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Offshore Renewable Energy

Early Fault Detection Using SCADA Data: an exploration of E.ON's intelligent use of operational data to identify faults

Dr Conaill Soraghan, Renewable Technology Engineer

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This study explores how E.ON Technologies is making intelligent use of SCADA data to provide early warnings of potential wind farm failures.

It examines SpheriCAL, a software tool that was developed by E.ON Technologies, and looks at its performance in the field. The information for this case study was gathered through a series of interviews during August 2015 with technical experts at E.ON Technologies and the site-based operations team.

This is one in a series of offshore wind operations and maintenance (O&M)-focused case studies, supported by ORE Catapult's O&M Forum and funded by The Crown Estate and the Offshore Wind Prgramme Board. These studies aim to highlight game-changing O&M projects and share knowledge among the offshore wind O&M community.

Summary of findings

- SpheriCAL is a condition monitoring tool created by E.ON Technologies that uses bespoke advanced data science techniques to learn the behaviour of repeatable data patterns within a wind farm.
- Early fault detection is achieved by SpheriCAL, enabling avoidance of unplanned unavailability, targeting of work and opportunistic and optimised planning and logistics.
- SpheriCAL successfully completed a field trial at Robin Rigg in 2012.
- SpheriCAL has been developed pragmatically to ensure transparency, simplify the user experience and encourage uptake throughout the E.ON group.
- Implementation of SpheriCAL cultivates a more 'informed buyer', because a valuable knowledge base of maintenance history is also built up through an online portal.

Recommendations

- Access to data is critical – investing in the data historian software tool called OsiSoft PI at Robin Rigg was a primary factor in the successful trial of SpheriCAL
- Operators should ensure access to data is considered in the project design phase and in turbine supply and service/warranty contracts. Historic data sets allow reliable set up, or training, of value adding systems such as SpheriCAL that require the system to learn the behaviour of the turbines.
- Site-based buy-in to condition monitoring tools is vital: it is critical that alarms and other information provided are credible, false alarms are minimised and engineering feedback is provided to further improve the tool.
- Condition monitoring tools must be pragmatic, given the range of users that will be interacting with the tool and the business decisions influenced by the information generated.

Introduction

Modern wind turbines are equipped with approximately 3000 sensors, which collect a range of data. This data is communicated to the wind farm operator by way of a Supervisory Control And Data Acquisition (SCADA) system. This is the computer-based system that monitors and controls the physical processes ongoing within wind turbines.

E.ON Technologies, a subsidiary of the utility company E.ON, is based in Nottingham and provides engineering and technical expertise to the E.ON group and external organisations, including condition monitoring. In January 2016 E.ON Technologies changed its name to Uniper Technologies as part of a wider group decision to create Uniper as a new company from the existing E.ON business.

E.ON technologies – provision of design solutions and services to the E.ON group and to external companies:

* Innovation Delivery
* Asset Projects
* Asset Services
* Engineering Services
* Nuclear Services

Condition monitoring can include any signal that provides an insight into a system's operating state. E.ON Technologies partitions its condition monitoring services into Advanced Condition Monitoring (ACM), which incorporates all of the intelligent uses of SCADA data, and Online Vibration Monitoring, which delivers detailed spectral analysis of shaft-line, gearbox and even tower vibration. The vibration analysis service is outside the scope of this case study.

E.ON Technologies has developed a tool called SpheriCAL, which uses SCADA data to learn what the normal operational states of a wind turbine are and triggers an alarm and an engineering interpretation when an anomaly is detected. This case study focuses on how SpheriCAL is implemented to provide early detection of potential wind turbine faults. SpheriCAL does not rely on any 'black box' or neural networks and there is no physical modelling of the wind farm: instead, early fault detection is achieved by grouping real data from multiple SCADA signals to form a model of acceptable historical behaviour. Any sustained period of operation away from this historical behaviour constitutes a potential issue and triggers an alarm.

A SpheriCAL model can be made from just a few, or up to hundreds of signals, depending on the repeatability of the data's behaviour. Signal trending, combined with simple visualisation of the modelling outputs, is then used to monitor the current state of the plant.

This case study will explore how E.ON Technologies is making intelligent use of SCADA data as part of the ACM service and features results of how SpheriCAL has managed to provide early warnings of potential failures. The information for this case study was gathered through a series of interviews during August 2015 with technical experts and the site-based operations team.

The challenge

Operations and maintenance (O&M) costs constitute approximately 30% of the levelised cost of energy (LCoE) for offshore wind farms[1] and one of the major contributors to O&M costs is the management of unexpected failures.

The main driver for E.ON to scrutinise operational data is the potential for avoiding unplanned unavailability by effectively monitoring the operational state of the turbines and attempting to intervene if there is evidence of potential faults.

This approach not only reduces O&M costs, but also lowers the associated lost revenue resulting from unplanned downtime. SCADA data is already collected for the wind farm controller, so an owner or operator such as E.ON can be opportunistic with this data. It is a cost-effective approach to monitoring asset integrity and performance issues that does not require any additional hardware, such as sensors, in challenging locations.

While SCADA-data-based condition monitoring may be accessible, challenges exist for a company with little combined engineering and data science expertise, such as how to collect the correct data; what to do with it; and how to effectively communicate any results.

The extensive fleet of generation technologies that E.ON owns and operates produces a vast amount of operational data, and selecting and accessing relevant data from the data available can be taxing.

Furthermore, identification of abnormal behaviour requires models of normal operation and this is a difficult task, given that wind farms are complex systems operating within variable conditions.

In addition, once data has been collected and processed, it is critical that the knowledge and information created is both stored and communicated effectively to maximise the value of such a condition monitoring system.

The approach adopted

E.ON Technologies provides engineering and technical support to both E.ON power plants and the external power industry sector and has been monitoring E.ON's major generation assets online since the 1990s.

The organisation has strong competencies in data management, data science and other power engineering disciplines and applied these in the development of SpheriCAL, a tool for SCADA-data based condition monitoring system for early warning of failures.

Here, we provide a brief overview of how SpheriCAL works, the history of how the tool was developed and a description of the valuable knowledge management system that was created in support of it.

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1 Tavner, Peter, "Offshore Wind Turbines: Reliability, Availability and Maintenance", IEE Power & Energy Systems, Energy Engineering (2012).

How SpheriCAL works

SpheriCAL is a SCADA-data based condition monitoring system for early warning of performance issues and potential failures.

The wind farm is broken down into a group of independent models or sub-systems, each of which is represented by an appropriate set of variables that are available through the SCADA system.

The early warning predictions are based upon the principle that in a particular operating mode, the variation of multiple measurements will remain normally distributed. The system identifies the mode operation and any substantial sustained deviation away from historical behaviour is flagged as a warning of a potential fault.

The wind farm is partitioned into collections of related signals and data from these signals is converted into models. Each model can be used to derive the condition of the modelled system. For example, a hypothetical turbine lubrication oil model could consist of seven data signals.

The representation of this system as related data signals is shown in Figure 3, where each of the small bubbles indicates one of the signals used in the representation of the system:

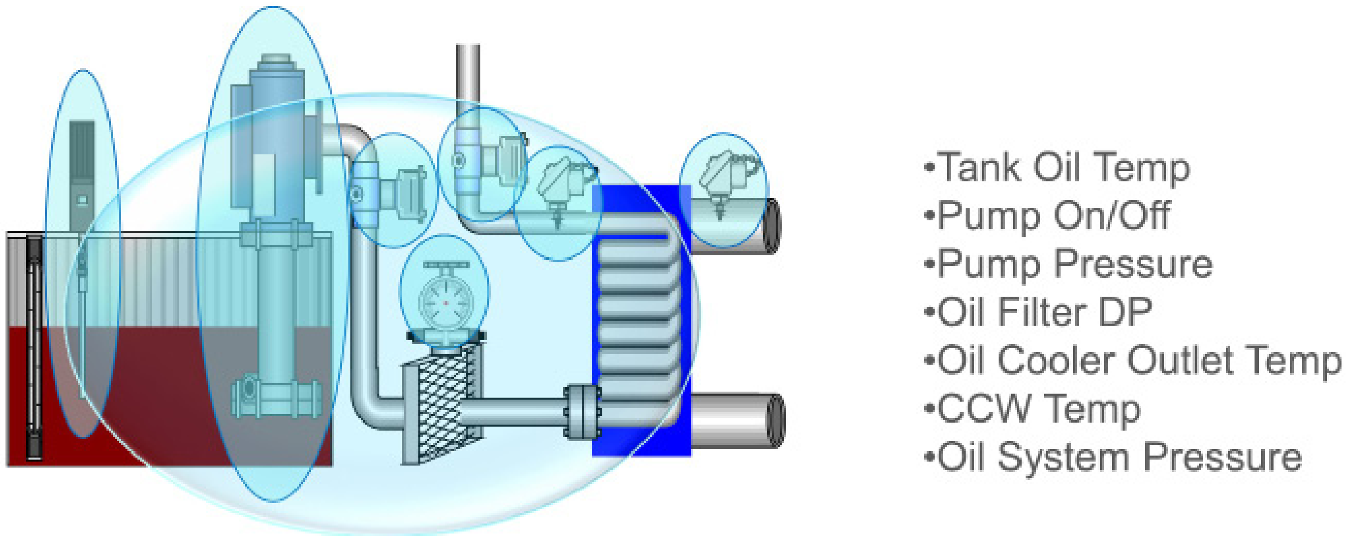

Figure 3: Turbine lubrication oil system

There is a range of condition monitoring techniques available to the operator to enable scrutiny of SCADA to infer the health of wind turbine assets. The main categories of these techniques are neural networks, physical modelling and signal trending[2].

The E.ON Technologies tool, SpheriCAL, adopts a pragmatic approach to modelling, combining physical understanding and pattern recognition

2 Wilkinson, Michael, et al., "Comparison of methods for wind turbine condition monitoring with SCADA data.", IET Renewable Power Generation 8.4 (2014)

Consider a model represented by three data tags, load, pressure and temperature as shown in Figure 4. The three values can be considered as coordinates in a three dimensional space. For a given moment in time, SpheriCAL represents the state of each model as a vector of data points.

As time progresses, the point plotted by these coordinates will move and trace out a trajectory due to variation in the wind turbine system being modelled and the turbulent wind driving the system. The fundamental idea underpinning SpheriCAL is that in this three dimensional example, for a fixed operating mode of the turbine, the trajectory will remain within a bounded sphere.

One sphere in Figure 4 can be considered as representing one normal mode of operation. If the coordinate (or state vector) showing live measured data travels outside all of the defined spheres for more than a prescribed time consecutively, then SpheriCAL will flag up that there is an anomaly within the signals' behaviour. For a system represented by more than three signals, the same logic applies, but is far more difficult to visualise.

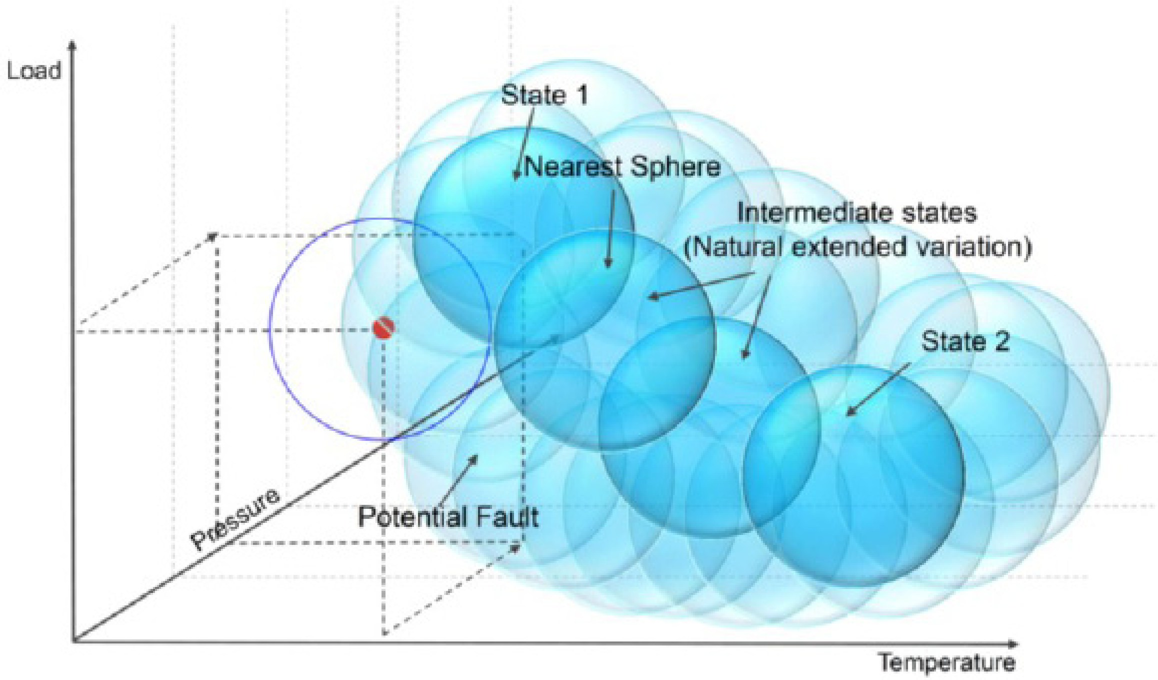

Figure 4: Three-dimensional coordinate representation of a sub-system modelled using load, pressure and temperature

Each individual model must be trained using historical data from periods of good operation. The objective of the training period is for the tool to identify what the normal operating modes are for that particular turbine.

Similar turbines in similar locations can have variations in operating conditions, such as equilibrium oil temperature, and consequently the training can lead to different normal operating modes from turbine to turbine; therefore, each turbine must be trained individually.

The minimum training period is three months and each turbine's model set must be trained with data from that turbine.

When SpheriCAL is in use, it reads live SCADA data every 10 minutes. It uses this to identify the closest operating mode (or sphere) and the turbine is assumed to be operating in that mode. As mentioned previously, if the live measured SCADA data falls outside that mode and all other normal operating modes for more than a predetermined time period, then alarms are generated.

SpheriCAL can be configured to work with any data historian and any SCADA signal can be incorporated into SpheriCAL, making it an extremely flexible tool. For example, if an operator was to install an extra temperature sensor on a gearbox, that output can be assimilated into the SpheriCAL gearbox model. One limitation is that SpheriCAL is not generally applied to vibrational measurements, because additional analysis is required to extract frequencies of interest. The flexible structure of the underlying SpheriCAL models allows the team at E.ON Technologies to also remove a signal from a model if, for example, a sensor fails in service.

The developers were aware that SpheriCAL was intended to be employed by a wide range of customers for many uses. Therefore, a design principle of the system was that it should be developed in a pragmatic manner and this open and clear approach to the system's architecture has underpinned the successful uptake of the system. Business decisions such as scheduling maintenance can be influenced based on SpheriCAL outputs, because the team at E.ON Technologies can unambiguously outline what a SpheriCAL alarm represents.

The evolution of SpheriCAL

SpheriCAL began as the university project of a physics undergraduate under the supervision of engineers from E.ON Technologies in 2009.

The original application was for condition monitoring of vibration signals from the shaft-lines of combined cycle gas turbines (CCGTs) and coal powered steam turbines during run-down; however, it was recognised that the solution he created was suitable for any set of related signals.

On graduating, this student was employed by E.ON and continued to develop his condition monitoring tool. In 2011, the SpheriCAL tool was benchmarked in a closed tender competition against the world-wide market leader in this field.

The results demonstrated that not only was SpheriCAL fit for purpose, but it also provided significantly more value to the company than its closest competitor. After the start of the global roll out of the SpheriCAL tool across E.ON's major CCGTs, it was proposed that there may also be a value case for offshore wind.

SpheriCAL had its first wind farm trial at Robin Rigg between 2012 and 2013. This wind farm was selected because it had the OsiSoft PI data historian system implemented, which meant that the team at E.ON Technologies had access to a rich source of historical data for comprehensive model training with data available from the start of windfarm operations.

The tool was considered to be a success and the results were found to be repeatable (results from this demonstration are detailed on page 9).

Following the success of the Robin Rigg trial, SpheriCAL was implemented at Roscoe and Pyron onshore wind farms in the USA. The final demonstration was intended to be at the Danish Rodsand offshore wind farm: however, due to insufficient data, SpheriCAL was not implemented.

Today, SpheriCAL is a commercial product that can be used on a wide range of mechanical and electrical systems employing SCADA technology.

Integrating SpheriCAL information into daily operations

The effectiveness of the SpheriCAL alarms is only delivered when positive action on a windfarm site is taken in response to information provided by the system.

The use of SpheriCAL at Robin Rigg (both during the pilot project and in the current enduring use) has been integrated into the site's daily planning routine. The windfarm team hold a daily planning meeting on site to discuss and finalise maintenance priorities. SpheriCAL alarm data is available during this meeting and assists directly in prioritising tasks and ensuring follow-up activities are planned. The Production Manager also ensures that feedback is provided to the E.ON Technologies Team as part of an active feedback loop and also advises of events which could benefit from the creation of new SpheriCAL models.

This championing of SpheriCAL at a site level delivers true value by turning information into positive practical actions.

SpheriCAL's communication platform and Knowledge Management

One valuable feature associated with the SpheriCAL system is the web-based Production Support Portal that has been developed to support the knowledge generated when acting upon SpheriCAL alarms, as illustrated in Figure 5:

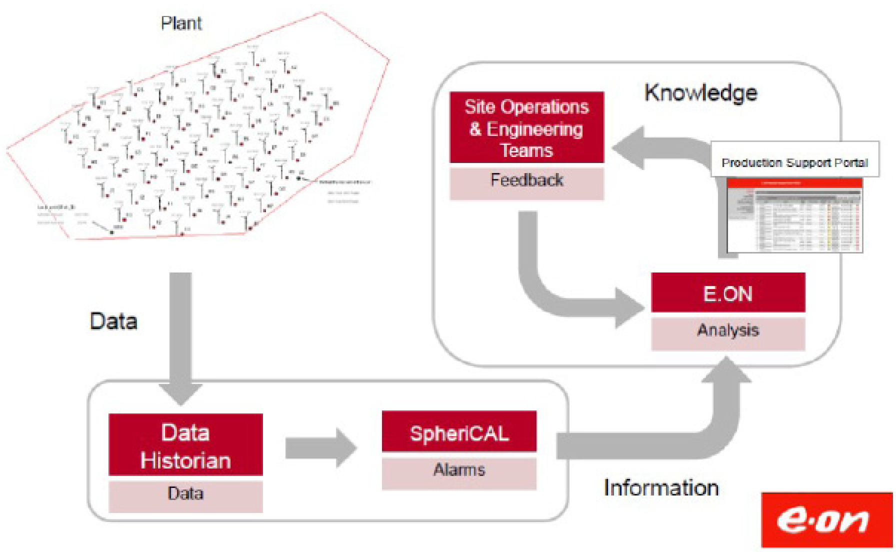

Figure 5: SpheriCAL Production Support Portal integrated into the O&M information workflow

All SCADA data is collected from site and any SpheriCAL alarms are sent to E.ON Technologies. Each SpheriCAL alarm is reviewed by E.ON Technologies and, if deemed of significance, is logged as an alert in the Production Support Portal. This web-based system can be accessed by all stakeholders, including E.ON Technologies, the site operations/engineering teams and third parties subcontracted to support the wind farm.

The site-based teams are able to track these alerts and update them with feedback from the wind farm operations. This feedback loop facilitates improvement of the condition monitoring tool implemented and ultimately builds up a valuable knowledge base of failure modes, successful identifiers and successful repair activity. Communication channels are also available to site-based teams to complement the raw alarms generated by SpheriCAL. Furthermore, the information collected facilitates evidence-based communication between operator and OEM to help optimise maintenance plans and contractual issues.

The design of the Production Support Portal mirrors the pragmatic approach employed when developing SpheriCAL. User experience has been at the forefront of the design process. It has been created in such a way that most primary functionality only requires one click access directly from alert notification emails to minimise effort and training required by users.

There is a potential risk that site-based teams may not utilise the additional information provided by SpheriCAL, but a successful track record of creditable alarms has underpinned excellent integration of the tool on the sites that have rolled it out. A key element of the successful roll out is a strong owner's presence and the integration of system information into day-to-day operational decision-making.

> "Site-based buy-in at Robin Rigg was achieved relatively early. As soon as the first three SpheriCAL alarms flagged up necessary maintenance issues, the site operations team were on-board."
>
> *David Futter, Technical Head – Condition Monitoring, E.ON Technologies*

The results

SpheriCAL has been used in the field and the business case is compelling: for example, where SpheriCAL was employed at an onshore wind farm to monitor gearbox temperatures. The key benefits of the system and lessons learned by the team of developers during this demonstration phase are detailed below.

SpheriCAL demonstration: gearbox temperature

SpheriCAL has been used at an onshore wind farm to successfully identify and support planning of maintenance of gearbox oil coolers. The SpheriCAL gearbox model uses gearbox temperature as one of the relevant data tags and consistent and progressively higher values led to an alarm.

Figure 6 shows the time series of the gearbox model over the period of 01/05/2015 to 11/05/2015. The measured gearbox temperature exceeded the predicted temperature multiple occasions in this period as highlighted by the red ovals. This behaviour triggered a SpheriCAL gearbox alarm.

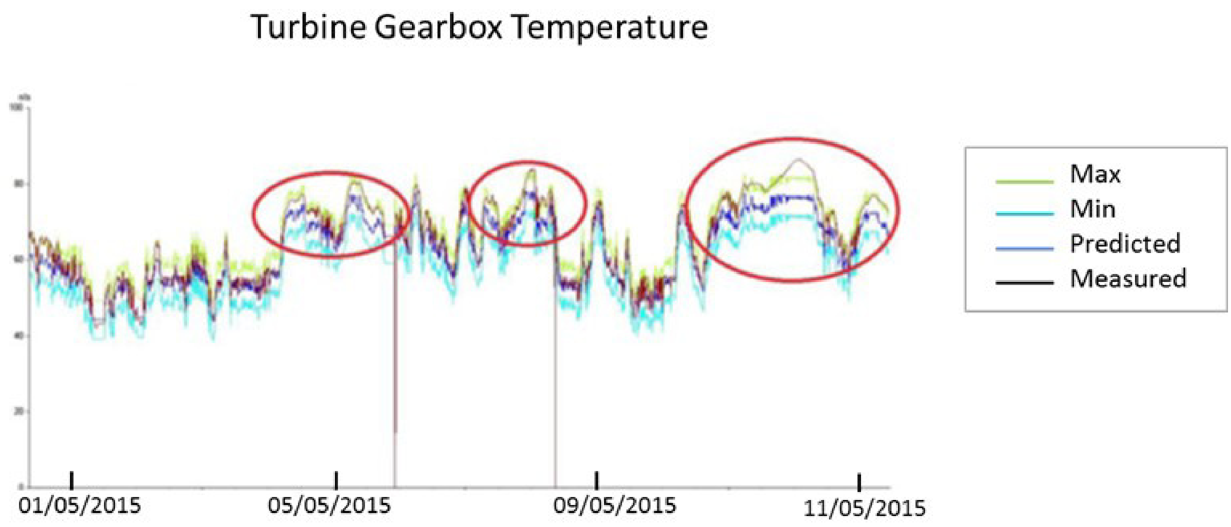

Figure 6: Measured turbine gearbox temperature plotted against expected and bounding thresholds

When such SpheriCAL alarms were seen, a technician would be sent to clean the oil cooler on the affected turbines. There were two cleaning kits available: one chemical, and one steam. It was noted that, following cleaning, the temperatures dropped further on those where the steam cleaner had been used.

In response, the site purchased a second steam cleaner and discarded the chemical cleaning method. In addition it was realised that the cleaning could be dictated entirely by triggering from SpheriCAL alarms, although in practice cleaning still takes place during routine scheduled maintenance visits.

The key aspect of this example is that SpheriCAL can be used to initiate targeted and opportunistic maintenance at relatively low cost.

The gearbox cleaning tasks were already scheduled, so this investigation required marginal effort. Furthermore, the example serves to demonstrate that the technical insight provided by E.ON Technologies to complement the alarms is critical and shows that the value of SpheriCAL alarms can be enhanced by an intelligent interpretation.

The value case – benefits

The E.ON Technologies team responsible for designing, implementing and enhancing SpheriCAL identified the following key benefits to farms employing the condition monitoring tool:

- Prudent investment: Deployment of ACM on wind turbine sites has seen a payback within one year and with a cost to value return in the range 200-400%.

- Avoiding unplanned unavailability: Early identification of a defect that otherwise would eventually lead to unavailability.

- Improved O&M: Supports condition based maintenance strategy, allowing for a lower number of maintenance events. SpheriCAL enables more cost efficient maintenance as issues are identified at an early stage enabling better targeting of work and further benefits from improved planning and logistics.

- More informed buyer: Greater awareness of issues enabling owners to challenge Original Equipment Manufacturers (OEMs).

- Flexible system configurable to many requirements: the flexible architecture of SpheriCAL allows it to work with any data historian and be tailored to suit any sub-system.

- Identification of sensor issues: Analysis of the grouped data tags has revealed consistently anomalous readings and hence flagged faulty sensors. This remotely informs the site teams that the sensor requires maintenance and the work can be scheduled to suit other planned activity.

- Valuable knowledge base of maintenance history: the SpheriCAL Production Support Portal has built up a valuable collection of information regarding failures and associated repair activity.

Lessons learned

The following key lessons were identified by the E.ON team:

1. Access to good quality data is critical

Successful implementation of condition monitoring solutions with the capability of learning system behaviour depends on access to good data: an organisation with challenging business targets should be collecting data from the day turbines are installed.

Even when a wind farm is under warranty, it can be extremely valuable to collect O&M data in an independent data historian, as a reliable history of operational data can be used retrospectively to accurately train condition monitoring solutions.

In order to ensure access to the required data during the lifetime of the wind farm, it is important that interfaces are correctly specified, owner hardware to collect and store data is installed during the construction phase and that contracts include provision for data ownership and supply.

2. Feedback from site is critical

Variation in the quality of maintenance reporting has been an issue when deploying the SpheriCAL solution. Well documented fault reports are required for accurate interpretations and prognostics and to fully exploit the benefits of the feedback loop facilitated by the Production Support Portal.

3. Reluctance to integrate new software into existing processes has been a barrier

Despite the open access design of the SpheriCAL tool, one of the barriers faced when implementing it is that OEMs have their own software solutions. It can be extremely challenging to influence an OEM and integrate new software solutions into existing processes. Efficiency in communicating and scheduling maintenance could be improved by sharing data and standardising the tools used to capture and communicate O&M information.

People-related issues should not be overlooked – it is important to develop local ‘champions’, ensure operational teams understand potential benefits and integrate the use of the tool into operational planning and decision-making.

4. Further work is required to demonstrate and quantify the wider cost savings of a more proactive approach to maintenance

E.ON Technologies have demonstrated a successful product; however, the total value case needs to be evaluated on a site by site basis, based on data availability, maintenance practices and turbine reliability. While SpheriCAL provides the opportunity to move to a condition-based maintenance strategy, work is required to demonstrate and quantify the benefits and cost savings of different maintenance strategies, given that there will still be the need for scheduled maintenance, and the wider benefits to cost and revenue enhancement that improved reliability can bring.

System enhancements – what's next for ACM?

SpheriCAL is already a valuable product that can successfully flag up early indication of potential faults in an opportunistic manner by using SCADA data that is already collected for other purposes. The team at E.ON Technologies continue to look for further improvements and are developing enhancements to their condition monitoring service with various advanced concepts.

The E.ON Technologies team is continually aiming to enhance the condition monitoring services using data analytics techniques.

One development is the estimation of remaining component life based on vibrational analysis. By employing trend analysis techniques developed for the financial industry, they are able to provide estimates of time to failure of major components. One successful application of this was for rolling element bearings. A history of failure patterns in the vibration data has been collected over the last three years and, by using mathematical indicators of defect development, combined with the practical knowledge around the time to failure statistics, it is possible to define a projected path to failure for rolling element bearings all along the shaft-line and within the gearbox.

By using these advanced pattern recognition techniques, E.ON Technologies can provide predictions for bearing failure accurate to a six-week window as early as one year in advance, reducing to a one-week window three months in advance. This offers great potential to prevent unnecessary downtime for offshore wind turbines and optimise maintenance planning.

SpheriCAL alerts a user that a particular parameter may be showing abnormal values, but does not currently indicate automatically what the fault mode may be.

A lot of work is ongoing in the area of automatic diagnostics and prognostics. Using output from categorised SpheriCAL models, suggested fault types can be identified using a cross reference to previous alerts in the SpheriCAL Production Support Portal, based on the patterns within the SpheriCAL model outputs. There is a growing library of fault modes due to the intrinsic connection to live systems and several fault modes can now be identified automatically.

Conclusion

The benefits of an opportunistic approach to utilising data already generated by SCADA systems to enhance wind farm maintenance are clear, as demonstrated by the implementation of SpheriCAL.

A pragmatic system design, access to good quality data and enthusiastic site-based buy-in supported a successful roll-out of the product, facilitating valuable early fault detection and both on- and offshore wind farms.

Recommended reading

Tavner, Peter, *Offshore Wind Turbines: Reliability, Availability and Maintenance,* IEE Power & Energy Systems, Energy Engineering (2012).

Wilkinson, Michael, et al., *Comparison of methods for wind turbine condition monitoring with SCADA data*, IET Renewable Power Generation 8.4 (2014).

Interviewees' biographies

Ty Burridge-Oakland, Condition Monitoring Engineer, E.ON Technologies

Ty created SpheriCAL in 2009 and was the technical lead of both the field test in 2011 and the roll out of ACM for CCGT fleet between 2012 and 2014.

David Futter, Technical Head – Condition Monitoring, E.ON Technologies

David has extensive experience of condition monitoring of turbine generators for a range of coal, gas, CHP and nuclear power plants, principally using vibration.

He developed a condition monitoring strategy for wind turbines which has been adopted by E.ON Climate and Renewables and contributes to International Standards on Vibration of Machines and Condition Monitoring.

Adrian Smith, Head of Condition Monitoring, E.ON Technologies

Adrian has held various positions of responsibility within E.ON, including senior project manager of Generation Development (developing new power plants), optimising the performance of the power plants within the E.ON CCGT fleet and contract and interface manager.

He is currently Head of Condition Monitoring for E.ON Technologies.

Tim Morgan, Robin Rigg Plant Manager, E.ON

Tim has worked in the wind industry since 2004 and is now Plant Manager for E.ON at the Robin Rigg offshore windfarm.

Tim leads a team of 23 staff and is responsible for all aspects of O&M. Prior to his current role, Tim has worked within E.ON's asset management function leading on asset integrity, strategy and risk and also managed a portfolio of E.ON's onshore windfarms.

Author Profile

Dr Conaill Soraghan is a Renewable Technology Engineer with ORE Catapult.

He has a background in applied mathematics and completed a PhD in wind turbine design.

Conaill's main area of expertise is the management and optimisation of operational assets: he has extensive experience of the design and development of benchmarking systems and data/knowledge-sharing for the offshore wind industry.

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ORE Catapult

Inovo
121 George Street
Glasgow, G1 1RD

T +44 (0)333 004 1400

National Renewable Energy Centre
Offshore House, Albert Street, Blyth
Northumberland, NE24 1LZ

T +44 (0)1670 359 555

Fife Renewables Innovation Centre (FRIC)
Ajax Way
Leven, KY8 3RS

T +44 (0)1670 357 649

Email: info@ore.catapult.org.uk Web: www.ore.catapult.org.uk