PROJECT DELIVERABLE REPORT

OPTIMUS

Demonstration of Methods and Tools for the Optimisation of Operational Reliability of Large-Scale Industrial Wind Turbines

Collaborative project

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Summary

In order to implement a cost-effective condition monitoring methodology the consortium has assessed the condition monitoring requirements for onshore and offshore wind turbines in terms of benefit achieved versus investment cost as well as part of insurance requirements. In determining this, the differences in failure modes and maintenance issues influencing onshore and offshore wind turbines have also been considered.

Wind turbine manufacturers and operators have shown strong demand for the development of accurate condition monitoring systems for the evaluation of the key wind turbine components in order to achieve substantial improvement in the efficiency of maintenance activities by reducing the need for reactive or corrective maintenance to the lowest possible level.

The consortium of this project is involved in the development and demonstration of an integrated condition monitoring system based on a modular design, which will enable the accurate and reliable diagnosis and prognosis of gearbox and power electronic faults. The OPTIMUS system combines the use of acoustic emission sensors and vibration sensors which can be integrated with oil particle sensors for the detection and prognosis of gearbox faults with current, voltage, vibration and temperature sensors for the assessment of the turbine's power electronics. Integration of the aforementioned sensors allows the full assessment of the condition of two critical wind turbine components through the application of a single monitoring system based on a modular design which will also take into account generator currents and electric power output measurements.

1. Introduction

Condition monitoring of industrial wind turbines has increased in importance in recent years. Wind turbines are complex systems consisting of several sub-components which all need to operate together flawlessly in order to enable efficient wind energy harvesting.

Unfortunately, industrial scale wind turbines, either onshore or offshore, operate under harsh loading and environmental conditions which means the development of faults in different sub-components of the wind turbine is possible with time. Depending on the type of the fault and the component affected different maintenance strategies may be employed. In most cases, less severe faults which do not affect the overall operation of the wind turbine may be addressed in time during planned maintenance. However, severe faults and failures are currently addressed by most wind farm operators through corrective maintenance strategies.

For onshore wind farms, although corrective maintenance is not the most cost-efficient strategy, it is feasible since access to the affected wind turbine is usually not a problem. Accessibility to onshore wind turbines is normally a problem only during periods of heavy thunderstorms or heavy snowfall which rarely last for more than a few days. Unfortunately, this is not the case in offshore wind farms where accessibility can be restricted for several weeks or even months depending on the wave height as well as overall weather conditions prevailing in the area of the wind farm. Although there is always the possibility to deploy maintenance personnel via helicopter when wave heights are prohibited for a boat to approach the wind turbine, this practice restricts maintenance capabilities to relatively light intervention since heavy equipment and large spare parts can only be brought in by boat.

Condition monitoring capability is nowadays a requirement for all industrial wind turbines regardless of whether they are onshore of offshore. It is also a requirement from the insurance companies for wind turbines in order to be insured to have a certified Condition Monitoring System (CMS) installed.

The gearbox has been the sub-component which is primarily monitored in industrial wind turbines. Most CMS employ temperature and vibration sensors in order to monitor the condition of the gearbox. Unfortunately, due to the variable loads as well as the signal processing methodology used CMS do not provide the maximum benefit that could be offered to wind farm operators. Hence their applicability has remained questionable and in certain cases it has been employed simply due to the insurance requirement. It is very common for wind farm operators to rely on oil samples retrieved during regular maintenance and examined under an optical microscope in order to decide the wear level within the gearbox. Microscopy examination reveals the amount, size and type of debris in the lubricant which can influence extensively the overall fatigue lifetime of gearbox subcomponents.

Other components which may be monitored include the generator and main bearing of the wind turbine again using vibration for evaluation. In certain cases blades have been monitored using acoustic emission sensors which are permanently mounted in the internal surface but this is not a general practice yet. The power electronics of the wind turbine are not normally monitored and in cases where they are, monitoring is restricted to very basic measurements which are not ideal for the development of a sound predictive maintenance strategy.

1.1 Background

As wind turbines increase in size and move offshore, operations and maintenance procedures need to be optimised to increase reliability, safety and maximise cost effectiveness. The installation of CMS to allow real time monitoring of key wind turbine components has become a necessity during the last few years. However, CMS technology is yet to prove its usefulness particularly due to the challenges involved during measurements under variable loads and environmental conditions.

Commercial CMS consist of a series of sensors (accelerometers, proximity probes, temperature sensors, etc.) collecting physical data from key functional subsystems of the wind turbine and transferring them to a central location for processing. To date the majority of CMS systems have been vibration systems based around the drive train to measure the level of vibration present on key components of the drive train with the data acquisition units placed in the nacelle.

The purpose of CMS is to diagnose faults in the components monitored and if possible predict the time remaining to failure for a particular sub-component. At the moment commercial CMS offer the ability to diagnose faults although false alarms or missed faults are still possible predominantly due to the effect of variable loading during measurements. Prediction is a far more difficult task to achieve reliably since wind turbines are machines that do not work on constant load which makes the calculation of the remaining fatigue lifetime of a sub-component at least unreliable, if not entirely impossible. Therefore, prognosis of failure needs to be considered within the framework of probability of failure over a given time range.

Current experience of the OPTIMUS consortium members has shown that particularly for the gearbox once a certain fault develops it will in general become worse relatively rapidly. However, that does not necessitate that final failure will occur immediately afterwards. This depends on several other factors including amount of debris in the lubricant, time that the turbine has been operating at full load, wind variability as well as quality of materials used particularly in terms of wear resistance. Certain types of faults such as misalignment and imbalance can be fixed and if addressed in time, can extend the lifetime of gearbox components significantly. However, it is very important that at the same time the lubricant is as free of debris as possible and of course that there is no contamination by moisture in order to achieve effective lubrication.

As mentioned earlier, wind farm operators currently rely primarily on corrective maintenance strategies coupled with planned maintenance interventions. The implementation of predictive maintenance strategies is highly desirable but this requires the use of reliable diagnostic data in order to develop reliable prognosis.

The largest technical challenges being faced by the wind energy industry are the low reliability levels of the wind turbine units and the high Operation and Maintenance (O&M) costs [1-3]. Current offshore wind turbines were not designed specifically to cope effectively with the harsh marine environmental conditions, because onshore wind turbine designs have been employed in offshore wind farms [1-2, 4-5] which has resulted in the reduction of their reliability levels. In addition, maintenance practices used for onshore wind farms and employed in offshore wind farms are inadequate for future projects [3].

There is still a lot to be done in the field of CMS technology and signal processing before an efficient predictive maintenance strategy can be implemented. This will require the cooperation of all stakeholders involved but primarily wind farm operators and CMS developers.

2. Types of Maintenance Strategies

Wind farm operators have so far relied primarily on corrective maintenance practices. However, there have been instances particularly in offshore wind farms with frequent gearbox problems where proactive maintenance has also been employed. In most cases the proactive maintenance used has been based on preventative actions rather predictive. Predictive maintenance strategies are not robust enough to be considered sufficiently cost-efficient and this is largely due to the limitations of existing CMS.

There are two common maintenance strategies that are generally available to wind farm operators, proactive and corrective as shown in Figure 1.

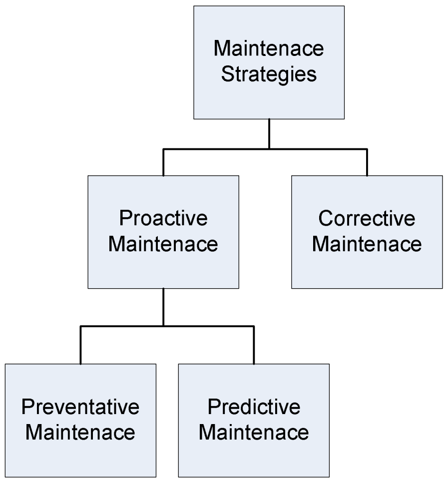

Figure 1: Schematic showing the different maintenance strategies available to wind farm operators. Currently wind farm operators tend to work on the basis of corrective maintenance actions.

1.2 Proactive Maintenance

This maintenance strategy is based on the principle of avoiding unnecessary downtime by monitoring system degradation and initiating minor repairs to return the system to full working order before a critical fault occurs.

Proactive maintenance can be further divided into preventative maintenance or predictive maintenance actions.

1.2.1 Preventative Maintenance

Preventative maintenance is often referred to as planned maintenance, and comprises of maintenance activities that are undertaken at specific points in time. The maintenance regime is based on a reliability analysis of the system based on its design characteristics. It therefore relies on knowing the probability that a system will fail in a specified period of time so that steps can be taken to change the component or components likely to fail.

The main advantages of this system are the extension of system life and the reduced probability of system down time. However, in the case of wind turbines due to the variable loading conditions preventative maintenance is not sufficiently reliable.

1.2.2 Predictive Maintenance

Predictive maintenance is also referred to as condition based maintenance. Under this maintenance strategy, maintenance tasks are undertaken in response to a specific system condition.

The condition is detected by monitoring equipment installed on the equipment and when the measured parameters reach a specified level corrective action is taken. Like preventative maintenance the aim is to reduce the probability of system breakdown with the advantage that repairs are only performed when required. This strategy relies on the efficiency of the CMS employed.

1.3 Corrective Maintenance

Corrective maintenance is a strategy based on maintenance actions performed after a failure or a severe fault has occurred and has been verified. The strategy requires part replacement once it has failed. With this strategy temporary repairs may be made in order to return the wind turbine to operation, with permanent repairs delayed until a later time risking however subsequent more serious failures of related components.

The advantage of this strategy is the simplified system topology. The main disadvantage of this strategy is the unscheduled and random downtime due to failures resulting in high replacement costs, loss of production and unnecessary downtime.

1.4 Wind Farm Operator Practices

A widely practiced maintenance strategy adopted by both onshore and offshore wind farm operators is Reactive Response or corrective maintenance [1, 6-7]. However, it has been reported that this O&M strategy has led to over-maintenance practices [3], leading to high cost per unit of energy. This O&M strategy has also been found to be inadequate when considering future large offshore wind farms in remote locations [3].

A more prognostic and preventive based maintenance policy is required in order to increase the efficiency of large wind farm projects. However, maintenance optimisations for both onshore and offshore wind farms are subjected to a variety of constraints such as reliability, adverse weather conditions, accessibility and availability of parts and crew that must be accounted for in the O&M optimisation. The overall effectiveness of the CMS employed is critical in achieving an efficient predictive maintenance strategy.

When considering the reliability of the power converter unit in wind turbines, it has been reported as being one of the components that suffer from the highest failure rates within the wind turbine assembly together with the gearbox [1-2, 4-5, 8-9]. Therefore, not only an optimisation of the O&M policy is required, but also the need for increasing the power converter availability is of high importance for the economic viability of future offshore wind farms [10].

Maintenance tasks in conventional power plants, e.g. coal fired and steam turbine power plants, are performed during low-load seasons, i.e. when the demand for electricity is low, with the maintenance time depending on system risk (critical items) and production cost [11].

Effective maintenance strategies for power plants aim to reduce the frequency of service interruptions and the undesirable consequences of interruptions, i.e. loss of energy production. The maintenance strategy affects items and system reliability in a way that if too little maintenance is performed, i.e. the system is returned in an ‘as good as operating’ condition, then a large number of costly in service failures and poor system performance results, which in turn degrades system reliability [11-13].

In contrast, if maintenance tasks are performed too often, reliability may improve but the cost of maintenance increases and revenue may decrease [12-13]. Therefore a cost-effective maintenance strategy optimisation involves balancing the cost of maintenance tasks and system reliability [11].

The main purpose of maintenance optimisation for power plants is to determine the most cost-effective maintenance strategy, which will provide the best possible balance between direct maintenance costs, e.g. labour, resources, materials and administration costs, and the consequences or penalty of not performing maintenance as required, e.g. loss of production and anticipated income and profit [14-15].

Considering other offshore structures, e.g. oil rigs located in the marine environment where the accessibility is restricted to times of good weather and where the cost of maintenance tasks are vastly increased because of the remote location, then the maintenance practices depend on whether the project is manned or unmanned [16].

For manned offshore structures, i.e. there is a permanent maintenance team on the structure, then item failures can be detected and repaired quickly and the system availability is kept high. Conversely when considering unmanned offshore structures, then the maintenance team has to be transported from the shore together with appropriate spares.

Clearly the transportation availability depends on the weather and sea state, e.g. in the North Sea region some offshore platforms are inaccessible for long periods of time between October and April, due to weather and sea state conditions [17], and also upon the ability to obtain the necessary resources including transport and each maintenance trip is potentially costly.

Considering offshore wind farms which are unmanned structures, then the optimisation of maintenance strategies is required to minimise the O&M costs that are incurred for transporting maintenance teams and spares, in order to achieve competitive prices for the produced electricity [18].

The current O&M practice adopted for existing offshore wind farms and most onshore wind farms is based on reactive response [3]. When a component in a wind turbine fails, resulting in it becoming non-operational, a maintenance expedition is launched at the first opportunity to carry out repairs. Failed items are repaired either in situ or by exchange. The maintenance strategy is therefore driven by the need to return the wind turbine to full operation as quickly as possible [19].

This approach to maintenance for offshore wind farms has been shown through experience to be effective but expensive [20-22].

This corrective maintenance strategy has been reported to be a suitable strategy for onshore wind farms, where accessibility is not usually a determining factor [18, 23]. Offshore wind farms (OWFs) OWFs are far more dependent upon environmental conditions, especially weather and sea state, and upon the availability of specialist vehicles such as ships and helicopters both of which affect accessibility [1, 6, 22].

Corrective maintenance strategy has two primary factors that contribute to high maintenance costs; limited accessibility and limited time to carry out repairs [1, 6-7, 12]. Limited accessibility occurs because access to offshore wind farms is heavily dependent upon the weather and sea state conditions [1, 6, 22] which vary over the year, and upon the location of the offshore wind farm, i.e. the further from shore a wind farm is located the more difficult it tends to be to access [19-21].

Time to carry out repairs is dependent upon available weather windows, limited light conditions especially in the winter months, and a generally more difficult working environment i.e. working at sea is more challenging than working onshore. As a consequence maintenance resources including manpower and equipment may not be able to be utilised effectively leading to higher maintenance costs [19].

A consequence of limited time for repairs is that maintenance tasks often tend to concentrate upon repairing failures with insufficient time being available to establish the root cause of the failure. For example, consider a power converter failure that causes a wind turbine to cease operation. With the corrective maintenance strategy, the power converter unit would be repaired or replaced and the wind turbine returned to service as quickly as possible, with only a modest attempt, if any, being made to determine the root cause of failure, which would allow an understanding of how to prevent a recurrence. Inevitably, such maintenance practice tends to result in a high number of maintenance visits resulting in high costs [24].

This O&M strategy for offshore wind farms has been reported to be based on over-maintenance practices, leading inevitably to high cost per unit of energy produced [3, 25]. Although this current strategy has not yet been proven to be the optimum economic solution, it is the only practical one taking into consideration the relative low number of wind turbines currently in operation, in existing offshore wind farms, which are located relatively close to shore in shallow waters. However when considering future offshore wind farms, which are likely to be located further away from the coast, in remote locations, with increased power ratings over today's wind turbines, then such a maintenance strategy is likely to require significant resources thereby becoming prohibitively expensive.

A Planned Intervention (PI) maintenance policy has not yet been adopted for offshore wind farms. This maintenance philosophy may, however, be more suitable when considering the maintenance of significant numbers of such wind farms. For large numbers of offshore wind farms the corrective maintenance strategy is likely to become economically unattractive, unless reliability levels of offshore wind turbines can be increased substantially, because significant maintenance resources will be needed.

A PI maintenance policy adopted for offshore wind turbines will offer greater effective use of maintenance resources and be more economically attractive. However, it is necessary to understand the implications of lost revenue from lower electricity production that may result.

A PI maintenance policy for offshore wind farms would involve scheduling visits to each wind turbine at specified points in time; the scheduled visits being determined by the reliability of the wind turbines and weather related accessibility. For example, an offshore wind farm using a PI maintenance policy would mean each wind turbine receiving a number of visits to maintain its availability above a specified level. The required availability level should be determined by economics, which involves balancing the maintenance costs i.e. manpower and transportation (ships and helicopters) and the cost of downtime i.e. loss of revenue.

PI involves planning maintenance periods for particular times so fixed intervals occur between each maintenance periods. This means that should wind turbines become non-operational between the planned intervention times the wind turbine will remain non-operational until the next planned intervention occurs. Wind turbines functioning correctly will be receiving preventive maintenance at their scheduled maintenance visit. The PI maintenance policy means that repairs and maintenance will effectively occur at the same time – at a time planned in advance as determined by their reliability, therefore allowing optimal use of maintenance equipment, manpower and resources, making however the use of prognostic and preventive maintenance practices essential.

Considering the above it becomes apparent that the merits expected from this maintenance philosophy are achievable when advanced planning techniques and advanced condition monitoring of the wind turbine components is engaged, in other words by shifting to a maintenance policy based on prognostic and preventive maintenance practices, [25] in comparison to current maintenance practices that are based on reaction to failures rather than proactively intervene. The condition monitoring of wind turbines that is currently used does not allow for advanced prognostic and preventive maintenance practices due to the low level of monitoring capabilities they incorporate.

Even for PI maintenance policy there are constraints which must be considered including weather conditions and sea state, the availability of vessels or helicopters to carry out the maintenance, lead time of spare parts for repairs, and the availability of manpower. Weather condition and sea state are highly dependent upon the location of the wind farm e.g. those wind farms far offshore are likely to be exposed to more adverse weather conditions and higher sea states. Furthermore, it generally becomes more expensive to maintain wind farms located further offshore simply because maintenance vessels and manpower are required for longer periods. Spare parts can be kept at hand but this requires additional inventory expenditure, whilst just-in-time delivery practices may leave the wind turbine inoperable should any delay occur in receiving the replacement parts.

Computer models of a PI maintenance strategy have been developed that allow investigations on the effect of the constraints that affect the offshore wind farm O&M strategy [3, 25]. These computer models have been used to investigate the advantages of the PI maintenance policy over the current O&M practices for OWFs, as reported in [3] and [25].

3. Key Wind Turbine Components

The purpose of the condition monitoring system is to detect the initiation and evolution of faults as well as reliably assess their location and severity. Reliable detection and evaluation faults or failures in wind turbine components is of paramount importance in order to decrease downtimes, increase reliability and minimise maintenance and repair costs. The reliable detection and quantification of faults particularly in the gearbox and power electronics will lead to a significant reduction of downtimes and associated maintenance costs allowing the implementation of predictive maintenance strategies in the medium to long term.

Although condition monitoring systems are generally stand alone systems which raise alarms whenever faults are detected, in the future they could be integrated into the control system. Integration of condition monitoring data to the control system will improve the overall efficiency of wind turbines as it will permit them to operate within an accurately monitored acceptable operational envelope. However, in order to achieve this, the reliability of the information generated by condition monitoring systems needs to be affirmed to avoid unnecessary losses in production due to false feedback. The following table summarises inspection and condition monitoring techniques for various nacelle components.

Table 1: Typical nacelle defects and common inspection/condition monitoring techniques employed by the wind energy industry for their detection and evaluation. A: Severity in case of occurrence (1=lowest, 5=highest), B: Interest in improving detection by the wind energy industry (1=lowest, 5=highest).

NACELLE DEFECTS, FAULTS, FAILURES	CURRENT INSPECTION	A	B
1. Main Bearings	Every 12 months, vibration analysis.	5	5
2. Gearbox			
Housing cracks	Every 6 monhs, standard preventive inspections.	5	3
Bearings	Every 6 months, standard preventive inspections (sound and/or debris). Videoscope inspections. Not scheduled. Every 12 months, vibration analysis.	4	5
Gears (Pitting, spalling, scuffing, cracks, corrosion...)	Every 6 months, standard preventive inspections (visual and/or debris). Videoscope inspections. Not scheduled. Every 12 months, vibration analysis.	5	5
Lubricant	Every 6 months, oil analysis	4	5
3. Coupling			
Misalignment	Every 12 months, vibration analysis. Alignment every 24 months.	3	5
4. Generator			
Bearings	Every 6 months, standard preventive inspection (sound) and global vibration measurement. Every 12 months, vibration analysis.	4	5
Unbalance	Every 12 months, vibration analysis	3	3
Other damages	Every 12 months, vibration analysis	3	5
5. Yaw System			
Yaw drive	Every 6 months, standard preventive inspections	2	4
Yaw gear	Every 6 months, standard preventive inspections	5	3
Yaw bearings		5	3
6. Blades bearings		5	5
7. Hydraulic Unit	Every 6 months, standard preventive inspections and oil analysis. Pressure sensors.	4	5

Table 2 summarises the main techniques currently used for the evaluation of the condition of individual nacelle components.

Table 2: Techniques used conventionally for evaluating the condition of specific nacelle components.

Nacelle Component	**Technique employed**
Gearbox	Vibration.
Bearing	Vibration. Oil Analysis. Temperature. Acoustic Emission.
Electrical System	Current. Voltage. Speed. Temperature.
Drive Train	Vibration. Frequency.
Generator	Current Spectrum.

4. Requirements for Condition Monitoring System

Wind turbine condition monitoring systems in general need to be permanent, but individual measurements with portable hand equipment are also beneficial and are required for verification purposes when a turbine is visited by maintenance personnel. Data should be trended in order to improve the accuracy of the condition monitoring system and minimise false alarms. Although the feedback received from the condition monitoring system does not replace recommended maintenance procedures it is possible to improve maintenance planning based on the data generated by such systems.

A condition monitoring system, although it does not replace a hardwired safety system nor does it replace the standard systems for the acquisition of operational data of the wind turbine, can be integrated with those. However, it is important that during condition monitoring system installation, care must be taken to ensure that no intervention affects the control or safety system. Self-diagnosis of the condition monitoring system is also desirable.

The condition monitoring system should be comprised of components of an industrial standard and therefore capable of working under extreme environmental conditions. Storage media of a suitable type must be used.

In order to evaluate on-line the condition of critical rotating components of wind turbines the following areas should be monitored:

- Main bearing;
- Gearbox (all stages);
- Generator bearing.

The integrated Acoustic Emission (AE) and Vibration Module implemented for the condition monitoring of the rotating parts of the nacelle should be capable of acquiring signals using sensors mounted on the external surface of the equipment and providing a reliable output grading the overall condition of the particular machine component. The AE and vibration modules should also be capable of distinguishing different deterioration modes and provide estimation of Failure Time. As reported by the partners within the consortium the rotational speed range of shafts are from 1 to 1500 rpm

AE Acquisition

AE transducers will be mounted using initially a Magnetic Hold Down and ultrasonic coupling on the outer surface of each bearing. This means that an AE sensor will be located on each bearing. Where this is not possible then sensor should be placed as close as possible to the bearing under consideration. Furthermore, on the gear box casing one additional sensor will be mounted. For this application the PAC R50a sensor has been selected with a broadband frequency response between 100 and 700 kHz. Considering input provided by end users the estimated number of AE sensors to be used will be five.

A typical schematic diagram of a single channel AE acquisition System is shown in Figure 2.

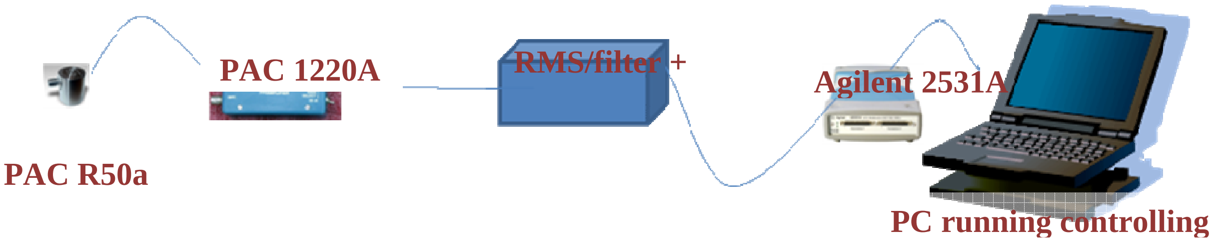

Figure 2: Measurement of AE single channel configuration

The transducer signal will be amplified by an AE preamplifier with selectable pre-amplification levels (20/40/60dB). The PAC 1220A has been chosen for this. The preamplifier incorporates a band pass filter between 0.1-1.2MHz. This filter will provide a considerable Signal to Noise Ratio filtering out most unwanted structural resonances.

The derived signal will be then processed by a suitable RMS/filter + power supply, capable of providing the preamplifier and sensor with 28V DC. The above device has the dual capability of providing as an output raw AE signal or the Moving RMS which is a low frequency demodulated transform of the initial high frequency modulated raw AE signal using selectable time constant.

AE acquisition will be at 500 ksamples/s per channel. The algorithms used for data processing include peak-peak, moving RMS, spike energy, spectral and cepstral analysis, crest factor and moving kurtosis.

The Agilent 2531A has been selected as the data acquisition (DAQ) board. This board will acquire at least 3 revolutions of the shaft and will be triggered by a timer. Alternatively it could be triggered via the SCADA or the wind turbine controller if the condition monitoring system is integrated with them. Regular readings (daily, weekly, etc.) are programmed.

The Agilent 2531A is a multi-purpose DAQ board that has some very important advantages which are related to AE sampling. It is a multi-channel DAQ (up to 64 channels) but the maximum sampling rate can reach 2Msamples/sec when using only one channel and 2MHz/(No of channels) when using more than one channel. That is one of the best sampling rates that can be obtained for a USB device. The latter was another reason for choosing this DAQ; it is very easy to use, install and start measuring. Furthermore, the device itself is very fast and there is no practical limit on the amount of data stored provided that i) there is enough hard disk space and ii) the hard disk is fast enough to be able to follow the data. The last reason for choosing this device is the fact that it has also the capability of inter-working with Matlab or Labview based software making it very easy at a later stage to integrate a final product (SW + HW).

The device has a 12 bit resolution, and a 0-10 unipolar dynamic range which is the output of the RMS/filter and a buffer size of 8 Msamples. There is also a very handy Agilent utility that is used for sampling which can also save the data in text format so Matlab can deal with them. In a later stage, all the control will be done by the SW, thus bypassing Agilent suite.

Customised software will be used to control the Agilent 2531A. The whole configuration including data acquisition times, sampling rates, gains and acquisition times will be controlled remotely using this software.

The DAQ board and industrial computer running the acquisition and analysis software require 230V AC supply. The acquired digitised signals are then processed by customized software. Some of its analysis capabilities are presented next:

- Raw data presentation;
- Evaluation of Moving RMS transform of signal of selectable time constant;
- Evaluation of Spike Energy of selectable time constant;
- Evaluation of Moving Skew transform of signal of selectable time constant;
- Evaluation of Moving Kurtosis transform of signal of selectable time constant;
- Evaluation of Moving Crest Factor transform of signal of selectable time constant;
- Power spectrum of above mentioned initial or time windowed signal or transforms;
- Power cepstrum of above mentioned initial or time windowed signal or transforms;
- Time windowing of above signal or transforms;
- Frequency windowing (filtering) of above signal or transforms maximum, minimum, and mean levels of above resulted signals;
- X-Y axis in log scale if selected;
- Cursor is also available for manual analysis.

Vibration Acquisition
Accelerometers will be mounted on each bearing plus one on the casing of the gear box. Tri-axial measurements in bearing locations will also be considered. The VM 7002LF Low Frequency Industrial Accelerometer has been selected. This has a frequency 5% between 1.2Hz to 5 kHz and 100mV/g sensitivity. In some locations of particular low rotational speed the VM 5102 shear type accelerometer could be also used providing a frequency 5% between 0.5Hz to 250 Hz and 500 mV/g sensitivity. Mounting pads will be used to keep accelerometers attached on the pre-defined measurement locations. In total eight accelerometers will be used.

Accelerometers will be provided with power through the Feldman power supply requiring 220V AC and with a frequency response between 0.5Hz to 100 kHz. This will be directly connected to the accelerometers since the later includes an integrated amplifier.

Output acceleration signals will be sampled at 25 kSamples/s using the Agilent DAQ. The configuration is depicted in Figure 3.

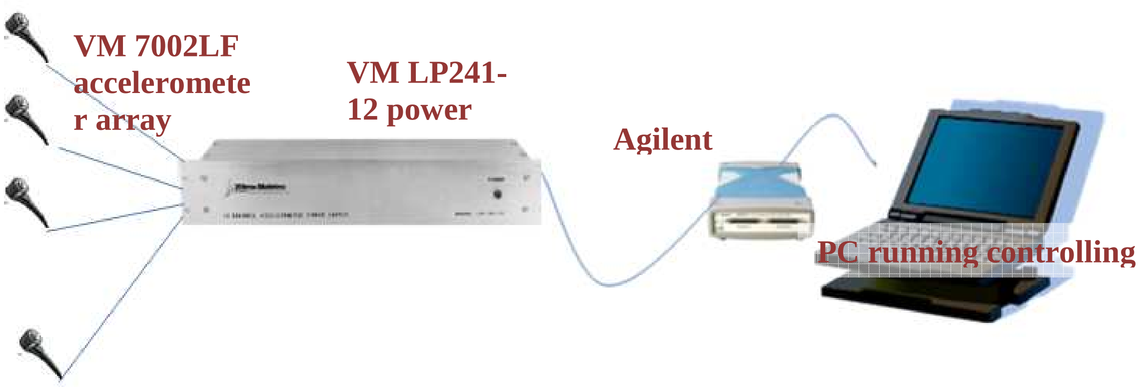

Figure 3: Measurement of Vibration multi-channel configuration.

Finally, acquired digitised signal will also be processed by Feldman proprietary PCM SW and correlated to the acoustic emission measurements.

The following external inputs are desirable:

- Shaft running speed (possible tachometer option incorporated);
- Number of Gear teeth per Gear;
- Bearing Characteristics;
- Wind speed.

Control and interaction with SCADA
The configuration described above (AE + vibration sensors) will be installed on each wind turbine permanently. The onsite measuring PC will be connected to a remote supervisory computer via 3G/4G connection. The measuring PC could be controlled remotely through the remote supervisory computer using a client/server configuration, with the client running on the measuring PC (one in each turbine) and the server on the main server computer. Regular or ad-hoc measurement will be possible to be programmed by the server. The analysis will be held on the measurement PCs and the results will be downloaded to the server for presentation and storage.

Condition Decision Making
Deterioration Modes and Fault Development Progress will be identified by comparing signal characteristics both in time and frequency domain between initial or free of defects condition with current and deteriorated condition. When specific levels of certain characteristics are reached then an alarm Indication will be given.

Condition will be graded as:

- Very Good;
- Acceptable;
- Yellow Condition;
- Red Condition;
- Shutdown Condition.

Based on this, trending should be possible as well as an estimation of the remaining lifetime of the monitored components. Due to the variable operation and loading conditions prevailing on wind turbines it is not possible to estimate the exact remaining lifetime. However, by taking into account the operational history of the turbine together with the results of the condition monitoring system, it is possible to predict the risk of failure and estimate a time range within which maintenance should be carried out to avoid catastrophic failure.

Furthermore, based on the experience of the partners in AE condition Monitoring Systems it is possible to establish reliable condition AE acceptance levels which when reached could easily grade machine condition without the requirement of close trending.

Typical Frequency Characteristic Responses of the AE sensors and accelerometers mentioned in this document are shown below.

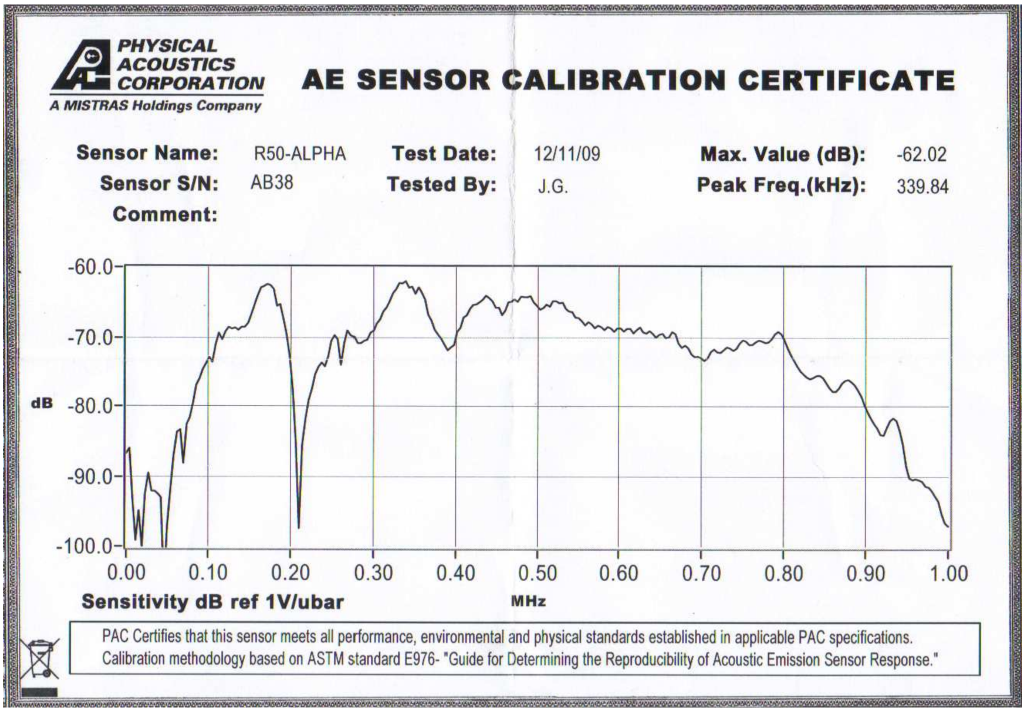

Figure 4: Typical frequency response of AE sensor PAC R50a.

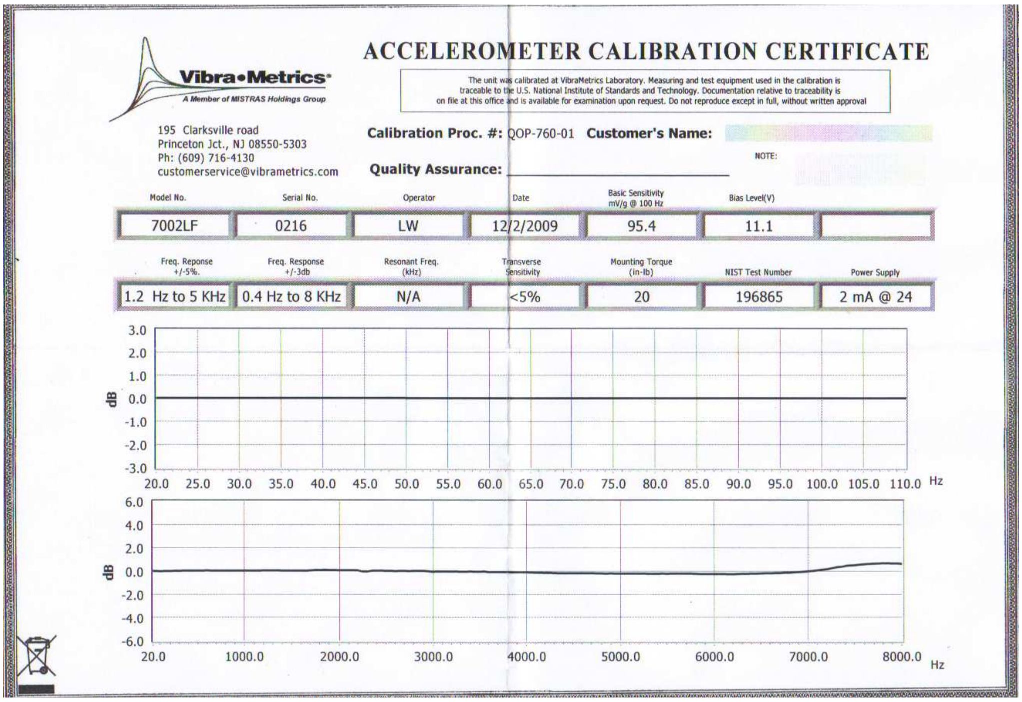

Figure 5: Typical frequency response of Accelerometer VM 7002LF.

Integration with oil particle analysis and oil temperature sensors

Online oil particle analysis and oil temperature sensors can be integrated with the AE/vibration system. Online oil particle analysis can provide useful information regarding the rate of wear, population and dimension of debris particles particularly at the early stages of degradation of the rotating components.

Variable load effect
The effect of variable loading condition prevailing on wind turbines is a key parameter which can affect dramatically the results produced by the condition monitoring system. The signal processing employed within the OPTIMUS condition monitoring system is appropriate for the removal of this effect thus enabling accurate diagnosis and prognosis capability for rotating components of the wind turbine.

Power electronics
The power electronics of the wind turbine are susceptible to frequent faults. For this reason condition monitoring is important to enable improved maintenance of these components.

The OPTIMUS condition monitoring system uses various sensors to monitor the vibration, temperature, humidity, currents and voltages in the power electronics of the wind turbine. These sensors enable the accurate diagnosis of the power electronic components monitored. However, prognosis is more complicated as the exact remaining lifetime of power electronic components is very difficult to determine. Nonetheless, from the condition monitoring data acquired it is possible to determine how much the power electronics of a particular wind turbine have been stressed thus providing an estimation of the risk to failure within a particular time period. The Rainflow algorithm will be used to analyse data acquired over time by the OPTIMUS condition monitoring system in order to determine the risk of failure for the wind turbines being monitored.

Figure 6 shows the current, voltage, humidity and temperature sensors employed for monitoring the power electronics.

Current sensor

Voltage sensor

Humidity sensor

Temperature sensor

Figure 6: Some of the sensors employed for monitoring the power electronics of the wind turbine.

5. Condition Monitoring System Cost Versus Benefit

It is known that the complete replacement of a gearbox can cost more than 10% of the total cost of a wind turbine. For a 1.5 – 3 MW turbine this could be in the range of €75,000 – €300,000. On top of this, one needs to consider the loss of revenue for the time that the wind turbine will remain inactive. A new gearbox usually takes 6 months to be delivered from the day of the order. This means that a 1.5 MW turbine can be inactive for a period of 6 months until the old gearbox has been replaced.

If we consider a 1.5MW turbine with 25% annual capacity factor then the annual electricity production of this turbine will be the equivalent to 3,285 MWh. The European Electricity Index provides a price base of €58.14 per MWh and a price peak of €70.05 EURO per MWh for late November 2012. More specifically in Germany the price base for the same period is €57.69 per MWh and the price peak €69.87. In France the corresponding price base is slightly higher at €58.895 and price peak at €69.87. In Switzerland the price base is even higher at €61.49 and price peak at €71.22.

In Germany, on 31st of May 2012 the consumer price of 1 kWh was at 24.31 €cents according to EEP. In Spain on 1st of July 2012 the consumer price of 1kWh was 17.05 €cents according to Iberdrola. In the UK on 1st of September 2012 it was 18.85 €cents according to nPower.

Considering these prices a 1.5 MW turbine with an installation cost of approximately €750,000 – €3,000,000, depending on the manufacturer and location (onshore or offshore) with 25% annual capacity factor is expected to generate an annual turnover of €560,000 – €800,000 under normal operation. If the wind turbine is out of order for 6 months due to gearbox failure then the loss of revenue will be anything between €280,000 - €400,000 plus the cost of the replacement gearbox which can be anything between €75,000 - €300,000. Thus the overall cost of a failed gearbox can reach up to €700,000.

It is noted that the average annual capacity factor in Europe usually exceeds 27% and in certain cases some wind farms can exceed 34%. Therefore the cost of downtime may increase further.

Gearbox reliability has been one of the biggest single concerns of the wind industry. Gearboxes and wind turbines in general carry a significant risk for their operators. The risk carried on gearboxes along by a relatively large wind turbine operator is in the range of several hundreds of million €. The number of failures increases significantly between 5-7 years in operation for onshore wind farms. So far experience with offshore wind turbines have shown that severe gearbox problems may occur as early as 1-2 years after commission.

According to the Renewable Energy Magazine World (June 2010) only in the U.S. approximately 8,000 MW or 8 GW of wind farm capacity are expected to go out of warranty period every year before the end of this decade.

In most cases gearboxes last approximately 5-11 years depending on the manufacturer. However, wind turbines are supposed to have an operational lifetime of 20 years by design. This means that unexpected failure is likely to occur and may result in very significant costs which can be close to the 1/3 of the original price of the turbine.

Condition monitoring can protect wind turbine operators as well as wind turbine manufacturers who provide warranties for their wind turbines for several years from unexpected failures. This can be achieved by finding faults on time before heavy damage takes place. This may require expensive replacement and significant downtimes.

The cost of the OPTIMUS system has been estimated to be in the range of €15,000 in its optimised version. The final price will heavily depend on the number of sensors used. However, ongoing research on fibre optic AE sensors can contribute significantly in the reduction of the cost even further. Fibre optic AE sensors are far cheaper than piezoelectric sensors.

Let’s assume that an average onshore wind farm consists of 20 wind turbines of 1.5MW power rating each. These wind turbines have been bought at a cost of €2,000,000 each. Let’s also assume that these wind turbines have no condition monitoring so they rely on manual inspection at regular period. It is logical to expect that in the first 10 years at least one of these wind turbines may experience one unexpected gearbox failure at a cost of €400,000. At a current estimated cost of €15,000 per OPTIMUS system, the operator or manufacturer providing the guarantee could have installed on every wind turbine an integrated condition monitoring system minimising the likelihood of such failure from occurring. Taking into account the fact that the maintenance personnel inspecting manually the wind turbines have also a significant cost then the manufacture not only would have broken even but also made a profit by using remote condition monitoring instead of manual inspection.

The above does not take into consideration the much improved maintenance scheduling and planning of availability of resources that would be achieved through accurate condition monitoring. Also on top of all this, one needs to consider the insurance regulations which dictate that unless a wind turbine has a condition monitoring system installed main bearings have to be replaced after 40,000 hours of operation (in Germany).

It should be emphasised that a single state-of-the-art vibration system by well known and reputable providers has a cost of about €10,000 per wind turbine. This is only limited for the gearbox and the OPTIMUS consortium is using an integrated condition monitoring system which combines gearbox and power electronics monitoring.

6. Conclusions

The economic benefit that can be achieved through being able to better plan maintenance measures has been demonstrated in a number of practical instances. It is particularly relevant for installations involving offshore wind turbines where access is dependent upon a suitable weather window. Preventing a fault from getting worse and causing further consequential damage is another obvious benefit to having a recognised Condition Monitoring System.

As the trend in the wind industry is for larger and larger wind turbines, the requirement for detailed information on the condition of the equipment will become increasing more important as the cost of the investment increases.

Adaptations in design which reduce component stress have a significant impact on component life. This is particularly so for variable speed drives and the stresses imparted to the drive train. In particular, the gearbox which is one of the main components within the system and it is also one of the main areas of concern for reliability and availability.

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