contribute to the FMEA and the relational model. In the long term these models might predict times to failure of specific components around which operators might modify inspection and maintenance schedules, or to learn about damaging conditions under which it may be better to forego generation to reduce future maintenance costs.

Through estimated life usage the damage model provides new capabilities which may help with maintenance planning and provide long term forecasts which will assist in realistic budgeting. Inspection and maintenance planning, particularly for offshore sites, could be very valuable in scheduling inspections and optimising any gearbox replacement projects. The damage model is developed from a first principles model, but it also comes with a disadvantage that this type of model is specific to the drivetrain and requires specialised knowledge to develop models for different drivetrain designs. Within the development of the prototype this required that Romax build the drivetrain damage model; although potentially, the functionality could be developed to allow other drivetrain experts to build models and import them, although still limited to using the RomaxWIND software. They would then be automatically converted into prognostic models.

The drivetrain prognostic models give component damage caused by fatigue failure mode. These models are based upon Romax drivetrain simulations using L10 fatigue life calculations. The L10 fatigue life is the number of cycles after which 90% of a group of apparently identical components would still be expected to be without failure. It must be recognised, however, that wind turbine drivetrains experience highly variable loading and operating conditions, and that many other failure modes exist. Where the failure modes are unknown the fatigue life calculations should be interpreted with care, and other types of data (i.e. conventional CMS data, SCADA data and O&M records) should be used in conjunction with the damage model to arrive at an assessment of the component health.

Validation of the damage models is a long term task with a large sample of turbines and could not be fully achieved in the short on-turbine validation exercise carried out in the InFLOW project. Whereas the vibration analysis capabilities could be validated offline using historical data, the damage models require load data from the blade monitoring unit, for which little data is available, and that which exists is not within the dataset of a conventional CMS. To validate and improve the accuracy of the prognostic models will require a process of long term validation and calibration and as such the models should only be used by experts or operators as an additional piece of information to support decision making.

5.7 Holistic

It is the holistic benefits which could act as the differentiator for the inFLOW system: any of the individual benefits could be accrued through fitting a monitoring system to deal with that single area only; in addition any of the damage models could be introduced separately. The holistic approach gives a number of theoretical advantages with respect the interaction between faults on different subsystems. The existence of multiple indicators from different systems also improves the confidence in the analysis, giving the potential to increase fault detection rates and to reduce false positives. The expected benefits of the holistic approach are predicated on the increased accuracy of monitoring resulting from taking all items together, but this is very difficult to validate, especially during a relatively limited trial period.

In this respect, fuller implementation of the Recovery diagnostic system through rigorous population of the FMEA would be needed, but even with that in place a great deal more data analysis capability would be necessary to exploit the potential to learn about the wind turbine systems.

Overall the holistic diagnostic tools have given only limited output.

5.8 Development and Communications Issues

The systems only reached a stage where they were viable for performing monitoring after October 2012, with considerable system bugs which were not removed until the end of the project. Prior to this the systems were collecting data, but collection and analysis was difficult. Communications issues were so bad for the E.ON turbines that no real-time analysis at all was possible until March 2013; while EDF had been able to make some comments on data from November 2011.

These issues significantly reduced the validation work which the project was able to perform.

6 MARKET STATUS FOR CONDITION MONITORING

The wind turbine market runs on tight margins, which is why there has been a requirement to underpin the industry with guaranteed tariffs. Reducing the cost of energy is a key driver for the industry, but there is very little funding available for investments, even where a good return is likely. Whilst this may not seem logical, it is the reality of commerce that you cannot spend money that is not available.

Unfortunately the nature of a multi-faceted system such as inFLOW is the reduced return on investment compared to conventional vibration based CMS and SCADA analysis. CMS implementation costs are considered borderline for implementation at €10,000 per turbine (fully installed) despite a claimed return on investment of up to 80x. The reluctance is due to the large multiplier - considering a fleet of 1000 turbines means the investment quickly becomes significant. There is also the factor that the savings are of money that was not necessarily budgeted to be spent, due to over-optimistic claims of OEMs as to component life and accuracy of construction. Requiring statutory disclosure of reliability data, as done in the German market, could improve future estimates of expected through life costs.

Every extra investment in condition monitoring provides a further reduction in cost of energy across the life of the turbine. However, the incremental rate of reduction reduces, and the cost of investment, being front-loaded and distributed across a large fleet, is not attractive. In general, the IRR is the key factor in deciding an investment, rather than simply the reduced cost of energy.

SCADA data analysis has much lower implementation costs; rudimentary off-turbine post analysis can be achieved with simple spreadsheet tools, and savings can be made relating to increases in turbine output or efficiency, although again this generally only returns the machine to the intended levels so does not represent increases in planned income, only reduced losses. This simple analysis for performance purposes is already in widespread use across the industry, and there is definite scope to widen the application of similar algorithms and increase the level of automation, particularly offshore.

The most expensive parts of the InFLOW system relate to parts with relatively low detectable failure rates, i.e. the blades. The data from the system is potentially very useful for diagnostics of pitch and yaw faults as the root cause of power losses and calculation of inputs to damage modelling (nod, thrust, torque), but there are potentially cheaper ways of identifying some of the effects, for example input torque loads to the gearboxes can be estimated from data available in the SCADA, particularly relating to damaging events such as gusts or emergency stops, and can be used for initial modelling of damage.

The greatest savings attributable to the tower monitoring system can actually be achieved through use of simple accelerometers of the correct specification connected to a suitably configured CMS system.

The condition monitoring market is crowded, with dozens of suppliers of reliable equipment vying to differentiate their product over the competitors. It is therefore hardly surprising that many of these have moved into the wind turbine sector, as the access issues mean that every turbine needs an analyser. The basic requirements of the systems are unchanged from standard equipment, but enhanced lightning protection and resistance to marine environments and physical movements have been incorporated. The main players are SKF, Prufteknik, Gram and Juhl, Bruel and Kjaer, Bentley Nevada, SPM and Emerson, although cheaper suppliers such as Commtest and Bachmann are making significant strides in functionality.

Prices vary relating to the complexity of the product and associated software, but ranged between €3,000 and €9,000 per turbine (plus around €8,000 installation) at the start of the project. Due to the maturity and competitive nature of the market, price was already about as low as could realistically be achieved, but there has been a continual increase in the capabilities of the products (particularly at the lower price points), and improvements in installation techniques.

Blade condition monitoring systems are less common; however, IGUS, Fos4X and Siemens all now have offerings in the market. The general trend is towards a situation where turbines built with Individual Pitch Control would be fitted with such systems, but installation purely for monitoring purposes from new is unlikely, and widespread retrofitting is prohibitively expensive. The systems may find a niche for design studies or troubleshooting investigations where one or two turbines of a large farm could be retrofitted to understand a specific problem that arose.

There are a number of providers of data correlation software, with the market leader being SmartSignal ™ (now a subsidiary of GE); however INSTEP, PredictIt, Ansys, Siemens and others all provide viable products, and in-house software can easily be written to provide the same capabilities (both EDF and E.ON have such capabilities). These have all begun to focus on the wind energy sector since the project began.

This leads us to a market position whereby the pricepoint of a full InFLOW system is significantly greater than existing competitors with established track records.

7 STRENGTHS AND WEAKNESSES OF THE PROTOTYPE

7.1 Strengths

The holistic nature of the system means that information from disparate parts can be brought together to give more information about the condition of the plant.

Loading information on the gearbox can be used to derive calculations of “life used” to help prioritise the exchange of gearboxes on turbines that have been subject to more extreme load conditions. However, cumulative solicitation of wind data could also be used to indicate gearboxes which have been subjected to extreme conditions.

Blade loadings give a much clearer indication of what is happening within the incoming wind field, and how the turbine is responding.

Real-time SCADA power curve analysis is available to ensure optimum turbine performance.

A single interface for all data provides a consistent working platform for the diagnostic engineer, speeding up and improving the confidence of diagnostic decisions.

The system provides the ability to display, trend, monitor and compare between all the Wind Turbine descriptors coming from different data sources (SCADA, blade, gear monitoring etc.)

7.2 Weaknesses

In this project it was not possible to replicate the wide ranging functionality and configurability available on existing vibration monitoring systems. Given that most new wind turbines now have vibration monitoring systems installed as standard it would be better to interface with these systems rather than attempt to compete in a very crowded and price competitive market.

Explicit data correlation tools which can be defined in response to turbine changes are a requirement.

The lack of configuration tools within the interface severely restricts the ability to improve and “tune” the system performance and diagnostic capabilities.

The pricepoint is too high to be competitive.

The deployment to new turbine types requires reworking of certain parameters by the suppliers.

The present system does not offer an efficient diagnostic interface.

The system does not include the possibility to generate automatic heath assessment reports.

8 IMPLICATIONS FOR ASSET MANAGERS

8.1 Use of Diagnostic and Prognostic Reports

Diagnostic and prognostic reports are already widely used to help schedule maintenance in all branches of industry, although there is a tendency to focus on this as a protection function. That is to say the asset managers will have a set of pre-defined maintenance tasks that will be carried out come what may, and a further set of “breakdown” maintenance tasks. Diagnostic reports are not strictly breakdown maintenance, they are predictive maintenance tasks, leading to lower downtime and consequential damage costs, so are viewed as very useful tools for reducing costs. There remains, however, a preventive maintenance mentality where maintenance planning is concerned.

One of the key users of these techniques are the OEMs. During warranty periods the use of CMS is widespread to minimise the costs to the OEM. This is done by attending to all equipment that is likely to fail prior to handover. In addition the CMS data can be used to judge the appropriate price for long term service agreement contracts, and again minimise the cost to the provider during this period.

8.2 Industry Adoption of these Technologies

Industry is willing to adopt any technique which leads to lower costs, and many companies are keen to become “informed buyers” with specialist in-house knowledge to allow them to challenge manufacturers’ claims and charges. There is a very low philosophical barrier to adopting these techniques, but any investment is very strongly challenged.

There is also a structural issue: many windfarms are maintained by local sub-contracting companies who do not receive the financial benefits from condition monitoring, and may even view it as a threat to their existing preventive maintenance routines.

Finally there is a very strong emphasis on availability which can affect the judgement of site managers when a fault is reported, due to a reluctance to switch off any wind turbine until it is obviously broken. This is a typical symptom of short-termism. If a subcontract company is in the last 6 months of a contract with penalties for loss of availability, there is little incentive to take a machine out of service to replace a part which won’t completely fail until after the end of the contract - even though the complete failure could lead to several weeks of downtime compared to a few hours’ work when tackled early.

8.3 Changes to Current Practices

A system of this holistic nature could allow a number of changes to current practices. The key area is around planned maintenance scheduling. If it is judged that the gearboxes in a farm will not survive the life of the farm, then a system of this nature can be used to define the schedule of changes, so that those with the greatest life usage are switched out first. This is a situation that asset managers are striving for, but have not yet achieved.

The system could also provide a much better differentiation from turbine to turbine as to whether planned maintenance is actually needed. Some locations in a farm suffer much less than others due to differences in turbine duty and turbulence in the incoming wind. This could allow maintenance schedules to better account for these differences, for example the omission or deferral of planned maintenance.

In addition to these standard practices the holistic system gives the opportunity for tuning of the behaviour of the turbines. In cases of minor damage the system could be partially de-rated to protect vulnerable parts, in order to optimise the life available until a convenient opportunity (e.g. a scheduled arrival of a crane vessel). There are also potential benefits in continuous assessment of the performance of the turbine with respect to its load curve, as opposed to periodic review as normally performed at present.

9 LESSONS LEARNED FROM THE PROJECT

A number of lessons have been learned about the development of a holistic system:

- The specification of a system should be very comprehensive and leave no room for interpretation. All compromises must be agreed across a consortium.
- Lack of understanding of detailed value drivers at the beginning of the project and the most likely way operators would use and apply the system.
- The communications issues and robustness of the system points to the need for any future design to include an enterprise based database mirror, or other similar architecture where data capture is on turbine, but data storage, analysis and alarm generation is centralised.
- The logistics of fitting the system make it very unattractive for offshore operators, but for new turbines with pre-installed data collection, then a software function to provide analysis could be implemented more easily.
- Existing CMS (vibration) systems are a mature technology, which have decades of development behind them; developing any new product to complete is not a sensible use of resources. An existing system should have been used rather than trying to start from scratch. The holistic and prognostic damage elements should sit above these functions - preferably at a farm or fleet level - as a data analysis capability.

10 POTENTIAL FOR FURTHER DEVELOPMENTS

- The future for holistic systems does not lie in a hardware solution, but should be implemented as an analysis tool sitting on top of data gathering and processing boxes, with interfaces to each of these to allow full parameter adjustment, and interfaces to the FMEA to allow the diagnostics to function and be continuously improved.
- The addition of a data correlation tool which would allow interactive development of alarms based on the interaction of multiple parameters with reference to known “good” data patterns.
- Feedback from the blade system incorporated into individual pitch control (IPC).
- Use of IPC to avoid damaging situations in turbulent or gusty conditions.
- Introduction of prediction tools for trending of parameters across the load range, possibly related to statistical summaries of site wind conditions.
- Where tower monitoring is deemed necessary, this can be incorporated into the CMS part of the system, with the appropriate frequency extraction tools.

- Incorporation of weather forecasts and therefore identification of likely windows of opportunity for maintenance.
- Cross farm data correlation tools.
- Comparison against a library of faulty patterns to enhance the diagnostic capabilities.

11 CONCLUSIONS

The overall experience leads to the conclusion that holistic data analysis and associated relational models would be applied more successfully at a different place within the measurement chain. To act as the control function for multiple data collection activities proved to be too ambitious for a new system being developed from scratch, especially given the advanced state of development of the condition monitoring market. The niche for a holistic monitoring system is as a set of advanced data fusion tools, fault logic and cross farm analysis sitting at the fleet-wide central database. Individual monitoring systems should then send appropriate values back to such a database to allow the temporal and topological correlation that can be applied by data fusion. In this case the holistic system would provide the overview of condition, but any examination of the data by experts to verify the situation would need to be done on the appropriate individual condition monitoring system.

There is some work to reach this level of sophistication for central databases, but this is potentially a much more tractable problem than the development of multiple hardware interfaces in the hostile environment of an offshore turbine. Much of the work involves persuading OEMs to open pre-existing software interfaces to turbine data they are already collecting for themselves.

The on-turbine testing has provided limited opportunities for field validation but transitory events have demonstrated system sensitivity. Along with several off-turbine validation approaches, this suggests that the system has a wide range of fault detection capabilities. However, the dataset is far too limited to give any validation of failure detection rates.

The ability to support “event” conclusions from one sub-system with data from across the turbine potentially allows better diagnostic decisions by reducing false positives. Cross correlation of rotor and SCADA data and fault algorithms is particularly powerful. However, much greater configurability than delivered in the prototype would be necessary to realise this potential.

The application of holistic relational models has been applied for the first time in wind turbines across a wide dataset. This capability shows promise to codify expert knowledge but would require further development and validation.

The use of prognostic damage models provides additional information to support inspection and maintenance optimisation. However, there is a need to build more experience with these models.

The introduction of SCADA fault algorithms into the system reflects current thinking in wind turbine fleets, and the models produced represent advanced examples of what can be achieved. These real time algorithms can be implemented in the control system or a data historian.

12 RECOMMENDATIONS

Operators should adopt suitable data correlation techniques for monitoring condition as well as performance.

The development of prognostic damage modelling should be pursued, in particular using simplified inputs from wind solicitation to gain experience in its application.

Any holistic condition monitoring system should be based on established providers of condition monitoring systems feeding data to an off-site database along with data from the wind turbine control system. The holistic element should then be used for scrutiny of this database to identify links, trends and patterns.

The potential value in judicious use of condition monitoring systems is significant, and could make a direct impact on the affordability of off-shore wind power. Based on the insights gained during the O&M cost modelling, all operators should adopt a high level of condition assessment across a wide range of fault types. The cost modelling work undertaken in the project should be widely disseminated.

Condition monitoring and process data should be made available via a single platform. Data access restrictions should be considered unacceptable.

Purchasers of Wind Turbines should include the condition that any data generated from any system on the wind turbine is the property of the wind turbine owner from first commissioning.

OEMs and operators should provide open access information about reliability and component life, in order to facilitate improved maintenance regimes for all.

13 REFERENCES

[1] Feuchtwang, J; Infield, D “Estimating the cost of offshore maintenance and the benefit from condition monitoring”; Offshore 2011 Conference & Exhibition RAI, Amsterdam.

[2] Spinato F, Tavner PJ, Bussel GJW van, Koutoulakos E, Reliability of wind turbine subassemblies, IET Renew Power Gen,2009,Vol3,Iss4,pp387-401.

[3] Wilkinson M, Hendriks B, Spinato F, et al, Methodology and Results of the Reliawind Reliability Field Study, EWEC2010 no58.

[4] Faulstich S, Hahn B, & Tavner PJ; Wind turbine downtime and its importance for offshore deployment; Wind Energy 2011; 14;327-337.

[5] Wang Y, Infield DG, Stephen B and Galloway SJ, “Copula based Method for Wind Turbine Power Curve Outlier Rejection”; University of Strathclyde, June 2013.

[6] Wang Y.et al, “Power Curve Based Online Condition Monitoring for Wind Turbines”; June 2013.