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Survey of Commercially Available Condition Monitoring Systems for Wind Turbines

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SUPERGEN WIND

Confidentiality

Previous Versions

The first survey completed, named *Survey of Commercially Available Wind Turbine Condition Monitoring Systems*, was initially prepared by P. J. Tavner (Durham University School of Engineering and Computing Sciences) as part of the SUPERGEN Wind Energy Technologies Consortium with help and contributions from W. Yang (Durham University, now Newcastle University), C. Booth (University of Strathclyde) and S. Watson (Loughborough University). It was then subject to constant revision up to April 2009 by W. Yang.

The current document is based on this earlier survey and is written by C. J. Crabtree (Durham University School of Engineering and Computing Sciences) as part of the UK EPSRC SUPERGEN Wind Energy Technologies Consortium, EP/D034566/1. It contains information contributed by the C. J. Crabtree, P. J. Tavner, Y. Feng and M. W. G. Whittle, obtained at European Wind Energy Conferences 2009 and 2010.

The survey of commercially available condition monitoring systems for wind turbines has been further revised by D. Zappalá & P. J. Tavner, as part of the UK EPSRC SUPERGEN Wind Energy Technologies programme, EP/H018662/1, who added information gathered at:

- European Wind Energy Conference 2011 held in Brussels, Belgium, from 14th to 17th of March 2011;
- European Wind Energy Conference 2012 held in Copenhagen, Denmark, from 16th to 19th of April 2012;
- Husum Wind Fair, Husum, Germany, 18th to 22nd September 2012;
- European Wind Energy Conference 2013 held in Vienna, Austria, from 4th to 7th of February 2013;
- European Wind Energy Conference 2014 held in Barcelona, Spain, from 10th to 13th of March 2014.

This document contains 22 (twenty two) pages including the cover page.

Abstract

As wind energy assumes greater importance in remote and offshore locations, effective and reliable condition monitoring techniques are required. Failure rate and downtime studies have also highlighted a need for condition monitoring of particular wind turbine drive train components. This survey discusses the reliability of wind turbines and different monitoring configurations currently in use. The document contains a survey of commercially available condition monitoring systems for wind turbines including information on their monitoring technologies based on available literature and discussion with the companies responsible. Observations are made concerning the nature of systems that are currently available and the apparent direction of future monitoring systems.

Contents

1. Introduction

As wind energy assumes greater importance in remote and offshore locations, affective and reliable condition monitoring (CM) techniques are required. Conventional CM methods used in the power generation industry have been adapted by a number of industrial companies and have been applied to wind turbines (WT) commercially.

This survey discusses commercially available condition monitoring systems (CMS) which are currently being applied in the WT industry. Information has been gathered over several years from conferences and websites and includes information available from product brochures, technical documents and discussion with company representatives. The research was carried out as part of:

- Theme X of the SUPERGEN Wind Energy Technologies Consortium, Phase 1, [1] whose objective was to devise a comprehensive CMS for practical application on WTs;
- Theme 2 of the SUPERGEN Wind Energy Technologies Consortium, Phase 2, [2] whose objective, built on the work in SUPERGEN Wind 1, was to develop turbine monitoring targeted at improving the reliability and availability of offshore wind farms.
- Theme 4.3 of the SUPERGEN Wind Energy Technologies Consortium, Phase 2, [3] whose objective was to develop fault identification methodologies for electrical and mechanical drivetrain systems.

The report also identifies some of the advantages and disadvantages of existing commercial CMSs alongside discussion of access, cost, connectivity and commercial issues surrounding the application of WT CMSs.

2. Reliability of Wind Turbines

Quantitative studies of WT reliability have recently been carried out based on publically available data [4][5]. These studies have shown WT gearboxes to be a mature technology with constant of slightly deteriorating reliability with time. This would suggest that WT gearboxes are not an issue however surveys by WMEP and LWK [6] have shown that gearboxes exhibit the highest downtime per failure among onshore sub-assemblies. This is shown graphically in Figure 1 where we clearly see consistently low gearbox failure rate between two surveys with high downtime per failure. Similar results have also been shown for the Egmond aan Zee wind farm [7] where gearbox failure rate is not high but the downtime and resulting costs are. The poor early reliabilities for gearbox and drive train reliability components has lead to an emphasis in WT CMSs on drive train components and therefore on vibration analysis.

The high downtime for gearboxes derives from complex repair procedures. Offshore WT maintenance can be a particular problem as this involves specialist equipment such as support vessels and cranes but has the additional issue of potentially unfavourable weather and wave conditions. The EU funded project ReliaWind has developed a systematic and consistent process to deal with detailed commercial data collected from operational wind farms. This includes the analysis of 10 minute average SCADA data as discussed above, automated fault logs and operation and maintenance reports. The research aimed to identify and understand WT gearbox failure mechanisms in greater detail [8]. However, more recent information on WT reliability and downtime, especially when considering offshore operation suggests that the target for WT CMSs should be widened from the drive train towards WT electrical and control systems [9].

As a result of low early reliability, particularly in large WTs, interest in CMSs has increased. This is being driven forward by the insurer Germanischer Lloyd who published guidelines for the certification of CMSs [10] and certification of WTs both onshore [11] and offshore [12].

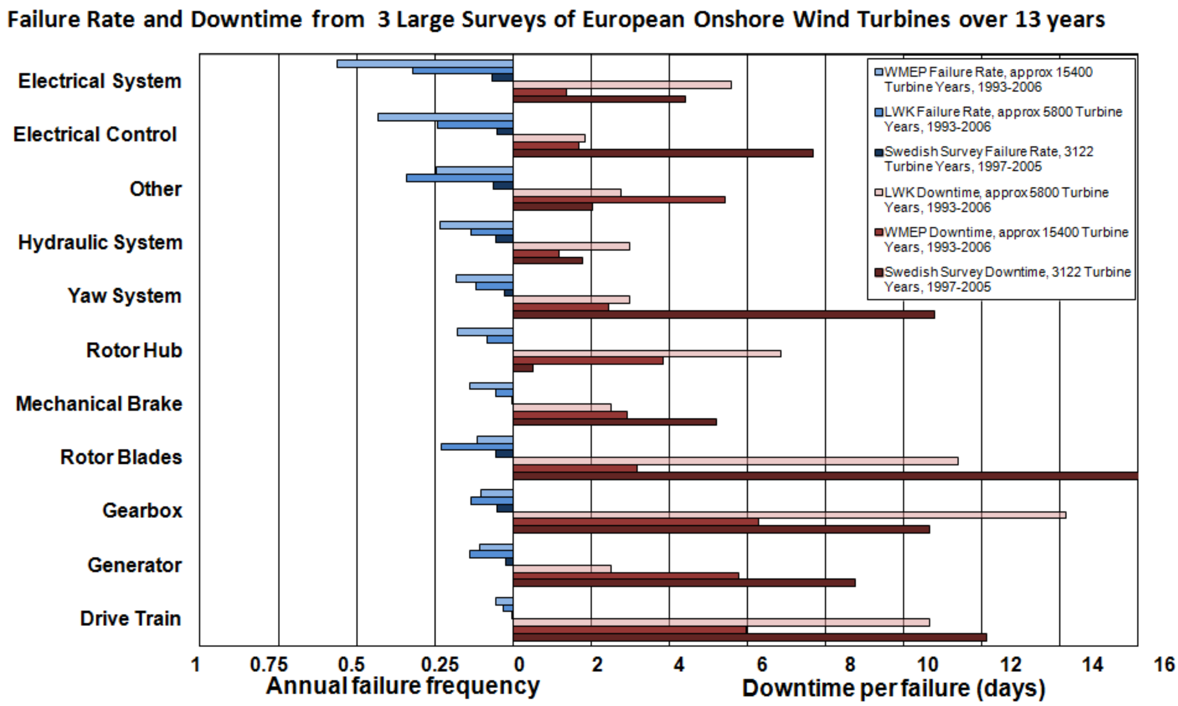

Figure 1: Wind turbine sub-assembly failure rate and downtime per failure from three surveys including over 24000 turbine years of data as published in [13]

3. Monitoring of Wind Turbines

WTs are monitored for a variety of reasons. There are a number of different classes into which monitoring systems could be placed and these are shown in Figure 2, showing the general layout and interaction of the various classes.

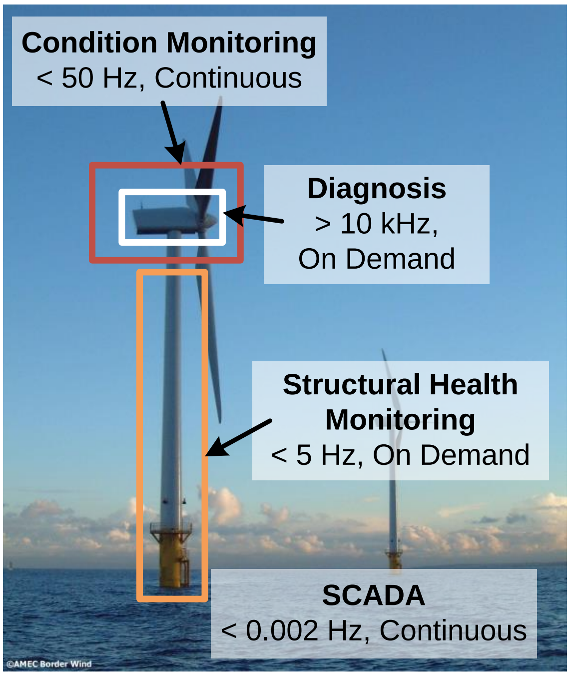

Figure 2: Structural health and condition monitoring of a wind turbine

Firstly, we have Supervisory Control and Data Acquisition (SCADA) systems. Initially these systems provided measurements for a WT's energy production and to confirm that the WT was operational through 5-10 minute averaged values transmitted to a central database. However, SCADA systems can also provide warning of impending malfunctions in the WT drive train. According to Zaher et al. [14] 10 minute averaged signals often monitored in modern SCADA systems include:

- Active power output (and standard deviation over 10 min interval);
- Anemometer-measured win d speed (and standard deviation over 10 min interval);
- Gearbox bearing temperature;
- Gearbox lubrication oil temperature;
- Generator winding temperature;
- Power factor;
- Reactive power;
- Phase currents, and;
- Nacelle temperature (1 hour average).

This SCADA configuration is designed to show the operating condition of a WT but not necessarily give an indication of the health and a WT. However, the much up to date SCADA systems include additional alarm settings based not only on temperature transducers mentioned above but also on vibration transducers. Often we find several transducers fitted to the WT gearbox, generator bearings and the turbine main bearing. The resultant alarms are based on the level of vibration being observed over the 10 minute average period. Research has being carried out into the CM of WTs through SCADA analysis in the EU project ReliaWind [15]. The research consortium consisted of a number of University partners alongside industrial consultants and WT manufacturers.

Secondly, there is the area of structural health monitoring (SHM). These systems aim to determine the integrity of the WT tower and foundations. SHM is generally carried out using low sampling frequencies below 5Hz.

While SCADA and SHM monitoring are key areas for WT monitoring, this survey will concentrate on the remaining two classes of CM and diagnosis systems.

Monitoring of the drive train is often considered to be most effective through the interaction of these two areas. CM itself may be considered as a method for determining whether a WT is operating correctly or whether a fault is present or developing. A WT Operator's main interest is likely to be in obtaining reliable alarms based on CM information which can enable them to take confident action with regard to shutting down for maintenance. The operator need not know the exact nature of the fault but would be alerted to the severity of the issue by the alarm signal. Reliable CM alarms will be essential for any operator with a large number of WTs under its ownership. On this basis, CM signals should not need to be collected on a high frequency basis as this will reduce bandwidth for transmission and space required for storage of data.

Once a fault has been detected through a reliable alarm signal from the CMS, a diagnosis system could be activated either automatically or by a monitoring engineer to determine the exact nature and location of the fault. For diagnosis systems, data recorded at a high sampling frequency is required for analysis however this need only be collected on an intermittent basis. The operational time of the system should be configured to provide enough data for detailed analysis but not to flood the monitoring system or data transmission network with excess information.

Finally, Figure 3 gives an indication of three sections of a WT which may require monitoring based on reliability data such as that in Figure 1 [13]. While each of the three areas are shown as separate entities it is possible that CM of the areas may well blur the boundaries between them in order to provide clear alarms and, subsequently, diagnostic information.

Many of the CMSs included in this survey are a combination of CMSs and diagnostic systems due to the high level of interaction that can exist between the two types of system.

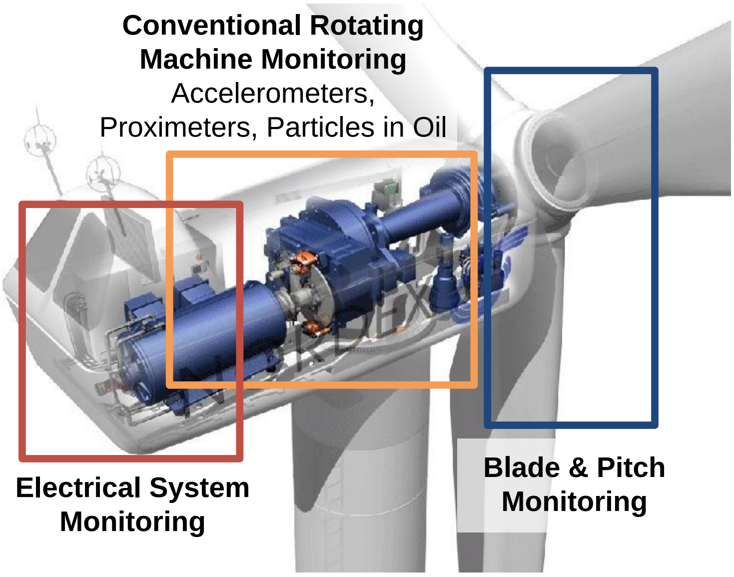

Figure 3: General layout of three areas for condition monitoring and diagnosis within the nacelle

4. Commercially Available Condition Monitoring Systems

Table 1, found on page 14 of this survey, provides a summary of a number of widely available and popular CMSs for WTs. The information in this table has been collected from interaction with CMS manufacturers, WT manufacturers and product brochures over a long period of time and is up to date as of the time of writing. However, since some information has been acquired through discussion with sales and product representatives and not from published brochures, it should be noted that the table may not be fully definitive and is as accurate as possible given the available information. The systems in Table 1 are arranged alphabetically by product name.

The first observation to make from Table 1 is that the CMSs nearly all focus on the same WT subassemblies. Moving through the WT these are:

- Blades
- Main bearing
- Gearbox internals
- Gearbox bearings
- Generator bearings

A quick summery of Table 1 shows that there are:

- 27 systems primarily based on drive train vibration analysis (1 – 27)
- 1 system using Motor Current Signature Analysis, Operational Modal Analysis and Acoustic Emission techniques (28)

- 4 systems solely for oil debris monitoring (29 – 32)
- 1 system using vibration analysis for WT blade monitoring (33).
- 3 systems based on fibre optic strain measurement in WT blades, mast and foundation (34, 35, 36)

It is quite clear when reading through the table that the majority of systems are based around monitoring methods originating from other, traditional rotating machinery industries. Indeed 27 of the 36 systems in the table are based on vibration monitoring using accelerometers typically using a configuration similar to that in Figure 4 for the Mita-Teknik WP4086 CMS (27).

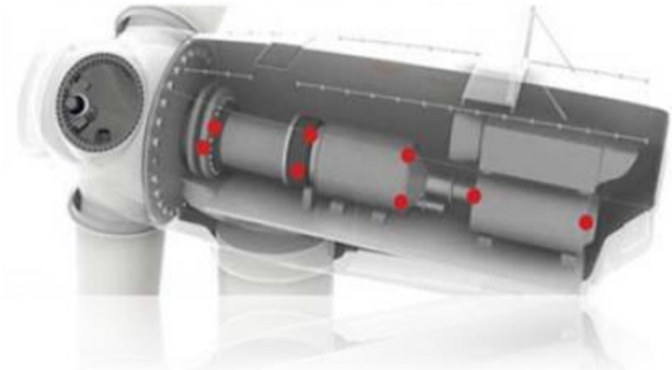

Figure 4: Typical accelerometer positions [16]

Of these 27 CMSs, all have the capability to carry out some form of diagnostic procedure once a fault has been detected. In most cases this is done through fast Fourier transform (FFT) analysis of high frequency data in order to detect fault-specific frequencies. In the case of the SKF WindCon 3.0 (23), the ACOEM OneProd Wind CMS (15) and several others, high data acquisition is triggered by operational parameters. For example, the SKF WindCon 3.0 CMS can be configured to collect a vibration spectrum on either a time basis or when a specific load and speed condition is achieved. The aim of this is to acquire data that is directly comparable between each point and, importantly, to allow spectra to be recorded in apparently stationary conditions. This is an important point to note when using traditional signal processing methods such as the FFT which require stationary signals in order to obtain a clear result. The Mita-Teknik WP4086 system (27), however, states that it includes advanced signal processing techniques such as comb filtering, whitening and Kurtogram analysis which in combination with re-sampling and order alignment approaches, allow the system to overcome the effects of WT speed variations.

An innovative vibration-based CMS is OrtoSense APPA (2) which is based on Auditory Perceptual Pulse Analysis. This patented technology outperforms the human ear by capturing a detailed interference pattern and detecting even the smallest indication of damaged or worn elements within the machine/turbine. OrtoSense states that its product is 4 to 10 time more sensitive compared to prevailing systems.

CMSWind (7) is still in the development phase but it represents an advanced system for WT CM utilising three new and novel techniques, specifically designed for wind turbines and their components. Motor Current Signature Analysis, Operational Modal Analysis and Acoustic Emission techniques will be used to monitor the condition of the generator, the gearbox and rotary components, respectively. All systems will be tied together through SCADA to provide supervisory control, data logging & analysis.

Six of the vibration-based CMSs also state that they are able to monitor the level of debris particles in the WT gearbox lubrication oil system. Further to this, included in the table are four systems which are not in themselves CMSs. These four (29 – 32) are oil quality monitoring systems or transducers rather than full CMSs but are included as discussion with industry has suggested that debris in oil plays a significant role in the damage and failure of gearbox components. Systems using these debris in oil transducers are using either cumulative particle counts or particle count rates.

Several of the 27 vibration-based CMSs also allow for other parameters to be recorded alongside vibration such as load, wind speed, generator speed and temperatures although the capabilities of some systems are unclear given the information available. There is some interest being shown as regards the importance of operational parameters in WT CM. This arises from the fact that many analysis techniques, for example the FFT, have been developed in constant speed, constant load environments. This can lead to difficulties when moving to the variable speed, variable load WT however experienced CM engineers are able to use these techniques and successfully detect faults.

Recent CM solutions, as (1), (7), (11), (13), (19), (24), (27), (28), (30), can be adapted and fully integrated with existing SCADA systems using standard protocols. Thanks to this integration, the analysis of the systems installed on the wind energy plant can also directly consider any other signals or variables of the entire controller network, as for example current performance and operating condition, without requiring a doubling of the sensor system. The database, integrated into a single unified plant operations' view, allows a trend analysis of the condition of the machine.

In some cases the CMS company offers also custom service solutions from 24/7 remote monitoring to on-demand technical support, examples are GE Energy ADAPT.wind (1), Moventas CMaS (10), ABS Wind Turbine In-Service (24) and several others.

Recently patented condition-based turbine health monitoring systems, as (4), (5), (13), (19), feature diagnostic and prognostic software unifying fleet wide CMS and SCADA enabling the identification of both source and cause of the fault and the application of prognostics to establish the remaining operational life of the component.

Three CMSs in the table (34, 35, 36) are based on strain measurement using fibre optic transducers. FS2500 (34) and RMS (35) are aimed at detection of damage to WT blades and, in the case of the Moog Insensys system (35), blade icing, mass unbalance or lightning strikes. SCAIME system (36) allows turbine structural monitoring with sensors mounted on the blades, the mast and the foundations. These three systems may be fitted to WT retrospectively. Compared to vibration monitoring techniques, these systems can be operated at low sampling rates as they are looking to observe changes in time domain. They are usually integrated in the WT control system but there are also some cases of integration, as an external input, into commercial available conventional vibration-based CMSs. In addition to (34) (35) and (36) there is the IGUS system (33) using accelerometers to monitor blade damage, icing and lightning strikes. This system compares the blade accelerometer FFT with stored spectra for similar operating conditions and has the power to automatically shut down or restart a WT based on the results. The system appears to be popular within industry.

5. Comments on Numbers of CMS Installed & Centrally Monitored

5.1. Bruel & Kjaer Vibro

It has been reported that B & K had sold 4000 Vibro systems world-wide, all for wind turbines with 2500 connected to their central monitoring service. It has been reported that Bachmann, a wind turbine controller manufacturer, is now a serious competitor. B & K take signals from CMS transducers and SCADA, as allowed by the WT OEM, which is straightforward with Vestas, where the B & K system is fitted to new turbines.

5.2. Gram & Juhl

It was reported that G & J had 6000 CMS systems installed worldwide but not all in wind turbines and that 2-3000 wind turbine systems are connected to the G & J monitoring centre. G & J take signals from CMS transducers and SCADA, as permitted by the WT OEM, which is straightforward with Siemens, where the G & J system is fitted to new turbines.

The process of automating CMS detection has proved very hard because it depends upon specific drive-train designs and required some learning of machine operation, that generally came from experienced CMS technicians.

5.3. Pruftechnik

Pruftechnik has more than 2000 systems installed in the wind industry with 800 wind turbine systems connected to their monitoring centre. They are not selling directly to wind turbine OEMs, except in rare cases, but did supply their system to gearbox OEMs, for example Winergy. They are also supplying an oil debris counter and handheld and alignment devices.

5.4. SKF Windcon

SKF have thousands of Windcon units fitted to wind turbines world-wide with about 1000 Windcons connected to their Hamburg Wind Centre.

It was reported that CMS is a difficult sell for wind turbines, as some Operators refuse to recognise the value of CMS because it cannot prevent failure without interpretation. Their philosophy is run to failure. However, on large wind farms in the US there is a growing interest as Operators begin to recognise the disadvantage of simple Availability benchmarks for operational performance measurement, where these can only be achieved at high O&M cost. Some Operators, particularly of large wind farms, are recognising the benefit of maintenance planning using integrated SCADA & CMS data.

5.5. Mita-Teknik

Mita-Technik continue to offer their CMS option within their SCADA offering. The value of integration between SCADA and CMS was stressed and only Mita Technik appeared to offer that advantage to Operators.

6. The Future of Wind Turbine Condition Monitoring

As can be seen from this survey of current CMSs there is a clear trend towards vibration monitoring of WTs. This is presumably a result of the wealth of knowledge gained from many years work in other fields. It is likely that this trend will continue however it would be reasonable to assume that other CM and diagnostic techniques will be incorporated into existing systems.

Currently these additions are those such as oil debris monitoring and fibre optic strain measurement. However, it is likely that major innovation will occur in terms of developing signal processing techniques. In particular, the industry is already noting the importance of operational parameters such as load and speed and so techniques may begin to adapt further to the WT environment leading to more reliable CMSs, diagnostics and alarm signals.

Automation of CM and diagnostic systems may also be an important development as WT operators acquire a larger number of turbines and manual inspection of data becomes impractical. Further to this, it is therefore essential that methods for reliable, automatic diagnosis are developed with consideration of multiple signals in order to improve detection and increase operator confidence in alarm signals. It is clear that CMS automation is difficult, because of individual plant peculiarities, but that with larger wind farms it is becoming more attractive for Operators.

However, it should be noted that a major hindrance to the development of CMSs and diagnostic techniques could be data confidentially meaning that few operators are able to divulge or obtain information concerning their own WTs. This is an issue which should be addressed if the art of CM is to progress quickly. Confidentiality has also led to a lack of publicly available cost justification of WT CM, which seems likely to provide overwhelming support for WT CM, particularly in the offshore environment where availability is at a premium.

Table 1: Table of commercially available condition monitoring systems

	Product and Company Information			Product Details (based on available literature and contact with industry including EWEC 2008, 2009, 2010, 2011, 2012, 2013, 2014)				
Ref.	**Product**	**Supplier or Manufacturer (Known Users)**	**Country of Origin**	**Description**	**Main Components Monitored**	**Monitoring Technology**	**Analysis Method(s)**	**Data Rate or Sampling Frequency**
1	ADAPT.wind	GE Energy	USA	Up to 150 static variables monitored and trended per WT. Planetary Cumulative Impulse Detection algorithm to detect debris particles through the gearbox planetary stage. Dynamic Energy Index algorithm to spread the variation over five bands of operation for spectral energy calculations and earlier fault detection. Sideband Energy Ratio algorithm to aid in the detection of gear tooth damage. Alarm, diagnostic, analytic and reporting capabilities facilitate maintenance with actionable recommendations. Possible integration with SCADA system.	Main bearing, gearbox, generator	Vibration (Accelerometer) Oil debris particle counter	FFT frequency domain analysis Time domain analysis	-
2	APPA System	OrtoSense	Denmark	Oscillation technology based on interference analysis that replicates the human ear's ability to perceive sound.	Main bearing, gearbox, generator	Vibration	Auditory Perceptual Pulse Analysis (APPA)	-
3	Ascent	Commtest	New Zealand	System available in 3 complexity levels. Level 3 includes frequency band alarms, machine template creation, statistical alarming.	Main shaft, gearbox, generator	Vibration (Accelerometer)	FFT frequency domain analysis Envelope analysis Time domain analysis	-
4	Brüel & Kjaer Vibro	Brüel & Kjaer (Vestas)	Denmark	Local data acquisition units, alarm management and review by the Condition Monitoring Centre analysts, reports on actionable information to customers. Vibration and process data automatically monitored at fixed intervals and remotely sent to the diagnostic server. Monitoring to specific power loadings and filtering out irrelevant alarms. Time waveform automatically stored before and after user-defined event for advanced vibration post-analysis. Severity classes, each related to an estimated lead-time. Severity is first estimated automatically by the Alarm Manager, followed by the diagnostic expert final assessment.	Main bearing, coupling, gearbox, generator, nacelle, support structure. Nacelle temperature. Noise in the nacelle	Vibration Temperature sensor Acoustic	Time domain FFT frequency analysis	Variable up to 40kHz. 25.6kHz.
5	Brüel & Kjaer VibroSuite	Brüel & Kjaer (Vestas)	Denmark	Stand-alone software packages, completely client-owned, enable end-users and operators to host, process and analyse the data in-house. AlarmManager processes and simplifies data, provides developing faults automated evaluation, severity level and lead-time to failure; AlamTracker for quick access to live alarms with alarm history and high-end functionality; WTG.Analyser diagnostic tool interprets signals and identifies root causes; EventMaster facilitates time and event based diagnostic data acquisition.	Main bearing, coupling, gearbox, generator, nacelle, support structure. Nacelle temperature. Noise in the nacelle	Vibration Temperature sensor Acoustic	Time domain FFT frequency analysis	Variable up to 40kHz. 25.6kHz.

6	CMS	Nordex	Germany	Start-up period acquires vibration 'fingerprint' components. Actual values automatically compared by frequency, envelope and order analysis, with the reference values stored in the system. Some Nordex turbines also use the Moog Insensys fibre optic measurement system.	Main bearing, gearbox, generator	Vibration (Accelerometer)	Time domain based on initial 'fingerprint'	-
7	Condition Based Maintenance System (CBM)	GE (Bently Nevada)	USA	This is built upon the Bently Nevada ADAPT.wind technology and System 1. Basis on System 1 gives monitoring and diagnostics of drive train parameters such as vibration and temperature. Correlate machine information with operational information such as machine speed, electrical load, and wind speed. Alarms are sent via the SCADA network.	Main bearing, gearbox, generator, nacelle Optional bearing and oil temperature	Vibration (Accelerometer)	FFT frequency domain analysis Acceleration enveloping	-
8	Condition Based Monitoring System	Bachmann electronic GmbH	Austria	Up to 9 piezoelectric acceleration sensors per module. Basic vibration analysis with 7 sensors. PRÜFTECHNIK solid borne sound sensors for low frequency diagnostics of slowly rotating bearings on the WT LSS. Three channels for the ±10V standard signal per module. Audibile sensor signals to assess the spectra acoustically. Fully integration in automation control system to link the measured values to operating parameters and increase diagnostic reliability. Traffic light system indicates if predefined thresholds are exceeded. Data analyzed by experienced diagnostics specialists using extensive tools, such as envelope and amplitude spectra, or frequency-based characteristic values. Integrated database enables data trend analysis.	Main drive train components Generator	Vibration (Accelerometer) Acoustic	Time domain FFT frequency analysis	24-bit res 190 kHz sample rate per channel 0.33 Hz (solid borne sound sensors)
9	Condition Diagnostics System	Winergy	Denmark	Up to 6 inputs per module. Advanced signal processing of vibration levels, load and oil to give automated machinery health diagnostics, forecasts and recommendations for corrective action. Automatic fault identification is provided. Relevant information provided in an automated format to the Operations and Maintenance centre, without any experts being involved. Information delivered to the appropriate parties in real time. Pitch, controller, yaw and inverter monitoring can also be included.	Main shaft, gearbox, generator	Vibration (Accelerometer) Oil debris particle counter	Time domain FFT frequency domain analysis	96kHz per channel
10	Condition Management System (CMaS)	Moventas	Finland	Compact remote system measuring temperature, vibration, load, pressure, speed, oil aging and oil particle count. 16 analogue channels can be extended with adapter. Performance monitoring, anticipate possible upcoming failures by providing timely updates and alerting maintenance crews. Data stored, analysed and reported to remote server via standard TCP/IP protocol. Mobile interface available. Moventas Remote Centre provides proactive gear expertise with specialists available for all customers on-call 24 hours a day, seven days a week.	Gearbox, main bearing, generator, rotor, turbine controller	Temperature Vibration Load Pressure RPM Oil condition/particles	Time domain (Possible FFT)	-

11	Distributed Condition Monitoring System	National Instruments	USA	Up to 32 channels; default configuration: 16 accelerometer/microphone, four proximity probe and eight tachometer input channels. Also provided mixed-measurement capability for strain, temperature, acoustics, voltage, current and electrical power. Oil particulate counts and fiber-optic sensing can also be added to the system. Possible integration into SCADA systems.	Main bearing, gearbox, generator	Vibration Acoustic	Spectral analysis Level measurements Order analysis Waterfall plots Order tracking Shaft centre-line measurements Bode plots	24-bit res 23.04 kHz of bandwidth with antialiasing filters per accelerometer/ microphone channel
12	HAICMON	Hainzl	Austria	The Monitoring Unit (CMU), mounted in the nacelle, performs the data acquisition, analysis and local intermediate storage. Up to 32 vibration inputs, 8 digital and optional 16 analog inputs. Web interface for configuration and visualization purpose. Automatic data analysis directly on the CMU with automatic alarming features. CMU can operate in standalone mode or in connection with the superior HAICMON ANALYSIS CENTER which features more computing power or database access functionality for advanced trend analysis. It also allows comparing different plants among each other and provides a reporting module.	Rotor bearing, gearbox, generator	Vibration Load Rotation speed Oil temperature	Time domain FFT frequency analysis Envelope analysis Cepstrum analysis	Variable up to 40kHz.
13	InSight intelligent Diagnostic System (iDS)	Romax Technology Ltd	UK	Diagnostic and prognostic software unifying fleet wide CMS and SCADA data. Suite of predictive maintenance technologies and services comprising: Inspection and Analysis; iDS that integrates vibration, SCADA and maintenance record data. This hardware independent software platform harmonises data from multiple manufacturers CMSs. Intuitive user interface and advanced diagnostic rules. iDS Manger provides managers with a clear dashboard displaying wind turbines' condition and notifying of alarm events via email. InSight Expert is a diagnostic platform aimed at vibration analysis experts which enables the identification of both fault source and cause and the application of prognostics.	Main drive train components	Vibration Temperature Oil debris particle counter	Time domain FFT frequency analysis	-
14	OMNITREND	Prüftechnik	Germany	WebReport creates customizable reports for analysing machine conditions, color-coded alarm classes in the status report identify machine problems at a glance; Online View, visualizes measurement data from online systems and machine conditions in real time; network capable multiuser PC software OMNITREND saves measurement data in a database, arranges routes for data collection and visualizes the results in easy-to-read diagrams. Practical tools support data evaluation and documentation. Data exchange between OMNITREND and a Computerized Maintenance Management System allows exchanging measurement data, sending status messages and using master data from ERP systems.	Main drive train components	Vibration	FFT frequency domain analysis	-

15	OneProd Wind System	ACOEM (01dB-Metravib)	France	8 to 32 channels; operating conditions trigger data acquisitions. Repetitive and abnormal shock warnings enable detection of failure modes; built-in diagnostic tool. Optional additional sensors for shaft displacement and permanent oil quality monitoring; structure low frequency sensors; current&voltage sensors. Graphics module for vibration analysis including many representation modes as trend, simple or concatenated spectrum, waterfall spectrum, time signal, circular view, and orbit; advanced cursors and post-processing are available. SUPERVISION web application provides information on alarm status together with expert diagnoses and recommendations.	Main bearing on LSS, Bearing on gearbox LSS, Bearing on intermediate gearbox shaft, on gearbox high-speed shaft, on generator Oil debris, structure, shaft displacement, electrical signals	Vibration Acoustic Electrical signals Thermography Oil debris particle counter	Time domain FFT frequency analysis Electrical signature analysis	-
16	SIPLUS CMS4000	Siemens	Germany	Acquisition and evaluation of analog and binary signals in individual wind turbines or complex wind farms. Data acquisitions and pre-processing performed with interface nodes that enable the recording of highly dynamic processes. Software X tools for analysis, diagnostics, visualisation and archiving for wind power plants. Data displayed via traffic lights, integrated message systems and spectrum-view in CMS X-Tools. Library of standard function blocks for FFT, envelope curve analysis, input filters, mathematical and communication functions and graphical creation of diagnostic models. Analysis blocks can be interconnected graphically to resolve specific measuring and diagnostic tasks. Modular, scalable system can be integrated into existing wind turbines and new ones.	Bearings , gearbox, tower	Vibration	FFT frequency domain analysis Envelope curve analysis Fingerprint comparison Trend Analysis Input filters	Exceeding 40kHz
17	SMP-8C	Gamesa Eolica	Spain	Continuous on-line vibration measurement of main shaft, gearbox and generator. Comparison of spectra trends. Warnings and alarm transmission connected to Wind Farm Management System.	Main shaft, gearbox, generator	Vibration	FFT frequency domain	-
18	System 1	Bently Nevada (GE)	USA	Monitoring and diagnostics of drive train parameters such as vibration and temperature. Correlate machine information with operational information such as machine speed, electrical load, and wind speed.	Main bearing, gearbox, generator, nacelle Optional bearing and oil temperature	Vibration (Accelerometer)	FFT frequency domain Acceleration enveloping	-

19	TCM (Turbine Condition Monitoring) Enterprise V6 Solution with SCADA integration	Gram & Juhl A/S	Denmark	Advanced signal analysis and process signals combined with automation rules and algorithms for generating references and alarms. M-System hardware features up to 24 synchronous channels, interface for Structural Vibration Monitoring and RPM sensors, extern process parameters and analog outputs. TCM Site Server stores data and does post data processing (data mining) and alarm handling. TCM Ocular Modeller models drive train and sensor configuration to relate measurement data to the kinematics of the turbine. Control room with web based operator interface. TCM Enterprise allows centralised remote monitoring on a global scale. Optional Structural Vibration Monitoring sensor to measure low frequency signals associated with tower sway, rotor imbalance and machine over speed. Integration with SCADA through OPC UA.	Tower, blades, shaft, nacelle Main bearing, gearbox, generator	Vibration (Accelerometer) Sound analysis Strain analysis Process signals analysis	FFT and Wavelet frequency domain analysis Envelope, time and frequency domain [analytic/Hilbert] analysis Cepstrum, Kurtosis, Spectral kurtosis, Skewness RMS analysis Order tracking analysis	40.960/81.920 kHz
20	TurbinePhD (Predictive Health Monitoring)	NRG Systems	USA	Automatically integrates multiple condition indicators into a single readily understandable health indicator for each turbine's drive train component delivering future health predictions. Actionable indicators and data supporting the diagnosis accessible via Internet. Optimise turbine maintenance schedules by predicting when components in the turbine's drive train are likely to fail and scheduling repairs at the most cost-effective time. Advanced diagnostic algorithms from the aerospace industry accounting for varying speed and torque conditions. Residual, energy operator, narrow band and modulation analysis tools for gear analysis; spectrum and envelope for bearing analysis; synchronous average for shaft analysis.	Main shaft, gearbox, main bearing	Vibration (Accelerometer)	FFT frequency domain analysis	0.78 to 100 Hz @24 bits (High Speed Vibration Sensor) 8 to 500 Hz (Low Speed Vibration Sensor)
21	VIBstudio WIND	EC Systems KAStrion project	Poland	Integrated embedded system for data acquisition; real-time verification through algorithms for automatic signal validation, to avoid generating false alarms, and advanced signal processing. Up to 24 vibration channels, 4 analog channels, 2 digital inputs and 3 digital outputs. Automated generation of analyses and thresholds; individually tuned, automated configuration of machine operational state; intelligent data selection and storage; tolerance for loss of connectivity. VIBmonitor Astrion module for automatic vibration analysis. VIBmonitor SMESA module for generator fault detection by electrical signature analysis.	Bearings, shaft, gearbox, generator	Vibration (Accelerometer)	Wideband analyses: PP, RMS, VRMS, Crest, Kurtosis Narrowband analyses: energy in the band, order spectrum and envelope spectrum	Vibration channels: Variable up to 100 kHz Process variable channels: up to 1 kHz
22	Wind AnalytiX	ICONICS	USA	This software solution uses Fault Detection and Diagnostics technology which identifies equipment and energy inefficiencies and provides possible causes that help in predicting plant operations, resulting in reduced downtime and costs related to diagnostic and repair.	Main WT components	Vibration (Accelerometer)	Unknown	-

23	WindCon 3.0	SKF	Sweden	Monitoring solution including sensors, data export, analysis and lubrication. Turbine health monitoring through vibration sensors and access to the turbine control system by means of the SKF WindCon software. WindCon 3.0 collects, analyses and compiles operating data that can be configured to suit management, operators or maintenance engineers. The system can be stand alone or linked together using SKF's WebCon, the web solution for data hosting and remote monitoring. WindCon can also be linked to the turbine lubrication system and fully integrated with the WindLub system for automated condition based lubrication and monitoirng of the lubrication pump.	Blade, main bearings, shaft, gearbox, generator, tower, generator electrical	Vibration (Accelerometer, proximity probe) Oil debris particle counter	FFT frequency domain analysis Envelope analysis Time domain analysis	Analogue: DC to 40kHz (Variable, chan dependent) Digital: 0.1 Hz - 20kHz
24	Wind Turbine In-Service	ABS Consulting	USA	Data gathered from inspections, vibration sensors and SCADA system. Ekho for WIND software features regular diagnostics, dynamic performance reports, key performance indicators, fleet-wide analysis, forecasts/schedules, and asset benchmarking. It generates alarms and notifications or triggers work orders for inspections or repairs.	Main bearing, gearbox, generator Gearbox and gear oil, rotor blades and coatings	Vibration Inspections	FFT frequency domain analysis Time domain analysis	-
25	WinTControl	Flender Service GmbH	Germany	Vibration measurements are taken when load and speed triggers are realised. Time and frequency domain analysis are possible.	Main bearing, gearbox, generator.	Vibration (Accelerometer)	FFT frequency domain Time domain analysis	32.5kHz
26	WiPro	FAG Industrial Services GmbH	Germany	Measurement of vibration and other parameters given appropriate sensors. Time and frequency domain analysis carried out during alarm situations. Allows speed-dependent frequency band tracking and speed-variable alarm level.	Main bearing, shaft, gearbox, generator, temperature. (Adaptable inputs)	Vibration (Accelerometer)	FFT frequency domain Time domain analysis	Variable up to 50kHz
27	WP4086	Mita-Teknik	Denmark	Up to 8 accelerometers for real-time frequency and time domain analysis. Warnings/Alarms set for both time and frequency domains based on predefined statistical/thresholds-based vibration limits. Operational parameters recorded alongside with vibration signals/spectra and full integration into Gateway SCADA system. Algorithm Toolbox for diagnostic analysis. Approx 5000 – 8000 variables covering different production classes.	Main bearing, gearbox, generator	Vibration (Accelerometer)	FFT amplitude spectra FFT envelope spectra Time domain magnitude Comb filtering, whitening, Kurtogram analysis	12-bit chan res Variable up to 10kHz
28	CMSWind (still in development phase)	CMSWind project	European Research & Development Project	Advanced condition monitoring system which utilises Motor Current Signature Analysis, Operational Modal Analysis and Acoustic Emission techniques to monitor the condition of the generator, the gearbox and rotary components, respectively. All systems are tied together through SCADA to provide supervisory control, data logging & analysis. Wireless sensors for rotating components monitoring using high performance powering and energy harvesting technologies.	Gearbox (including Main bearing, Yaw System, Hub), generator	Electrical signals operational paramters, acoustic	Motor Current Signature Analysis Operational Modal Analysis Acoustic Emission techniques	-

29	HYDACLab	HYDAC Filtertechnik GmbH	Germany	Permanent monitoring system to monitor particles (including air bubbles) in hydraulic and lube oil systems.	Lubrication oil & cooling fluid quality	Oil debris particle counter	N/A	-
30	Oil Contamination Monitor (OCM 30X)	C.C. Jensen	Denmark	Early warning for gearbox breakdown by measuring wear generation. Especially designed for high viscous oils, such as gear oils, and equipped with an air removal device to enable correct measurements. Very stable flow over a large viscosity range allows sensor accurate readings. Different options for communication with the SCADA system and wen based trends.	Lubrication oil quality and cleankiness	Oil debris particle counter Oil cleanliness sensor	N/A	-
31	PCM200	Pall Industrial Manufacturing (Pall Europe Ltd)	USA (UK)	Fluid cleanliness monitor reports test data in real-time so ongoing assessments can be made. Can be permanently installed or portable.	Lubrication oil cleanliness	Oil cleanliness sensor	N/A	-
32	TechAlert 10 TechAlert 20	MACOM	UK	TechAlert 10 is an inductive sensor to count and size ferrous and non-ferrous debris in circulating oil systems. TechAlert 20 is a magnetic sensor to count ferrous particles.	Lubrication oil quality	Inductive or magnetic oil debris particle counter	N/A	-
33	BLADEcontrol	IGUS ITS GmbH	Germany	Accelerometers are bonded directly to the blades and a hub measurement unit transfers data wirelessly to the nacelle. Blades are assesed by comparing spectra with those stored for common conditions. Measurement and analysis data are stored centrally and blade condition displayed using a web browser.	Blades	Accelerometer	FFT frequency domain	≈ 1kHz
34	FS2500	FiberSensing	Portugal	BraggSCOPE measurement unit designed for industrial environments to interrogate up to 4 Fiber Bragg Grating sensors. Acceleration, tilt, displacement, strain, temperature and pressure measurable.	Blades	Fibre optic	Unknown	Up to 2kHz
35	RMS (Rotor Monitoring System)	Moog Insensys Ltd.	UK	Modular blade sensing system consisting of 18 sensors, 6 per blade, installed in the cylindrical root section of each blade to provide edgewise and flapwise bending moment data. Can be designed-in during turbine manufacture or retrofitted. Monitors turbine rotor performance, mass and aerodynamic imbalance, blade bending moments, icing, damage and lightning strikes. Possible integration, as an external input, in commercial available CMSs.	Blades	Fibre optic strain	Time domain strain analysis	25 Hz/sensor
36	SCAIME Condition Monitoring Solutions	SCAIME	France	Fibre optic systems for structural monitoring. Sensors, made of glass fibre reinforced plastic or aluminium alloys, measure the stresses on the blades, the mast and the foundations. MDX400 data acquisition unit with an integrated web server for remote system and sensor setup. Emergency alarms generated when loads become too high and blade loads data used for pitch controller input. Data processing provides remaining life estimation, defect and ice detection. In the mast, sensors measure bending moments at different heights to monitor tower deformations and oscillations. Sensors monitor foundation aging due to load accumulation, soil pressure, grouting.	Blades Mast Foundation	Strain and temperature sensors Long base extensometers Displacement sensors Tilt-meters Accelerometers	Time domain analysis	100 Hz

7. Conclusions

From this survey we can conclude that:

- Current WT reliability is reasonable however in the offshore environment the failure rate will be unacceptable;
- Cost effective and reliable CM is required to enable planned maintenance, reduce unplanned WT downtime and improve capacity factors;
- Successful CMSs must be able to adapt to the non-stationary, variable speed nature of WTs;
- There is a wide variety of commercially available CMSs currently in use on operational WTs;
- Monitoring technology is currently based on techniques from other, conventional rotating machine industries;
- Vibration monitoring is currently favoured in commercially available systems using standard time and frequency domain techniques for analysis;
- These traditional techniques can be applied to detect WT faults but require experienced CM engineers for successful data analysis and diagnosis;
- Some commercially available CMSs are beginning to adapt to the WT environment and to be fully integrated into existing SCADA systems, and;
- Recently patented condition-based turbine health monitoring systems feature diagnostic and prognostic software enabling the identification of both source and cause of the fault and the application of prognostics to establish the remaining operational life of the component.
- A diverse range of new or developing technologies are moving into the WT CM market.

Finally, it should be noted that there is not currently a consensus in the WT industry as to the correct route forward for CM of WTs. Work in this document and its references suggest that CM of WTs will be beneficial for large onshore WTs but essential for all offshore development and should be considered carefully by the industry as a whole.

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