CONMOW

Condition Monitoring for Offshore Wind Farms

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CONMOW: Condition Monitoring for Offshore Wind Farms

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Abstract:

To investigate whether a cost-effective integral condition monitoring system can be realized in practice the European project CONMOW (Condition Monitoring for Offshore Wind Farms) was started in November 2002. A small wind farm of five turbines has been instrumented with several condition monitoring systems and also with the “traditional” measurement systems. Data analysis of these measurements aims to develop algorithms that can be integrated in SCADA systems. This should lower the cost of condition monitoring systems and produce more accurate information for O&M planning. In this paper the approach of the project, the instrumentation of the wind farm, and the results are outlined.

Keywords: Condition monitoring, Operation and Maintenance

1 Introduction

As offshore turbines are located at remote sites under harsh conditions, the demand for high reliability and low operational costs becomes higher than for onshore turbines. Recent studies for developing operation and maintenance (O&M) plans for offshore wind farms show that the costs for maintenance are too high, about 25 to 30% of the energy generation costs [1] and that a considerable percentage is caused by unexpected failures leading to corrective maintenance. These figures emphasize the need for an adequate O&M program that makes use of good diagnostics and condition monitoring techniques. By doing so the number of inspection visits and corrective maintenance actions can possibly be lowered including the related costs and downtime.

Condition monitoring techniques are being used successfully already for a long time in many branches of industry. Recently several different systems became commercially available for application in wind turbines, such as vibration based systems and oil monitoring systems for bearings and gearboxes. These systems have proven to operate well under the harsh conditions a wind turbine is operated. However, up to now only little experience is (publicly) available about the added value of the advanced condition monitoring techniques and signal analyses for wind turbine operators. To investigate whether a cost effective integral condition monitoring system can be realized in practice for wind energy applications, the European project CONMOW (Condition Monitoring for Offshore Wind Farms) was started in November 2002.

This paper briefly describes the CONMOW project approach in Section 3. Results of the different phases are given in Section 4 through 7. In Section 8 an assessment is made of the added value for wind energy offshore. First of all, in Section 2 an introduction is given on condition based maintenance and the use of condition monitoring to put the CONMOW project in its perspective.

2 Condition Based Maintenance

2.1 O&M Strategy

Condition monitoring will only have added value if it is well incorporated in the entire maintenance strategy which usually consists of (1) corrective maintenance and (2) preventive maintenance.

Corrective maintenance is performed after a breakdown or an obvious fault has occurred. For some failures the corrective maintenance action has to be performed immediately, for others the action can be deferred in time.

Preventive maintenance is intended to prevent equipment breakdown and holds repair, service, or component exchange. Preventive maintenance can be scheduled or condition based maintenance (sometimes called "predictive maintenance"), based on the actual health of the system.

For condition based maintenance it is necessary to determine the health of the system. This can be done by periodic inspections, analyzing offline measurements, oil samples, or SCADA data, or by analyzing online measurements. This means that for implementing a condition based maintenance strategy one is not limited to using online condition monitoring systems! Online condition monitoring is only one of many means to determine the health of a system. Too often online and automated condition monitoring is assumed to be a synonym for condition based maintenance.

Furthermore it should be noted that condition based maintenance mainly makes sense if (1) the design life of the component is shorter than that of the entire turbine and if (2) it is clear that wear indeed is the cause of failure. Gearbox oil for instance will be replaced several times during the turbine lifetime. Condition based maintenance can then be applied to determine if the oil needs to be changed after say 4 years (calendar-based) or maybe after 7 years (condition based). This could save one oil change within the turbine lifetime. So called "safe life components" such as rotor blades for instance are designed for a lifetime longer than that of the turbine lifetime. If such components are replaced during the lifetime, the failure cause is usually not wear but e.g. too high loading, poor manufacturing, or unforeseen conditions.

A successful application of condition based maintenance is schematized in Figure 1: at t = 5 a significant change in the condition is observed. At t = 6 a critical level ("yellow light") is exceeded and action should be taken. Repair is carried out during the next preventive maintenance at t = 7. Online monitoring would make sense if the fault would progress faster than the time between two inspections.

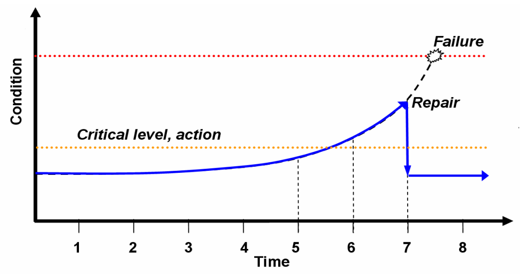

Figure 1: At regular intervals inspections and preventive maintenance are carried out.

2.2 The use of Condition Monitoring systems

A general definition of condition monitoring is:

***Condition monitoring** is the process of monitoring a parameter of condition in machinery, such that a significant change is indicative of a developing failure.*

From this definition the following three basic rules can be derived.

1. Detection of failure mechanism

It needs to be clear what the failure mechanism is and which diagnostic means should be available to detect the failure mechanism and its development. Components can fail in different ways and a Failure Mode and Effects Analysis (FMEA) can be performed to determine all possible failure modes, conceive mitigating measures and, if possible, determine "early indicators" that represent the development of the failure and the system condition.

2. Detection on time

The use of condition monitoring allows maintenance to be scheduled, or other actions to be taken to minimize the consequences of failure, before the failure occurs. This means that change in the machinery condition needs to be detected on time and prognoses need to be made about future developments in order to take mitigating measures. This also means that condition monitoring is not applicable to avoid sudden failures.

3. Measurable criteria

In fact, just measuring the failure and its development is not enough; clear and measurable criteria should be developed before it can be decided that actions should be taken. Simply said: a *green*, *yellow*, and *red* light should be available to assess the condition monitoring results. It should be clear what level is acceptable to determine that the system is healthy and what level should be exceeded before one decides that the failure starts developing. To determine such criteria long term experiences, including measurements during situations with failures, need to be available. The situation becomes even more complex if (like in wind energy) the development of the failure is caused by stochastic loading.

3 The CONMOW Project

3.1 Objectives

The CONMOW project has been defined to investigate if online condition monitoring techniques do have added value for optimizing the O&M strategies of large offshore wind farms. Secondly, it was the objective to find out if the already available data (often offline) such as SCADA data, PLC measurements or inspection reports can be used to make better use of condition based maintenance strategies. If both objectives could be achieved, the CONMOW project also had the ambition to implement the lessons learnt into a wind farm SCADA system and test it over a longer period and to contribute to newly developed wind turbine communication standards: IEC61400-25.4 [2].

3.2 Consortium and structure

A project team has been established representing:

- suppliers of vibration monitoring systems: Gram & Juhl A/S, DK and Prűftechnik CM GmbH, D;
- suppliers of online oil monitoring systems: Pall Europe Ltd., E;
- wind turbine manufacturers: Nordex Energy GmbH (D)

- suppliers of SCADA systems: Risø National Laboratory, DK, and Garrad Hassan and Partners Ltd., UK;
- R&D institutes: Energy research Centre of the Netherlands, ECN, NL and Loughborough University, CREST, UK.

The project was separated into two main phases. The first phase comprised the extensive instrumentation of a single turbine, not only with online condition monitoring techniques but also with the “traditional” measurement systems like load measurements. The objective of this phase was to carry out an extensive measurement campaign on a pitch controlled turbine with variable speed under normal operating conditions. With data from this campaign, inter-relationships can be determined between various turbine parameters and condition monitoring results and if turbine parameters could provide the same information as additional condition monitoring systems.

In the second phase the methods should be applied on a larger scale in a wind farm. The systems had to be tested over a longer period of time and continuously improved. Also a sensitivity study had to be performed to assess the potential cost benefits of applying condition monitoring in a typical offshore wind farm at the North Sea.

3.3 Execution

The execution of the CONMOW project was hampered by non-technical issues mainly. The most important ones were the following.

- An ongoing measurement campaign in phase 1 on a GE1.5S turbine in Zoetermeer had to be terminated after 1 year. A measurement campaign in phase 2, also foreseen on GE 1.5S wind turbines, could not start at all. Due to this, the project faced a delay of approximately 1.5 year. Finally a new campaign was started in 2005 with five Nordex N80/2.5MW turbines at ECN Wind turbine Test site Wieringermeer (EWTW) in the Netherlands. The measurement campaigns of phase 1 and 2 were combined for reasons of time.
- In order to configure the vibration monitoring systems kinematic data of the gearbox and bearings was necessary as input. This process took much longer than expected.
- The oil monitoring system was not implemented, because for this project no solution could be found to cover liability aspects.
- It was foreseen that several fault situations could be introduced during the measurement campaign. However due to contractual matters this was not possible. Only two relevant random failures were observed in this project during the measurements at the GE1.5s turbine, and one off-design condition at the N80 turbine.
- For the reasons mentioned above the knowledge gained during phase 1 was insufficient for implementing new algorithms in a wind farm SCADA system.

3.4 Results

First, an inventory was made of the state-of-the-art condition monitoring techniques that are presently available and could be applicable for wind turbines.

Prior to the measurement campaign, a Failure Mode and Effect Analysis (FMEA) has been performed to select meaningful condition monitoring systems for which new algorithms could be developed.

Secondly, an extensive measurement campaign has been carried out at the N80 turbines at the EWTW of ECN. The measured data (SCADA data, data from load measurements, and high frequent data from online condition monitoring systems) have been analyzed in various ways to detect degradation of components and to describe the new algorithms.

Since it was not possible to introduce fault situations in the turbines, several simulations were made to determine the relationship between the failed situation (e.g. rotor mass imbalance) and several "measurable parameters" (e.g. nacelle vibrations).

Finally, an economic assessment has been made of the added value of condition monitoring techniques for wind turbines. Several O&M cost studies have been carried out in which the potential of these systems to predict faults and remaining lifetimes has been investigated.

4 Identification of CM-techniques

4.1 State of the art CM-techniques

There is a wide number of condition monitoring techniques used throughout industry [3], [4]. To date, techniques such as vibration and process parameter analysis have been applied to wind turbines. From the research work carried out to date, the most promising areas for the application of condition monitoring of wind turbines, particularly moving offshore, would seem to be:

- vibration, acoustic and fiber optic strain analysis of the blades;
- acoustic and vibration analysis of selected drive train components;
- themographic analysis of electrical components;
- analysis of oil quality;
- time and frequency domain analysis of the electrical power;
- trending of key component response functions;
- inclusion of visual/aural examination to enhance maintenance planning.

At the time of drafting the state of the art report, no examples were found in literature of successful applications of condition monitoring techniques in wind turbines which actually prove the added value.

4.2 Failure Mode and Effect Analysis

The FMEA is generally intended to identify all possible failure modes of a system, their likelihood, and their consequences in terms of costs, downtime, safety, etc. The FMEA results in a list with the most vulnerable items and recommendations on how to reduce their criticality. A possibility is to reduce the likelihood, e.g. by choosing components with a lower failure rate or limiting the consequences. This can be done for instance by design changes towards more effective maintenance.

The objective of the FMEA in the CONMOW project was to identify those failure modes that show up gradually and which can be detected in an early stage by (online) health monitoring. For those failures, the maintenance action might become easier and cheaper, and the production losses can be reduced. For this reason, a *Failure Repair Class* (F-1 through F-7) has been assigned to each failure mode, see Table 1.

Table 1: Classification of Repair Classes

Failure Repair Class
F-1: Alarm with remote reset
F-2: Alarm with repair
F-3: Alarm with replacement
F-4: Service with repair
F-5: Service with replacements
F-6: Failure of large components
F-7: Lightning strike

A generator bearing failure for instance can cause consequence damage when it is not detected in an early stage. This might result in a replacement of the generator, which is classified as Failure Repair Class F-6. This implies high repair costs and production loss. For such bearings, condition monitoring techniques are available from the market and the potential for cost reduction is considered high, see Tables 2 and 3. Application of a CM-system can reduce the failure class from F-6 to F-5, which means that the repair itself can be done on location by replacement of the bearing as planned maintenance without significant additional production loss. For slow running pitch bearings however, a condition monitoring system is presently not available.

Table 2: Classification of CM-potential

	Early fault detection possible	Detection tools/instr. available	Potential maint. cost reduction
CM-1 [1]	+	+	++
CM-2 [1]	+	+	+
CM-3 [2]	+	-	++
CM-4 [2]	+	-	+
CM-5	-	-	-

1: CM-systems available on the market
2: CM-techniques under development

In total 56 possible failure modes have been listed, divided over 27 components. More information can be found in [5].

Table 3: Classification of CM-potential

Failure mode	Failure Class	Potential
Generator bearing		
Surface fatigue failure	F-6 ⇒ F-5	CM-1
Fretting	F-6 ⇒ F-5	CM-1
False brinelling	F-6 ⇒ F-5	CM-1
Wear	F-6 ⇒ F-5	CM-1
Oil circuit		
Insufficient lubrication	F-6 ⇒ F-5	CM-1
Insufficient cooling	F2	N/A
Filter full	F5	N/A
Electrical pitch system		
Failure of motor controller or motor/reduction box	F-3 ⇒ F-2	CM-4
Failure of battery charger Insufficient battery cap.	F-3	
Damage of bearing	F-6	CM-5

5 Measurement campaign

5.1 Overview

Five N80 turbines at the ECN test site EWTW have been instrumented for the CONMOW project. The following measurement systems are operational (see Figure 2):

- five different drive-train vibration monitoring systems (3 Prűftechnik and 2 Gram&Juhl), producing time series and spectra of bearings and gearboxes;
- load measurement systems for blades and tower from a single turbine (ECN), producing time series at 32 Hz;
- system for measuring meteo data from nearby meteo mast (ECN), at 4 Hz;
- measurement system to acquire operational data for all turbines (ECN, Nordex), at 25 Hz.

From other sources the following data were available:

- operational statistics of all turbines (Nordex), 10-minutes statistics;
- simulation data of fault conditions with GH Bladed (GH).

High frequency measurement data and statistics from CM-systems and from the traditional measurements have been collected since November 2005.The partners have online access to measurement data and analysis results.

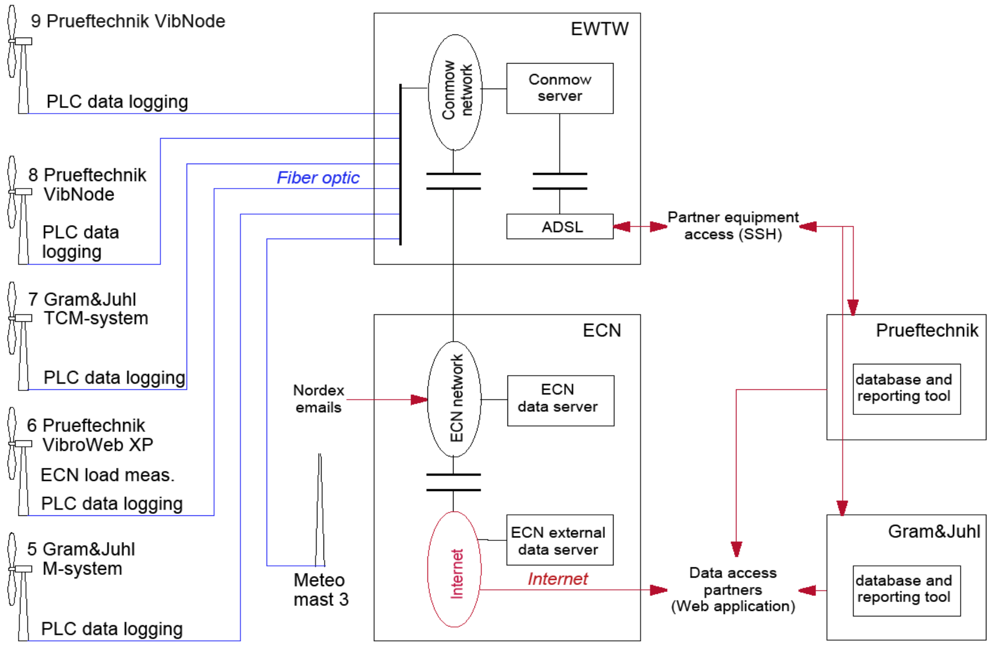

Figure 2: Schematic overview of measurement and communication infrastructure

6 Analysis results

6.1 Time series processing algorithms

The data analysis has focused on high speed measurements of the electrical power output and of the pitching and yawing mechanism. Also a variety of signals from the SCADA system, both time series and statistics, have been analyzed.

Both theory [6], [7] and practice [8] suggest that some vibration frequency components caused by faulty mechanical elements could appear in electrical signals. As the electrical and mechanical signals produced by faulty elements in wind turbines are irregular and non-stationary and the measurements cannot be easily controlled [9], [10], we have developed a particular algorithm that employs both discrete and continuous wavelet transforms. A certain wavelet type is used to extract a particular signature in the wind turbine power output sampled at 32Hz. To discriminate the difference between healthy and damaged elements, the maximum amplitude of the wavelet coefficients are estimated by a fast Fourier transform (FFT) and the root-mean-square (RMS). We take the RMS values to monitor the mechanical elements, because results show that the maximum amplitude of the wavelet coefficients has a similar trend to the RMS values.

Using the algorithms outlined above, it was possible to detect evidence of damage by analysis of the wind turbine power signal. Examples are given in Figure 3 and 4. The amplitude of the Fourier transformed wavelet component in the frequency range 2.5 to 3 Hz of the power output of the GE1.5S wind turbine in Figure 3 shows an increase in November 2003. In January 2004, a generator misalignment was noted and an attempt made to correct this. This attempt was not successful and in March 2004, the generator bearing failed. When the bearing was replaced the amplitude was reduced. It can be seen that this technique detected the misalignment at least three months before failure occurred.

Figure 4 indicates some evidence that high amplitudes of the Fourier transformed wavelet component in the frequency range 6.5 to 7.5Hz of the power output of one of the Nordex N80 wind turbines existed from January to May 2006. As Prűftechnik detected a mechanical vibration incitation associated with the generator bearing in December 2005, we believe it is possible that pulsating torque signals are produced in the developed electromagnetic torque due to the fluctuation in the permeance of the air gap. This may be caused by a bearing misalignment problem, though this needs further investigation, particularly with regard to information on corrective maintenance carried out in May 2006.

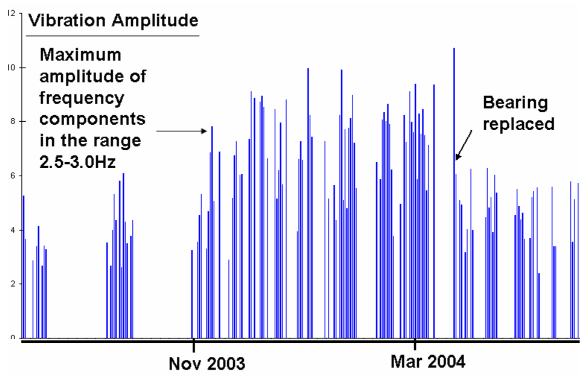

Figure 3: Maximum daily amplitude of the wavelet FFT filtered GE 1.5S wind turbine power output within the frequency range 2.5 and 3.0Hz.

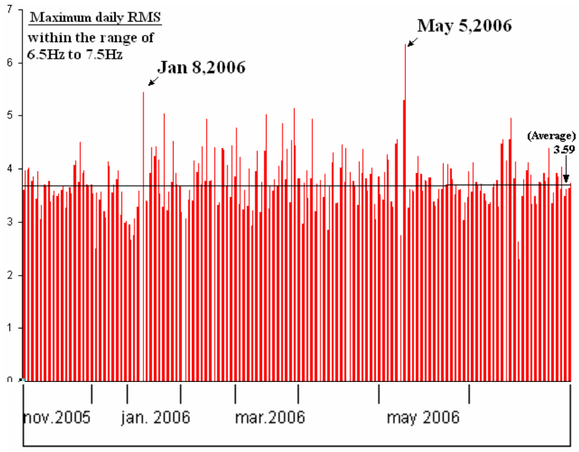

Figure 4: Maximum daily RMS of one of the wavelet filtered Nordex N80 wind turbine power outputs within the frequency range 6.5 and 7.5Hz.

6.2 SCADA data processing

De-trending of wind turbine SCADA data has been looked at as a way of picking out potential deviations from 'normal' behavior. Figure 5a shows an example of ten-minute averaged temperature measurements on a generator bearing of one of the Nordex N80 turbines as a function of power output. To enhance the trend, the data have been linearly corrected for ambient temperature (using data over a small rotational speed range) and the values plotted have been averaged in bins corresponding to increments of 0.1m/s. In practice, monitoring of this trend would compare values against normal bounds determined from historic data. An increase in bearing temperature due to bearing wear or possibly shaft misalignment could then manifest itself by observations being consistently above the maximum level of the set normal bounds as a function of power output. The advantage of this approach over standard alarm levels is that it allows a larger degree of sensitivity, i.e. corrects for ambient temperature and power output which will naturally increase the bearing temperature.

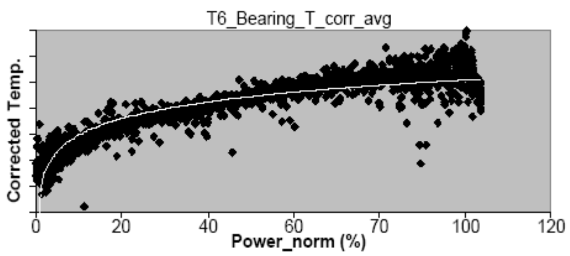

Figure 5a: Nordex N80 generator bearing temperature (corrected for ambient temperature) as a function of power output.

Another approach is to de-trend the data using not only ambient temperature but also the electrical power, see Figure 5b.

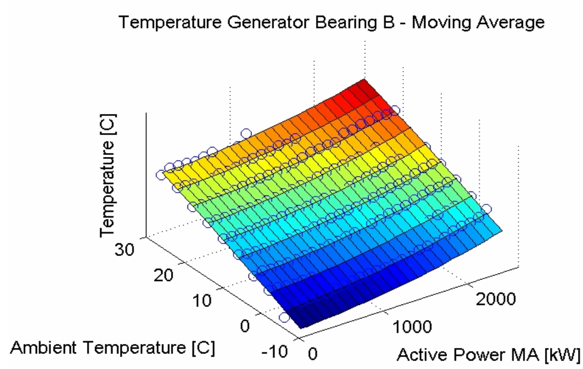

Figure 5b: Example of de-trending of SCADA data.

Figure 6 shows a similar plot this time showing ten-minute averaged nacelle accelerometer (z-direction) vibration measurements as a function of the square of the wind speed (as a proxy for thrust).

In both cases, clear trends are seen and the value in terms of condition monitoring is to establish acceptable bounds for the trend lines which may be determined from the standard deviation of points around the trend lines during periods of known 'normal operation'. Subsequent measurements outside these bounds would trigger an analysis of the data point and comparison with other measurements (e.g. high frequency vibration measurements) to confirm possible operational problems. An example of abnormal behavior in this case might be an increasing drive train misalignment resulting in points significantly and consistently above the normal operating envelope about the straight line fit in Figure 6.

Although the effectiveness of these methods could not be demonstrated in the project because no major failures had occurred, it is already clear that the processed signals are limited within narrower bounds and are presented orderly. This makes it easier to detect coming failures of the turbines. This will help operators to analyze their SCADA data more accurately and quickly. Obviously more experience with these methods is needed, e.g. in order to define proper bounds for normal operation of each signal.

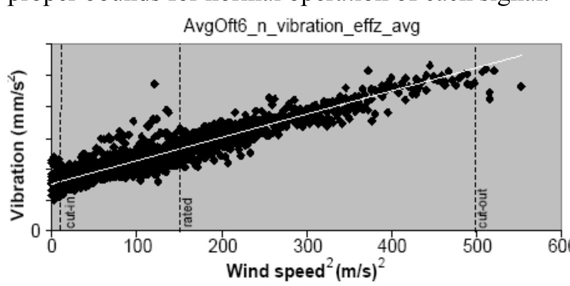

Figure 6: Nordex N80 nacelle accelerometer axial vibration as a function of the square of wind speed.

6.3 Drive train vibration monitoring

Prüftechnik Condition Monitoring GmbH has installed one VIBROWEB® XP certified CM-system in one N80 turbine and two VIBNODE® systems, newly developed for smaller wind turbines in two N80 turbines. VIBROWEB® XP is the standard CMS in all Nordex-Turbines with Premium Service contracts and base for Telediagnostic service of Prűftechnik and Nordex. The VIBNODE® CMS is cheaper and does not feature additional functions as rotational (re-)sampling and measuring in two operational states (according to GL-Regulations [11]). Instead it continuously measures the vibration behavior and performs real-time diagnosis and preliminary evaluations over the whole operating range, thereby reducing the amount of data for later offline analysis in the diagnostic center, see also [12]. The system has shown to detect phenomena, e.g. high vibration levels, outside of the two operating states as applied in certified systems. Within the CONMOW project, the system has showed high vibration levels in one of the Nordex turbines. Inspections revealed that the cause was generator misalignment and action was taken to realign the high-speed shaft.

Gram & Juhl A/S has applied the TCM® (Turbine Condition Monitoring) System on two Nordex turbines. A large practical experience is available with TCM® from more than a 1000 turbines monitored online. The TCM® system to day is a standard component on all SIEMENS wind turbines. Similar to the analysis of SCADA data it is concluded that no failures occurred during the measurements that could be detected by the TCM® System. In this project Gram & Juhl has also optimized their automatic fault frequency detection algorithms and measurement setup model, so that faults can be detected earlier.

Partly based on the results of the CONMOW project, but mainly on the experiences of Prűftechnik and Gram & Juhl elsewhere the following was learned.

A) The CM-systems and other measurement systems operated very reliably in general. One CM-system needed to be restarted and a flash disk had to be replaced. Further, the wiring of the blade load monitoring was repaired.
B) Both the VIBNODE® systems and the Gram&Juhl M-system use displacement sensors at the low speed section of the drive-train, e.g. main bearing, which are superior to vibration sensors because of the slow rotational speeds. Prűftechnik also monitors the axial movements and vibrations of the planet carrier in the gear unit.
C) At least 5 requirements must be met, to implement a well functioning condition monitoring system for wind turbines (this underpins the theory in Section 2.2)
   1. Drive-train vibration monitoring must be permanent and online, as failures may develop within a period of time that is shorter than the regular maintenance interval. Further, vibrations often show up under specific operating conditions
   2. Signals must be correlated and sorted with the wind turbine status parameters, active power, wind speed, yaw error etc. Gram & Juhl implements this as binning and conditional recording
   3. Data should be centralized stored so cross analysis and comparisons between turbines and sites can be made. Also post processing is necessary.
   4. A large number of turbines must be monitored to gain sufficient experience with a specific wind turbine type
   5. The systems produce large amounts of data which are difficult and time consuming to interpret by wind turbine owners. A dedicated expert team should work with monitoring results, i.e. interpretation of measurement signals, handling of alarms, planning maintenance, design feedback etc.

6.4 Oil quality monitoring

The understanding of the effects of contamination (solid particles, water and air) on fluid systems has promoted fluid cleanliness monitoring to a front line maintenance technique.

Studies have shown that between 55 and 70% of failures to fluid systems are caused by the presence of contaminants in the hydraulic fluid or lubricant, so this is still one significant area to remedy by the application of contamination control techniques.

It was foreseen that the following Pall Diagnostic Monitoring products were going to be build in into at least one of the N80 turbines.

A) The PCM200 series portable online fluid cleanliness monitor to measure contamination.
B) Water sensor probe WS05S to determine the percentage of saturation of the fluid and a temperature in °C.
C) The DeltaSense differential pressure transmitter to monitor the filter element service life.

With the online monitoring equipment timely preventive actions to restore the target oil cleanliness level can be taken, such as flushing the gear box using a filter element with a finer micron rate. These actions are relatively cheap and may well prevent consequence damage resulting in lower O&M costs. Unfortunately, the systems could not be built in into the turbines. As a result the benefits of online oil monitoring as compared to periodically analyzing oil samples offline could not be assessed.

7 Simulation results

Since it was not possible to introduce fault situations in the turbines, several simulations were made to determine the relationship between the failed situation and several "measurable parameters". Garrad Hassan has performed two studies in this area using GH Bladed software with a Nordex N80 model.

7.1 Pitch bearing friction

An investigation into the feasibility of predicting pitch bearing friction from likely measurement signals. The aim of this investigation was to ascertain whether or not it is possible to infer levels of pitch bearing friction from existing measurement signals with reasonable accuracy. Such a derived value of pitch bearing friction would naturally be very useful for condition monitoring of the pitch bearings.

The measured input signals that are assumed to be available are: Pitch angle, Pitch rate and Pitch actuator torque. Measurements of wind speed from turbine mounted anemometry are ignored as these are though to be potentially unreliable.

10 Minute simulations were carried out using wind speeds above the rated wind speed as this is where blade pitching occurs: 16 to 24 m/s with 10 turbulence seeds. The standard linear model for pitch bearing friction was used. Balance of torque and moments at the blade pitch bearing:

$$M_{\text{friction}} = Q_{\text{a}} G + M_{\text{Z}}$$, where:

Q_{a} is the pitch actuator torque

G is the pitch actuator gear ratio of gearbox and pinion

M_{Z} is the internal moment at the blade root

Therefore, if an accurate estimate of M_{Z} can be made (for example, as a function of pitch angle) then the true pitch bearing friction can be estimated at any time including periods outside normal operating conditions, when a pitch bearing fault has occurred. The focus then shifts to making an accurate estimate of M_{Z} for a given averaging period. Unfortunately it was found that even averaging over multiple whole rotor rotations, it was impossible to make a satisfactorily accurate estimate of M_{Z} as it is only a weak function of pitch angle. The investigation therefore shows it is not possible to make a reliable estimate of pitch bearing friction from the assumed input signals.

7.2 Rotor imbalance

Several turbine fault conditions were simulated including rotor mass imbalance and rotor aerodynamic imbalance (i.e. a set angle difference between blades). The aim was to study the resulting output to ascertain the most reliable signal for condition monitoring use. This was selected in terms of the periodic component of a signal having a clear correlation with the fault condition and a good signal to noise ratio.

Ten minute long simulations were performed with turbulent wind conditions at a mean wind speed of 12m/s. Figures 7 shows the periodic component for two signals: nacelle side-to-side (y-dir.) acceleration.

Rotor mass imbalance imparts a sinusoidal periodic force due to gravity once per rotor revolution (1P) at the hub and manifestations of this periodic variation are seen in both signals and also other signals, e.g. pitch angle and electrical power. The nacelle side-to-side acceleration clearly shows the best signal to noise ratio at this wind speed of 12 m/s together with a plain difference between balanced and unbalanced cases.

From this result, nacelle side-to-side acceleration was investigated at other wind speeds: 4m/s and 24 m/s. These simulations show that the difference between the two cases is less apparent at lower wind speeds. The signal to noise ratio degrades slightly at higher wind speeds.

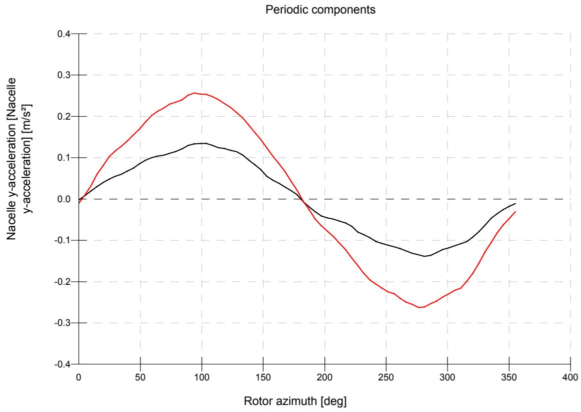

Figure 7: Fault modeling: rotor mass imbalance (red line), 12m/s, nacelle side-to-side acceleration

Rain flow cycle counting of the tower top side-to-side forces (F_Y) was performed to give damage equivalent loading (for an associated reference number of cycles) at a range of mass imbalances. The results in Figure 8 show that if such real time processing is possible, this seems very robustly correlated with rotor mass imbalance.

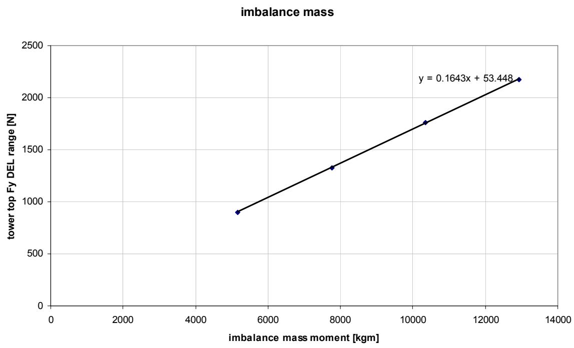

Figure 8: Fault modeling: F_Y DEL vs. rotor mass imbalance

8 Added value assessment

To investigate the economic benefits of condition monitoring techniques on the expected O&M effort, cost estimates have been made for a fictitious but realistic offshore wind farm. As a starting point a fictive but realistic wind farm has been defined consisting of 100 turbines of 2.5MW with some adjustments for offshore, such as a small platform crane above the splash zone. The wind farm is located at the North Sea at 15km from a harbor from which the maintenance can be arranged. The wind- and wave conditions for the location “IJmuiden Munitiestortplaats” have been used. For the baseline configuration the failure rate is set to 4.5 failures per year per turbine, divided over 5 different maintenance categories of varying seriousness of this wind farm has been defined. For this baseline configuration the ECN cost modeling tools [13] have been applied to determine the long-term average effort and costs for maintaining the wind farm and to calculate the downtime and revenue losses.

Next two different scenarios for condition monitoring have been considered. In the 1st scenario the effect of early fault detection is addressed, and it is assumed that for a number of failures the consequence damage can be limited by applying condition monitoring techniques (less severe Failure Repair Class in Table 1). In this scenario it is assumed that in case of an alarm the turbine still has to be shut down. The effectiveness of the condition monitoring system has been considered by varying:

- the capability of early detection (non detected failures are set to 20%, 40% and 60%);
- the quality of the system (false alarms are set to 10%, 30%, and 50%);
- the fraction of failures that can be repaired in a less severe maintenance category, f.i. for the repair a simple supply boat is sufficient instead of a large crane ship and with less material costs.

In a second scenario it is assumed that after an alarm the turbines are inspected and based on the results of the inspection it is decided whether it is allowed to keep the turbine in operation for some time, so that the maintenance can be carried out at a suitable moment. This scenario is a further completion of scenario 1 with the following aspects is considered:

- the fraction of failures for which the repair can be postponed while the turbine is kept in operation (fraction is set to 20%, 40% and 60%);
- the period during which the turbine can be kept in operation after a degradation has been detected (delays of 1, 3, 6 and 12 months).

For the baseline the availability has been calculated as 90.0%, which corresponds with a revenue loss of about € 70,000.- per year per turbine. The costs of repair amount to 0.29 €ct/kWh. All variants for both scenarios have been analyzed by the ECN costs modeling tools also, where the results have been split up for the main systems (gearbox, generator, etc.). As the results of these analyses strongly depend on the assumptions made for the baseline, the effect for the different variants is calculated as the relative improvement as compared to the baseline. As an example of scenario 1 the reduction in revenue losses and the reduction in repair costs for the gearbox are depicted in Figure 9.

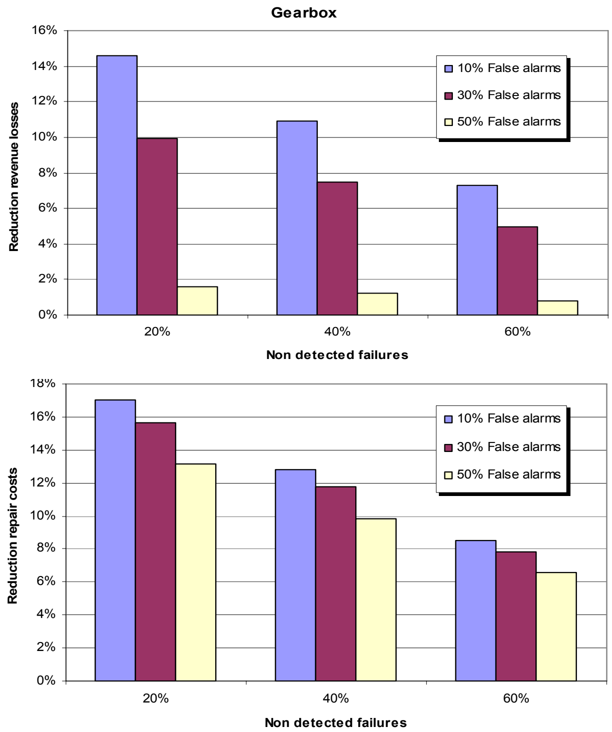

Figure 9: Relative reduction in revenue losses and repair costs as function of the fractions of non-detected failures and false alarms. The fraction of failures that can be shifted to a less severe maintenance category is set to 60%.

The reduction is given as function of the fraction of non-detected failures, and the number of false alarms, while the fraction of failures that can be shifted to a less severe maintenance category equals 60%. Based on these type of analyses decisions can be made about the technical requirements to be demanded for a condition monitoring system in relation to investments to be made to install and operate such a system.

9 Conclusions

The progress of the CONMOW project was hampered by mainly non-technical issues. Therefore the actual time for carrying out measurements and experiments was reduced from three years to about one year. Moreover, not all tasks could be performed, e.g. no online oil monitoring has been installed, and no experiments with new algorithms in SCADA systems have been done. Taking these limitations into account, the following conclusions were drawn from the CONMOW project.

- A FMEA has proven to be an effective way to assess which condition monitoring system can be used for which kind of component failure.
- Promising methods and algorithms have been developed to process 10-minute averaged SCADA data. De-trending the data result in graphs with little scatter which make it easier to assess if parameters (e.g. temperatures or accelerations) are changing slowly over time. Such change could be an indication for

component degradation. Due to the limited measurement time during which no failures occurred in the turbines, no proof was found that the methods indeed are useful to determine failures at an early stage.

- Time series have been analyzed in various ways. Most promising results were obtained by using the wavelet transformations. The analysis of the power output signal using this method indicated a shaft misalignment, which was confirmed by vibration measurements. Prognoses for the remaining lifetime however could not be made due to insufficient knowledge.
- The presently available systems for drive train monitoring, supplied by Gram&Juhl and Prűftechnik performed well and reliable. It was demonstrated that the systems are able to detect (1) component errors at an early stage, and (2) off-design conditions such as shaft misalignment.
- Up to now, the response on abnormalities in the data is either more frequent inspections or an immediate shut down to avoid consequence damage. Within the CONMOW project it was concluded (and also confirmed by experiences outside the project) that at present insufficient knowledge is available to make prognoses how the failures will develop in order to change from *calendar based maintenance* to *condition based maintenance*. Such knowledge can only be obtained from a larger population of identical wind turbines and longer measurement periods during which faults occur.
- For all types of measurements (SCADA data, time series, vibration monitoring) it is concluded that large amounts of data are being produced which are difficult to interpret by wind farm operators. A dedicated expert team is required to derive meaningful recommendations for O&M optimization.
- Simulations clearly indicated that off-design conditions such as rotor mass imbalance or aerodynamic imbalance can be detected from time series normally acquired by the turbine PLC.
- An economic assessment has been carried out to determine the benefits of condition monitoring systems. In fact, general conclusions cannot be drawn from this, but the method is able to quantify the added value taking into account aspects like false alarms, the capability of early detection, the fraction of failures that can be repaired in a less severe maintenance category, and the fraction of failures for which the repair can be postponed. Based on these type of analyses decisions can be made about the technical requirements to be demanded for a condition monitoring system in relation to investments to be made to install and operate such a system.
- Standards for communications contribute in easier installation and compatibility of CM-provisions. Configuration of CM-systems requires significant effort.

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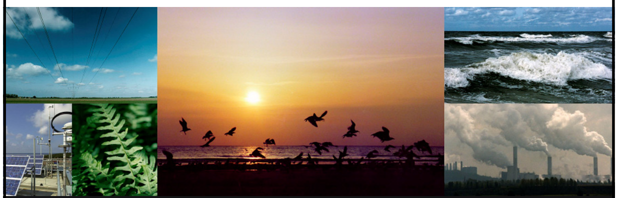
Energy research Centre of the Netherlands

CONMOW: Condition Monitoring for Offshore Wind Farms

Luc Rademakers and Edwin Wiggelinkhuizen



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Contents

- Condition monitoring related to maintenance concepts
- CONMOW: objectives and structure
- CONMOW: results
  - instrumentation and experiments
  - examples of measured faults
  - added value assessment
- Conclusions

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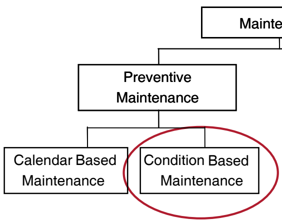
Maintenance concepts



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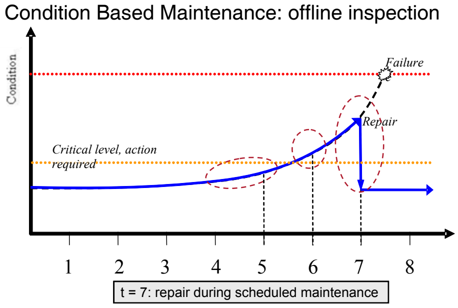
Maintenance concepts

Condition Based Maintenance: offline inspection



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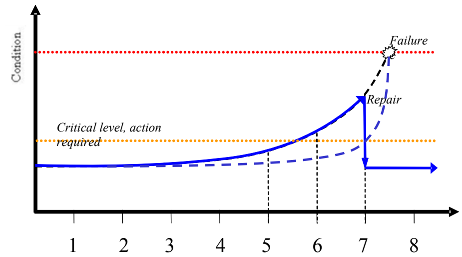
Maintenance concepts

Condition Based Maintenance: online measurements



Inspection interval too long

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Maintenance concepts

Condition monitoring *is the process of monitoring a parameter of condition in machinery, such that a significant change is indicative of a developing failure*

So three conditions to be fulfilled

1. Detection of failure mechanism (early indicator)
2. Detection on time to make prognosis
3. Criteria (**green**, **yellow**, **red** light)

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CONMOW project: Objectives

CONdition **MO**nitoring for **O**ffshore **W**ind farms

Overall objective: Investigation of added value for operators and owners of offshore wind farms

Objectives

- Online CMS ⟺ SCADA data, PLC data, etc.
- Development of new algorithms for early fault detection
- Implementation of algorithms for farm operation
- Quantification of added value CMS

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CONMOW project: Consortium

Financial contributions EU-FP5 and SenterNovem

Suppliers of CMS
- Gram & Juhl A/S, DK
- Prüftechnik CM GmbH, D
- Pall Europe Ltd., E

Suppliers of SCADA systems
- Risø National Laboratory, DK
- Garrad Hassan and Partners Ltd., UK

R&D institutes
- Energy research Centre of the Netherlands, ECN, NL
- Loughborough University, CREST, UK

Wind farm operator
- Siemens NL (*withdrawn after phase 1*)

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CONMOW project: Approach

Single turbine:

Phase 1

- Online CMS and load measurements
- Interrelationships CMS results and turbine parameters
- New algorithms for fault detection

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CONMOW project: Approach

Single turbine:

Phase 1

- Online CMS and load measurements
- Interrelationships CMS results and turbine parameters
- New algorithms for fault detection

Wind farm:

Phase 2

- Apply and test selected methods at wind farm scale
- Assess potential cost benefits of CM for offshore wind farms

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Results: Instrumentation and Experiments

Practical matters

- Liability issues
  - (1) prevented installation of oil monitoring
  - (2) prevented application of "faults" *(pitch, yaw errors)*
  - (3) caused delay (meas. time ≈ 1.5 yr instead of 3 yrs)
- Limited results single turbine applied at farm level
- Only few failures occurred during experiments

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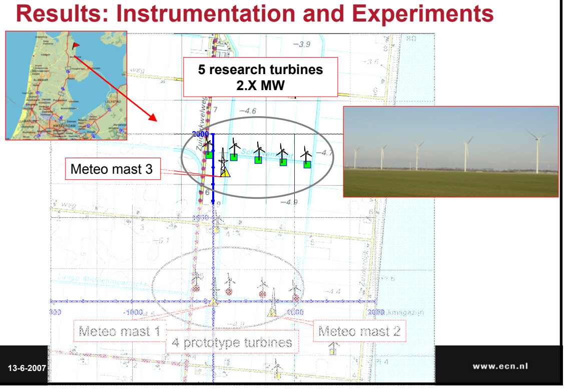
Results: Instrumentation and Experiments



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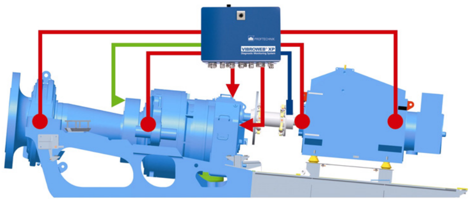
Results: Instrumentation and Experiments



Typical configuration
- Main bearing 2D-displacement
- Gearbox meshes and bearings
- Generator bearings

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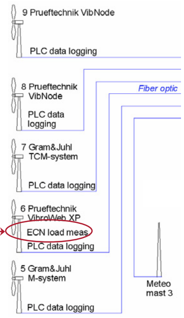
Results: Instrumentation and Experiments

All turbines:
- Drive train vibration monitoring
- PLC data (20 Hz)

Turbine 6:
- Load measurements (32 Hz)



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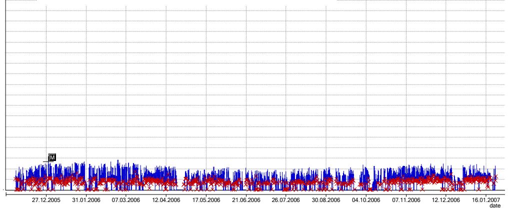
Results: (1) High vibration level generator

- Vibration level 10 Hz- 30 Hz
- Below **X mm/s** for most turbines



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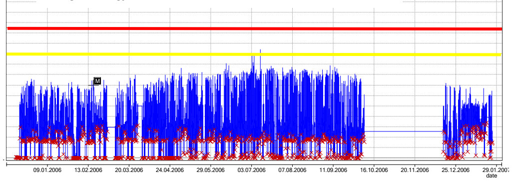
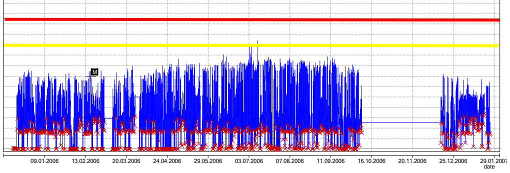
Results: (1) High vibration level generator

- Turbine 8: above **2·X mm/s** and increasing
- Probably shaft mis-alignment
- Now what????



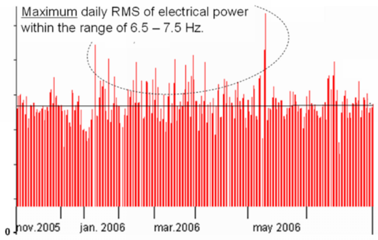
Results: (1) High vibration level generator

1. Confirmed by other analyses (high frequencies)
2. Inspections and alignment, but no real improvement
3. Continuation of monitoring recommended



Results: (1) High vibration level generator

Similar results found from electrical power PLC data (time series)



Results: (1) High vibration level generator

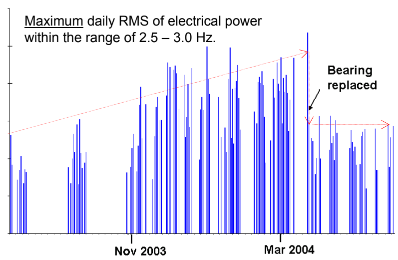
Assessment

1. Detection of failure mechanism (early indicator)
   Yes for CM; unclear from PLC data
2. Detection on time to make prognosis
   No, unclear how fast fault will develop
3. Criteria (**green**, **yellow**, **red** light)
   Yes, but arbitrary, danger of false alarms

Applicable for fault detection, not yet for PM planning

Results: (2) High vibration level bearing

High RMS value from electrical power PLC data (time series)



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Results: (2) High vibration level bearing

Assessment

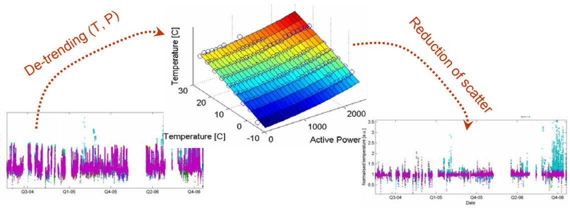
1. Detection of failure mechanism (early indicator)
   <u>Unclear</u> from PLC data; potential for CM
2. Detection on time to make prognosis
   <u>No</u>, unclear how fault will develop
3. Criteria (**green**, **yellow**, **red** light)
   <u>No</u>

Applicable for fault detection, not yet for PM planning

ECN

Results: (3) SCADA data

Is it possible to determine "early indicators"?



- De-trending effectively reduces signal variability
- However, no deviations from fingerprint found during measurement period

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Conclusions: Data analysis

- <u>Condition Monitoring (online drive train vibration)</u>:
  - Failure cause detection OK
  - Insufficient knowledge for: 1) criteria (**green**, **yellow**, **red**)
    2) prognoses of degradation
- <u>PLC data:</u>
  Deviations difficult to correlate with failure cause
- <u>SCADA data</u>:
  Potential, but not yet demonstrated

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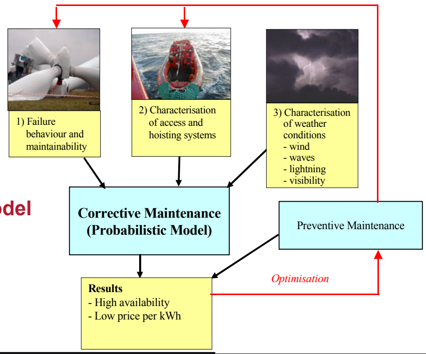
Results: Added value assessment

Scenario studies with O&M cost model

<u>Baseline</u>

- 100 turbines, 2.5 MW
- 15 km from harbour
- Wind & wave conditions: North Sea
- 4.5 failures/turbine/yr

O&M cost model



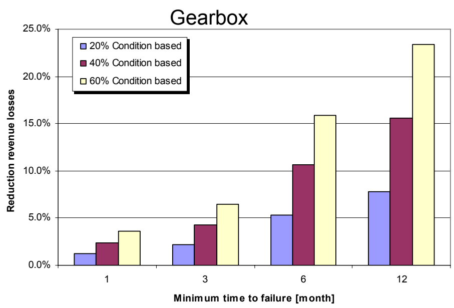
Results: Added value assessment

<u>Scenario 1:</u> Fault detection, less severe failure class, immediate shut down and inspection

<u>Scenario 2:</u> Repair postponed in time until PM

- the fraction of failures turbine in operation *(20%, 40% and 60%)*
- the period turbine in operation, after detected degradation *(delays of 1, 3, 6 and 12 months)*

Results: Added value assessment



Conclusions: Added value assessment

<u>Scenario studies</u>

- Strong tool to determine cost benefits of CMS
- Case study also shows negative effects
- Outcome wind farm specific; no general conclusions

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Overall Conclusions

- Systems have proven to work well and reliable
- Large amounts of data: specialists needed for interpretation
- Applicable for early fault detection and limiting consequence damage
- A large number of turbines must be monitored to gain sufficient experience with a specific wind turbine type

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Overall Conclusions

- Use of CMS to change from “*Corrective Maintenance*” to “*Condition Based Maintenance*” not demonstrated *(criteria and prognoses missing)*
- Recommended to make economic assessment to justify investments and operational costs