Wind Turbine Condition Monitoring: Technical & Commercial Challenges

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Abstract Deployment of larger scale wind turbine systems, particularly offshore, requires more organized operation and maintenance strategies to ensure systems are safe, profitable and cost-effective. Among existing maintenance strategies, reliability centred maintenance (RCM) is regarded as best for offshore wind turbines, delivering corrective and proactive (i.e. preventive and predictive) maintenance techniques enabling wind turbines to achieve high availability and low cost of energy. RCM analysis may demonstrate that an accurate and reliable condition monitoring system is one method to increase availability and decrease the cost of energy of wind turbines. In recent years, efforts have been made to develop efficient and cost-effective condition monitoring techniques for wind turbines. A number of commercial wind turbine monitoring systems are available in the market, most based on existing techniques from other rotating machine industries. Other wind turbine condition monitoring reviews have been published but have not addressed the technical and commercial challenges, in particular reliability and value for money. The purpose of this paper is to fill this gap and present the wind industry with a detailed analysis of the current practical challenges with existing wind turbine condition monitoring technology.

Key words wind turbine condition monitoring
reliability analysis reliability centred maintenance

1 Background

Despite the current economic recession, the wind industry is still growing worldwide. According to a survey by the Global Wind Energy Council (GWEC), the total global installed wind capacity has reached 194 GW by the end of 2010 versus the total installed capacity of 159 GW by the end of 2009 [1]. That means that more than 100,000 large wind turbines (WTs) of different sizes, makes and ages are operating in the world today. They are located in different world regions and operate in a wide variety of environments. To keep these machines running safely, continuously and profitably is challenging. Moreover, their operation and maintenance (O&M) tends to be sophisticated as they are remote, robotic power sources with the following wind-dependent issues:

- **Sites**

  WTs are being increasingly deployed in remote sites with larger wind resources. In particular, offshore wind power is attracting interest in populous countries with significant seaboards, such as Denmark, UK, Germany, Netherlands and China, because of the resource available, the avoidance of land-use issues and close proximity to large consumer load.

- **Diversity**

  WTs of various concepts are being built based upon experience, see Fig.1. Nowadays, geared-drive WTs dominate the market, whilst direct-drive WTs are fashionable and gaining an increasing market share, although their contribution to WT reliability and economy has not yet been demonstrated[2]. In addition, interest in hybrid or so-called semi-direct-drive WTs is growing. The GW3000kW developed by Goldwind[3] is an example of this concept. Other companies, such as DeWind & Voith [4] and Bosch Rexroth [5], are developing hydraulic drives with WT manufacturer partners to secure higher reliability machines. These novel designs aim to improve WT reliability, however their practical benefit needs further verification.

- **Size**

  Fig.1 shows that to lower manufacturing and installation capital cost/MW, WTs are becoming larger. For example:

  - Repower M104, 3.4MW;
  - GE 4.0-110, 4.0MW;

- Gamesa G-128, 4.5MW;
- XEMC Darwind DD115, 5MW;
- Enercon E-126, 7MW;
- AMSC superconductor WT, 10MW in development[6];
- Wind Power Ltd Aerogenerator X,10MW in development[7].

Other companies and organizations are following this by developing enhanced WT testing services for larger machines, for example the National Renewable Energy Centre (Narec) in UK[8], National Renewable Energy Laboratory (NREL) in US, CENER in Spain, and Risø in Denmark.

- **Control**

Modern WTs are using more intelligent control. For example, initial WTs were passive stall-regulated load control, fixed-speed machines working in a narrow wind speed range. Subsequently, they evolved to active pitch-regulated, variable-speed machines. The application of collective blade pitch control has allowed modern WTs to be larger in size and work over wider wind speed ranges. The newly developed individual blade pitch control is enabling modern WTs to deliver higher power with lower blade and tower loads[9, 10]. Today, more advanced blade control technology, the Intelligent Blade[11], is being researched to allow the blade to measure wind speed and adapt automatically to wind conditions. It is believed that with the aid of the Intelligent Blade, the efficiency and reliability of new generation of WTs will be further enhanced. However, it is already recognized that the increase use of intelligent control loops in the rotor and generator systems also creates reliability and power quality challenges for the WT.

- **Cost**

Increasing WT size and consequent lowering cost/MW will lower wind power Cost of Energy (COE) although this is countered offshore by increases in installation and connection costs. For example, UK onshore wind farm (WF) capital costs have dropped significantly in the last two decades. The first British commercial WF began operation in 1991 with capital costs around £1.00M/MW and these have reduced by 2009 to around £0.70M/MW. According to the UK Energy Research Centre (UKERC)[12], data from early offshore WFs supports this trend, even though the offshore industry is still in its infancy, see the following offshore WFs for example:

- Vindeby, Denmark, 1991 cost €2.60M/MW (about £2.26M/MW);

- Horns Rev I, Denmark, 2002 cost €1.67M/MW (about £1.45M/MW);
- North Hoyle, UK, 2003 cost £1.35M/MW;
- Scroby Sands, UK, 2003 cost £1.26M/MW.

However, offshore costs have escalated in the last 5 years, with capital costs doubling from £1.5-3.0M/MW in 2009[13].This is because offshore sites have moved from near-shore to further offshore and deeper waters.

All these issues affect the WF O&M and therefore the industry's condition monitoring (CM) approach. To meet this need, efforts have been made to understand the true value of WT Condition Monitoring System (WTCMS) in recent literature [14,15,16,17,18]. However, these references need further work to relate WTCMS to RCM and address WTCMS' own reliability and value for money. That is the subject of this paper, arranged as follows:

In Section 2, the new requirements for monitoring newly developing WT designs are discussed;

In Section 3, available non-destructive techniques are briefly reviewed to identify the techniques most suitable to WT CM;

In Section 4, the WTCMSs currently available in commercial market are reviewed in a survey to identify the experiences and lessons of using these systems;

In Section 5, the survey is reviewed to show the most popular CM signal processing techniques and approaches used by commercial WTCMSs[19];

In Section 6, based on these reviews, the future work needed to develop a reliable and cost-effective WTCMS is discussed;

In Section 7, conclusions.

2 New Requirements for a Modern WTCMS

To fit the development of wind power WT CM technologies need further improvement against the issues raised in Section 1 as follows.

- **Site**

  Moving WFs to remote onshore sites or offshore brings WT O&M challenges because they may not be accessible for parts of the year. This means that WT maintenance activities must be carried out during accessible seasons and this requires prediction and planning. Components which have partially lost functionality or are likely to fail during unfavourable seasons need to be repaired or replaced in advance to avoid down-time. However, in practice it is currently difficult to decide whether a defective component should be replaced immediately or not. Harsh offshore working environments make such decisions less predictable. However, a wrong decision could result in a significant economic loss. WTCMS should therefore be a tool to enhance decision reliability by detecting faults correctly, assessing severity and predicting development accurately, particularly under the WT's constantly varying load.

- **Diversity**

  Different WT concepts have different hardware configurations requiring different CM techniques. In view of the high cost and long down-time of gearbox failures current commercial WTCMSs are mostly vibration-based, good at detecting gear and bearing faults. However, it is questionable whether these systems can be equally applied to direct, hybrid or hydraulic-drive WTs. Recent surveys have shown that WT electrical and converter units experience significant numbers of failures [2] and these cannot be monitored by vibration-based systems. Therefore new generations of WTCMS should be universal, applicable to WTs of various technologies and capable of dealing with both mechanical and electrical signals.

- **Size**

  Although in theory the reliability of a WT should be independent of its size, a survey of more than 6,000 onshore WT years for turbines ranging in size from 300-1800 kW in Denmark and Germany over 11 years[2], has shown that larger WTs experience more faults than smaller ones. Rapid growth in design size, the increased use of variable speed and more sophisticated controls and a lack of operational experience with larger WTs could account for this result. Considering that larger WTs have greater economic benefits and therefore incur greater breakdown economic losses, future WTCMS should be more alert to the incipient defects of these larger WTs and able to aid the control system to prevent secondary damage, in particular protecting the WT from the consequent damage of extreme loads.

- **Control**

  As described, modern WTs use sophisticated control systems for the pitch, generator and converter. However, long-term experience has shown that currently electrical and electronic components are proving less reliable than mechanical components[20,21].

Moreover, the down-time and economic losses of these failures are more significant offshore or in remote locations, due to reduced accessibility. However, current WTCMSs are not effective for detecting electrical and electronic failures, although preliminary research is trying to improve this situation[22]. Future WTCMS should monitor the whole WT, including electrical and electronic components, rather than concentrating solely on the mechanical components. In particular for offshore, down-time will be dominated by time waiting for favourable access conditions rather than by component repair or replacement times.

- **Cost**

  The development of smart grids and the need to reduce wind power COE is encouraging the development of huge WFs. For example, almost all planned UK offshore Round 3 wind projects are larger than 1 GW[12]. That means that hundreds of WTs need to work simultaneously in the same farm. Today, WTCMS unit prices vary but are generally > £5k/unit therefore a few millions pounds would be needed to purchase these systems for a WF if each turbine is equipped. Once a WTCMS fails, not only the individual WT is left unprotected but a significant capital asset will be ineffective. So, future WTCMSs must not only be cost-effective but also reliable, even more so when working offshore.

3 Techniques Applicable to WT CM

A number of non-destructive testing techniques are applicable to a WTCMS. They are either laboratory tested or have already been used in practice, their mechanisms have been introduced in [16,17,23,24,25] and their features are reviewed in Table 1 where the costs are classified as follows:

Low:	< £2,000;
Medium:	£2,000-5,000;
High:	£5,000-10,000;
Very High:	>£10,000

However, costs vary depending on measurement accuracy, resolution, functionality and applicable environment.

From Table 1, it can be seen that:

- Vibration analysis and oil particle counters, being low cost and well-proven, are feasible monitoring techniques. Moreover, their combined use could be a key to WT drive train monitoring. Currently vibration analysis is more widely used for tracing the growth of WT gearbox and bearing faults than oil particle counters;
- Oil quality analysis is valuable for gearbox gear and bearing monitoring in particular fault diagnosis through analysing the composition and shapes of lubrication oil metal particles. In the meantime, it is also an effective approach to monitoring the aging and contamination of the lubrication oil itself. However, it is costly online so it is likely to be used in future off-line;
- Shaft torque and torsional vibration measurement have been investigated but torque transducer installation will be costly and may be limited by the compact structures of new generation WTs;
- Ultrasonic testing is a potentially effective tool for detecting the early WT blade or tower defects, although its application requires methods for scanning the individual components;
- Thermocouples are cheap and reliable. They are extensively used for monitoring the nacelle, gearbox and generator bearings, lubrication and hydraulic oil, and power electronic temperatures. By contrast, thermography is rarely used because of the high cost of the thermographic camera and difficulties in practical application in operating WTs, although its potential application in WTCMS has been investigated[24];
- Fibre-optic strain measurements are proving a valuable technique for measuring blade-root bending moments as an input to advanced pitch controllers and can be used to monitor WT blades. They have been demonstrated in operation and improvements in costs and reliability are expected. By contrast, mechanical strain gauges are used only in lab tests as they are prone to failure under impact and fatigue loads;
- Acoustic emissions could be helpful for detecting drive train, blade or tower defects during type tests but is wide bandwidth and costly, both to measure and analyse. Vibro-acoustic techniques have had success for example in the aerospace industry, but their costs would be prohibitive for the wind industry and the WT nacelle is not ideal for collecting microphone data;
- Electric signals have been widely used for CM of rotating electric machine [26,27] but have not been used in WTCMS because of lack of WT industry experience;

- Shock pulse method (SPM) could be an alternative online approach to detecting WT bearing faults, although further experience is still needed in wind industry.

4 Commercial WTCMS and Its Issues

Two types of WTCMSs are currently available in the commercial wind market. The first is based on the Supervisory Control and Data Acquisition (SCADA) systems, already installed on large WTs. The second is purpose-designed CMS specifically for WTs. Both systems have been recently surveyed [19, 28]. Their features and issues are discussed as follows.

4.1 WT SCADA

Fig.2 shows how WTs and associated equipment in a WF are connected via a SCADA system, which is initially designed for operating WTs, ensuring they are conforming to their power curve and running safely and efficiently.

A SCADA system monitors signals and alarms, usually at 10 min intervals to reduce the transmitted data bandwidth from the WF, and will include the following parameters [29]:

- Active power output, and standard deviation;
- Reactive power;
- Power factor;
- Generator currents and voltages;
- Anemometer measured wind speed, and standard deviation;
- Turbine and generator shaft speeds;
- Gearbox bearing temperatures (for geared-drive turbines);
- Gearbox lubrication oil temperature (for geared-drive turbines);
- Generator winding temperatures;
- Generator bearing temperatures;
- Average nacelle temperature.

Alarm status will also be monitored by the SCADA system for operational purposes. Potentially, these alarms can help a turbine operator to understand the WT and key components status but in a large WF these alarms are currently too frequent for rational analysis. Their added values could be explored in more detail. To date, some SCADA-based WT performance monitoring systems have been developed as listed in Appendix 1[28], which shows that the industry has applied WT SCADA for CM because it is available at no additional cost. However, few operators are aware of the potential for SCADA to reinforce a CMS, because of its low 10 min sampling rate has been considered too low for accurate fault diagnosis. Due to WT varying loads SCADA systems frequently give false alarms which overwhelm operators, although efforts are being made to tackle this issue[28]. SCADA data at higher sampling frequency has been researched, for example at 32Hz in the EU FP6 CONMOW project [30,31,32], however accurate WT CM was still unachieved for the practical reasons mentioned in [30] but also due to influence of varying loads on CM results and the lack of suitable data analysis tools.

Currently the EU FP7 ReliaWind project [33] is using SCADA data to provide CM for WT generator, gearbox and pitch faults and progress has been made in developing simple signal algorithms to prevent false alarms [34, 35], although the techniques need further verification.

In summary, SCADA-based CM is cheap and informs the operator the approximate WT condition, but cannot replace a professional purpose-designed WTCMS at the moment for the following reasons:

- SCADA system does not collect the signals necessary for full WT CM;
- SCADA data are collected at a low sampling frequency, which cannot meet the wide bandwidth needs of some CM and fault diagnosis;
- A successful CM-purposed SCADA data analysis tool has not been achieved;
- An abnormal SCADA data change, for example a bearing temperature increase, is considered as a late-stage indication of a fault not giving the necessary prognostic lead time for useful WT CM.

4.2 WTCMS

WTCMS application has been requested by certification bodies, for example GermanischerLIoyd[36,37,38] following a catastrophic series of WT gearbox failures in the late 1990s. Today, a number of commercial WTCMSs are available to the wind industry[19] many having been developed by experienced CM practioners, such as SKF, Brüel & Kjær, GE Bently Nevada, Prüeftechnik and Gram & Juhl, based upon experience of monitoring conventional rotating machines as shown in Appendix 2. It shows that the majority are vibration-based systems although some are used in combination with oil particle counters and fibre-optic strain gauges to enhance their WT CM capabilities[39,40]. There are a few systems based on shaft torque or torsional vibration measurement and some use structural health monitoring[16,17]. It can also be seen that the available WTCMSs focus mainly on monitoring the WT drive train, i.e. the main bearing, shaft, gearbox and generator, using spectral analysis techniques. A few systems are specifically designed for WT gearbox lubrication oil or blade monitoring. This is because the WT drive train and blade components are expensive and their failure causes long down-times[2,20,21]. A typical vibration-based WTCMS is outlined in Fig.3, where fibre-optic strain gauges and oil particle counter are optional. In principle, the application of this system will be helpful in reducing WT operational risk. However, to date no published work has demonstrated its effectiveness in improving WT availability and there have been false alarms and ineffective fault reports. The high cost of WTCMSs and their interpretation complexity has discouraged WT operators from making wider use of them, despite the fact that they are fitted to the majority of large WTs (>1.5 MW) in Europe. The root-cause of this situation is that WTCMS suppliers have applied existing knowledge to WT problems, there is insufficient knowledge amongst WT maintenance staff of their potential and that there is inadequate experience of their application to common WT faults.

WTs are different from traditional rotating machines as they usually operate in remote locations, rotate at low and variable speed and work under constantly varying loads. WT CM signals, such as vibrations and temperatures, are dependant not only on component integrity, but also on the operating conditions, including rotational speed, loading and ambient temperature. In other words, WT component vibration and temperature changes do not necessarily indicate a fault occurrence, although the presence of a fault may lead to such changes. To demonstrate this, Fig.4 shows the transverse vibration of a perfect shaft rotating at variable speed and subject to varying load, collected from a specially designed WT CM test rig, introduced in detail in [41,42].

From Fig.4, it is seen that even without damage the shaft transverse vibration varies with WT load torque and rotational speed. Moreover, the larger the torque delivered, the stronger the vibration. Thus, shaft vibration is affected not only by machine dynamic integrity of itself, but also by its operating conditions.

Likewise component temperatures, for example generator bearing or gearbox oil temperatures, also correlate with WT load and nacelle temperature. In order to demonstrate this, a simulated correlation relationship of generator bearing temperature versus generator power and ambient temperature is shown in Fig.5[43].

From Fig.5, it is seen that generator bearing temperature increases monotonically with either ambient temperature or generator power increases. To demonstrate this further, a practical CM data set measured from an operational WT is shown in Fig.6 where generator bearing temperature fluctuations clearly correspond to generator power fluctuations.

So, it can be concluded that whilst a generator bearing fault can lead to a bearing temperature increase, that increase could also correlate to changes in both ambient temperature and generator power even though the generator cooling system is in good condition.

From the above one can conclude that vibration, temperature or other WT fault-related parameter responses are not uniquely dependent on WT integrity. In other words, changes in these fault-related parameters do not necessarily indicate the presence of a fault. In order to reduce false alarm, a WTCMS must carry out a more detailed investigation than merely measuring amplitude to discern the true cause of variation, and triggering a fault alarm.

In addition, the WT operating environment exposes the machine to extreme temperatures, wind gusts and lightning strikes. As a consequence WT electrical and power electronic systems are also prone to failure, like mechanical systems, see Fig.7 [44] taken from the ReliaWind project and their deterioration may be accelerated in the harsh offshore environment by corrosion and erosion. Although onshore such failures could be repaired quickly, offshore high wind speeds and access difficulties will exacerbate the effects of these failures and cause longer down-times. Existing WTCMSs have not yet taken into account the detection, diagnosis and prognosis of failures in such conditions.

The cost of a WTCMS is also an issue since a large WF may require millions of pounds to equip the entire WF with such a WTCMS, excluding fees for periodic recalibration. The operator also faces the challenge of processing, transmitting, storing and interpreting the large amount of data generated by these systems.

Both low and high speed rotating components are included in the WT. In theory, CM data from components with different rotational speeds should be collected using different sampling frequencies to minimize the CM data size. For example, shaft vibration data are usually sampled at 2kHz; gearbox vibration data at 20kHz; and so on. However, this is not normally realized in practice due to hardware limitations. To minimize data transmission, WTCMSs analyse WT data and transmit trends to the WTCMS microprocessor continuously while spectral analysis occurs only when settings detect an unusual condition. Such a strategy mitigates the burden of data transmission from the WT, however increases the risks of losing raw historic data, due to limited WTCMS memory size.

The last issue concerns WTCMS maintenance itself, which because composed of electronic components and transducers, are particularly prone to failure in inclement environments such as offshore. So, regular WTCMS maintenance and recalibration are essential during maintenance periods, however, offshore these are short and WTCMS reliability may be problematic.

4.3 Justifying WTCMS

A WTCMS, such as SKF WindCon, costs around £14k/unit for software, transducers, cabling and installation. So equipping WTs with such a system would be a significant financial investment for a WF operator. The cost justification of CMS for wind power has not been as clear as for traditional fossil-fired or nuclear power plants. Individual WTs are relatively low power and currently low priority generators with less individual energy value than large conventional units. Table 2 compares the cost to an operator of unplanned down-time on a 500MW conventional fossil-fired generation unit and on a 3MW WT generation unit.

Table 2 shows that even at a low capacity factor fossil-fired plant CM is entirely justified through the avoidance of unplanned down-time costs by early fault detection. This is not the case for the WT, despite the energy price increase, including ROCs, of £76/MWh [45]. Perhaps more relevant to WTs are the failure rates, cost of repair and associated down-time. Failure down-time has a significant impact on the overall cost of failure as WT equipment and components have significant lead times, access restrictions offshore, due to weather, can further increase down-time.

The following justification considers gearbox failure costs and the cost advantages of avoiding complete failure through successful WT CM. The current failure rate of onshore WT gearboxes is around 0.15 failures/turbine/year[46];an increased failure rate of 0.2 failures/turbine/year is assumed here for offshore installations. According to [2], typical onshore gearbox failure down-time is 12 days/failure, however [45] suggests 30 days/failure onshore, rising to 41 days offshore. The latter figures include waiting times for jack-up vessels, cranes and other associated equipment. The cost of onshore maintenance by two technicians is taken as £1.2k/day (€1.5k) against £1.4k/day (€1.7k) offshore[47]assuming 3 days are for gearbox replacement or 1 day for bearing replacement. Following discussions with a large WT operator, the capital cost of a gearbox is taken as £170k and, when failure is avoided, the capital cost of bearing replacement is taken as £2.5k. Table 3 gives a cost analysis using the above figures for individual 3MW turbines onshore or offshore, and for an offshore WF, Scroby Sands (UK) comprising 30, 2MW WTs.

This example does not take account of crane hire or monitoring engineer employment costs, there is clearly a benefit in using WTCMS to eliminate gearbox failures, according to published failure rates. The figures for Scroby Sands offshore WF are particularly favourable and suggest that offshore WTCMS is essential for the avoidance of serious down-time and wasted offshore attendance. In addition, other major sub-assemblies, such as generator, blades and converter, not included here, would make a significant contribution to the WTCMS financial case, as would an extension of WF working life but all depends upon the reliability of the WTCMS and the ability of the operator to make use of its indications.

5 Existing Signal Processing Techniques for WT CM and their Issues

The selection of appropriate signal processing and data analysis techniques is critical for WT CM success. If the fault-related characteristics can be correctly extracted using these techniques, fault growth can be assessed by observing characteristic variations and these characteristics are also important clues for fault diagnosis. To present a clear review the techniques that are already used by commercial WTCMSs and those that are still in research are discussed separately in the following sections.

5.1 Techniques already used by commercial CMSs

Both time and frequency domain signal processing techniques have been adopted by commercial CMSs, for example the SKF WindCon3.0 shown in Fig.8.

- Time domain analysis

The system sets time domain warning and alarm levels and plots data trends against time, load or rotational speed, when a trend reaches a pre-defined threshold, the system triggers an alarm. Time domain trends are usually obtained from well-known parameters, such as overall vibration level, Crest factor, average vibration level and so on and the whole CM process is implemented online. However, CM results are inevitably influenced by varying load and environmental factors. The system also allows user to review raw signal time waveforms and shaft vibration orbits. But practice has shown that it is hard to assess WT's health condition by observing the signal waveforms alone, particularly when the turbine is working under varying load. In practice, some WT performance monitoring systems evaluate a WT's health status by comparing signals with neighbouring WTs[48], see Fig.9.

From Fig.9, it is found that an almost constant correlation is maintained when both monitored WTs are normal. Once the health of either changes, their relationship, indicated by correlation coefficient, will be modified. Such a technique is simple in calculation but its accuracy is affected by local WF terrain factors such as individual WT site, wind direction, wind shear and wind speed;

- Frequency domain analysis

Frequency domain techniques used in the WTCMS, for example envelope analysis[49,50], cepstrum analysis[51] and spectral Kurtosis [52], are based upon the Fast Fourier transform (FFT) . Considering the FFT was initially designed for processing linear stationary signals with constant amplitudes and fixed frequency compositions, the maximum variations of the inspected WT CM signals need to be defined in advance, so that signal analysis accuracy can be guaranteed. Historic spectra can be traced with the aid of waterfall diagram. However, as WTs rotate at variable speed and load, the waterfall diagram obtained is 'noisy' and difficult to interpret even after calibration by the rotational speed. The WindCon system also provides a tool aiding user to calculate the characteristic frequencies of the components at any rotational speed. The cursor function enables user to select peaks, harmonics and sidebands in the spectrum. If adequate information about the machine or component is known, the type of the fault could be readily judged with the aid of this tool. The signal processing techniques used in other WTCMSs are similar, although differences exist between different systems. For example, some WTCMSs use either FFT or cepstrum analyses; some for example the WP4086 developed by Mita-Teknik and the CBM by GE Bently Nevada, use acceleration envelope spectra; while some, for example the system developed by Brüel&Kjær, use both envelope and cepstrum analysis. Both envelope and cepstrum analyses are based upon the FFT and have been proved powerful in extracting faulty features from gearbox and bearing vibration signals. Although the FFT is widely used, it is not an ideal tool for processing WT CM signals which are non-linear and non-stationary, due to varying speeds and loads and the negative influences of the environment on WT control. So, more advanced signal processing techniques should be investigated for WT CM.

5.2 Techniques in research

Today, a number of advanced signal processing techniques [53,54,55,56,57,58,29,59,60], including time-frequency analysis and neural network, are being researched to overcome the problems of conventional FFT-based techniques and find better solution for WT CM. A review of these has been made by the authors and some are listed in Table 4 considering the following four aspects:

- Advantages;
- Disadvantages;
- Online CM capability;
- Fault diagnosis capability.

From Table 4 the following concerns arise:

- Most new techniques are good for offline CM and fault diagnosis but not for online use because of complex calculations;
- The proposed techniques have not been fully demonstrated, although they may have been tested on one or two types of faults. The difficulties of gathering true WT conditions from overhauls and rebuilds and the fact that not all operational WTs have been monitored properly, means that at the moment it is a challenging task to test or prove these techniques;
- Neural network [29] and genetic programming [60] can be used for online application but appropriate data training for them is challenging.

Other techniques, such as self-organizing maps [61] and support vector machines [62], are potentially applicable to WT CM because of their powerful complex nonlinear classification capability, however their application in WT CM field has not yet been reported.

6 Future Work for WT CM

Future work is also needed, in addition to addressing the issues above, to the following three priorities.

6.1 CM Techniques for other Key Sub-assemblies

Currently available WTCMSs mainly focus on the gearbox, generator and main bearings CM. However, the electrical and power electronic systems as well as the yaw and pitch systems of the WTs suffer more problems, as Fig.7 indicates. Moreover, failures occurring in these systems also cause long down-times, particularly offshore. So, for offshore WTs, more key sub-assemblies need monitoring besides the gearbox, generator and main bearings. Moreover, more attention should be focused on sub-assemblies with higher failure rates regardless of their ease of replacement or repair. The increased deployment of direct-drive WTs also emphasises this requirement.

6.2 WT Prognosis

Prognosis is an essential requirement for WF CM, permitting safety, scheduling and maintenance improvements. In wind industry, if WT fault progression is predictable, then a predictive condition-based maintenance strategy will be realistic. Once prognosis is achieved, it will significantly improve the WT availabilities, reducing maintenance costs and down-time, allowing WT operators to manage spare parts and invest maintenance expenditure efficiently, generating significant economic benefit. With the increasing deployment of WTs onshore and offshore in recent years, the industry has shown growing interest in such techniques. However, to date a real prognosis system has not yet appeared in either traditional or wind industries due to the difficulties of setting the requisite mathematical models, although a number of efforts have recently been made [63].

6.3 WTCMS Reliability

The economic benefits of WTCMS and how it can be a cost-effective system have been researched recently[45, 64]. It was concluded that to be cost-effective the WTCMS must provide correct diagnosis in around 60-80% of cases, depending on the cost of maintenance actions. The more expensive the maintenance action, the better the WTCMS needs to perform. That means that WTCMS developed for future larger offshore WTs should be more accurate and reliable. Thus, efforts must be made to improve WTCMS accuracy and reliability.

7 Conclusions

WT CM challenges are reviewed in this paper with the following conclusions:

1) SCADA- and CMS-based monitoring are currently available to modern WTs:
   - The former has low frequency resolution and is cheap but less able to carry out diagnosis and prognosis;

- The latter is of higher frequency resolution and expensive, capable of diagnosis and prognosis but improvements are needed to make it comprehensible to operators and maintainers;
- More effort should be made to integrate these disparate monitoring methods.

2) New developments in large WTs and offshore deployment bring pressing requirements for effective WT monitoring, which should be:
   - Applicable to a wider range of WT types than hitherto;
   - Able to monitor the whole WT system rather than only the drive train;
   - Capable of detecting incipient defects and preventing secondary damage;
   - Capable of correctly detecting, diagnosing and prognosing faults;
   - Cost-effective, accurate and reliable.
3) Monitoring is more critical to offshore WFs because they:
   - Incorporate WTs of larger ratings;
   - Experience stronger wind profiles and harsher environment;
   - Experience longer repair and replacement down-times;
   - Experience higher repair and replacement O&M costs.
4) Vibration and oil analysis are currently effective WT CM techniques. However, they cannot meet all future WT CM requirements;
5) Research should be done to:
   - Process nonlinear CM signals more accurately and rapidly;
   - Analyse CM time- or frequency-domain signal changes under incipient fault conditions as faults progress from detection to failure, thereby providing the information necessary to validate CM techniques;
   - Develop CM techniques for WT electrical and electronic systems, which dominate WT failures. Such failures cause low onshore down-time but they are causing long offshore down-time due to offshore WT inaccessibility.

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Appendix

Appendix 1: Survey of Commercial WT SCADA Systems Available

No.	Name		Product information	
	Product	Company	Major functions	Notes
1	Wind Asset Monitoring Solution	Matrikon (Canada)	Monitor and manage all remote assets, leverage and integrate with SCADA and CMSs.	The solution bridges the gap between instrumentation and management systems.
2	Wind Systems	SmartSignal (USA)	Model maintenance, monitoring services, and predictive diagnosis.	The system analyses real time data and detects and notifies wind farm of impending problems, allowing owners to focus on fixing problems early and efficiently.
3	WindCapture	SCADA Solution (CANADA)	Real-time data reporting with the highest degree of accuracy.	It is a SCADA software package used for monitoring, controlling and data collection, and reporting for WT generators. It was designed and tailored to the demands of manufacturers of wind energy project and facilities.
4	SIMAP	Molinos del Ebro, S.A. (Spain)	Continuous collecting data, processing information, forecasting failure risk, and scheduling maintenance.	It is based on artificial intelligence, able to create and adapt a maintenance calendar for the WT being monitored.
5	InduSoft Wind Power Solutions	InduSoft (USA)	WT monitoring, maintenance assistance, and control.	It is a powerful HMI/SCADA package able to monitor and adjust any operating set point in the controller or PLC.
6	GH SCADA	GL (Germany)	Remote control of individual WT. Online data viewing, reporting &analysing.	It is used for wind farm operating, analysing and reporting.
7	Enercon SCADA system	Enercon (Germany)	Request status data, store operating data, wind farm communication and open/loop control.	It enables the customer and Enercon service to monitor and analyse the operating state of WTs, and save operating data.
8	BaxEnergyWindPower Dashboard	BaxEnergy GmbH (Germany)	Real-time data acquisition and visualization, alarm analytics and data reporting.	It offers an extensive and comprehensive customization for full integration of SCADA system applications and SCADA software.
9	GamesaWindNet	Gamesa (Spain)	Supervision and control of WTs, meteorological masts. Alarm and warning management, report generation and user management.	It is configured with a basic hardware and software platform based on Windows technology, allowing a friendly interface to conduct SCADA application with specific options for optimal supervision and control of wind farm devices (e.g. WTs, meteorological mast, etc.).
10	GE-HMI/SCADA-iFIX 5.1	GE (USA)	It is a superior proven real-time data management, control, and information analysis system.	It is open, flexible and scalable which includes impressive visualizations, a reliable control engine, and a powerful built in historian.
11	ICONICS for Renewable Energy	ICONICS Inc. (USA)	Portals for complete operations, data histories and reports, geo SCADA with meteorological updates.	It provides portals for complete operations, including energy analysis, data histories and reports, geo SCADA with meteorological updates.
12	INGESYS Wind IT	IngeTeam (Spain)	It provides advanced reporting, client/server architecture, standard protocols and formats.	The system makes it possible to integrate wind farms into a single system and provide clients with advanced reporting services.
13	reSCADA	Kinetic Automation Pty. Ltd. (USA)	Office 2007 GUI style, data visulation, diary and mapping tools,	Targeting and specializing in renewable energy industries. Help saving time, effort and cost in developing HMI/SCADA.
14	SgurrTREND	SgurrEnergy (UK)	Wind monitoring, process and archive the data, and reporting services.	It provides a variety of wind monitoring solutions to evaluate the wind resources potential at wind farm, offers a one stop shop for all mast services from planning application, data collection and mast decommissioning to wind analysis services for energy yield prediction, project layout and design services.
15	Gateway System	Mita-Teknik (Denmark)	Data acquisition and reporting, user-friendly operation, life time data, CMS algorithm toolbox, instant alarm notification.	It is a PC-based software package designed to collect, handle, analyse and illustrate the data from controller with simple graphics and text.

Appendix 2: Survey of Commercial WTCMSs

No	Name		Product information	
	Product	Company	Major functions	Notes
1	WindCon 3.0	SKF (Sweden)	Collect, analyse and compile condition monitoring data that can be configured to suit management, operators and maintenance engineers.	The system focuses on the condition monitoring of wind turbine blades, main bearing, shaft, gearbox, generator, and tower by the combined use of vibration transducers and a lube oil debris counter.
2	TCM	Gram &Juhl (Denmark)	Advanced signal analyses on vibration, vibro-acoustic, and strain, combined with automation rules and algorithms for generating references and alarms.	The WT blades, main bearing, shaft, gearbox, generator, nacelle, and tower are monitored by using spectral analysis methods.
3	WP4086	Mita-Teknik (Denmark)	Integrated with WT SCADA, the system provides real-time frequency and time domain analyses of turbine operational signals and gives off alarms based on predefined thresholds.	With the aid of eight accelerometers, the WT main bearing, gearbox and generator are monitored by using both time and frequency domain analysis techniques.
4	Brüel&KjærVibro	Brüel&Kjær (Denmark)	Collect and process data at fixed intervals and remotely send results to diagnostic server. The time-waveform of the data at any time is accessible for further analysis.	The WT main bearing, gearbox, generator, and nacelle (temperature and noise) are monitored by the approach of vibration analysis in combination with temperature and acoustic analyses.
5	CBM	GE Bently Nevada (USA)	The system gives monitoring and diagnosis of drive train parameters. Correlate CM signals with WT operational information (e.g. wind and shaft rotating speeds), and give off alarms via SCADA.	The vibrations of WT main bearing, gearbox, generator, and nacelle as well as bearing and oil temperatures are monitored.
6	CMS	Nordex (Germany)	Actual vibration values during WT start-up period are compared with the reference values. Some Nordex turbines also use the Moog Insensys Fibre Optic measurement system.	The system focuses on the monitoring of main bearing, gearbox, and generator. The WT blades are also monitored if the WTs also install Insensys' Fibre Optic system.
7	SMP-8C	GamesaEolica (Spain)	Continuous online analyse WT main shaft, gearbox and generator and compare their spectral trends. Warnings and alarms are given through wind farm management system.	WT main shaft, gearbox and generator are online monitored through the spectral analyses of their vibrations.
8	PCM200	Pall Europe Ltd (UK)	This is a real-time system for testing and assessing fluid cleanliness.	The cleanliness of gearbox lubrication oil is monitored.
9	TechAlert 10/20	MACOM (UK)	TechAlert 10 is an inductive sensor to count and size the ferrous and non-ferrous debris, while TechAlert 20 is a sensor only for counting ferrous particles.	Both systems are designed for monitoring the debris containing in lubrication or other circulating oils.
10	Rotor Monitoring System (RMS)	Moog Insensys Ltd. (UK)	RMS is in fact a blade monitoring system, conducting the condition monitoring of wind turbine blades and rotor by measuring the strains in blade root sections using fibre optic technology.	The load measurement by RMS is also helpful for the load control of pitch regulated wind turbines.
11	MDSWind MDSWind-T	VULKAN SEACOM (Germany)	MDSWind measures the vibrations of main bearing, gearbox, generator, and tower of the wind turbine, calculate and display their statistic indices (e.g. RMS, Crest factor) online.	MDSWind-T is a four channel portable system developed based on MDSWind.
12	Ascent	Commtest (New Zealand)	Ascent is a vibration analysis system for monitoring the main shaft, gearbox and generator of the turbine by the approach of spectral analyses and time domain statistics.	System available in 3 complexity levels. Level 3 includes frequency band alarms, machine template creation, and statistical alarming.

13	Condition Diagnostics System	Winergy (Germany)	The system analyses vibrations, load and oil to give diagnosis, predict and recommend for corrective action. Automatic fault identification is provided. Pitch, yaw and inverter monitoring can also be integrated into the system.	It mainly focuses on the health monitoring of wind turbine main shaft, gearbox and generator through vibration analysis and oil debris counter.
14	Condition management System	Moventas (Finland)	It is a compact system initially designed for monitoring wind turbine gearbox by measuring temperature, vibration, load, pressure, speed, oil aging and oil particles.	The system can be extended to monitor the generator and rotor as well as the controller of the wind turbine.
15	OneProd Wind	Areva (France)	The system monitors the main bearing, gearbox and generator of the wind turbine by measuring oil debris, structure and shaft displacement, and electrical signals.	It consists of operating condition channels to trigger data acquisitions, measurement channels for surveillance and diagnosis, optional additional channels for extended monitoring.
16	WinTControl	Flender Service GmbH (Germany)	It is a vibration monitoring system for assessing the health condition of wind turbine main bearing, gearbox and generator. Both time and frequency domain analyses are adopted.	Vibration measurements are taken when load and speed trigger are realised.
17	WiPro	FAG Industrial Services GmbH (Germany)	Temperature and vibration measurements are taken for monitoring the main bearing, main shaft, gearbox and generator of the wind turbine.	Time frequency analysis used in the system allows speed-dependent frequency band tracking and speed-variable alarm level.
18	HYDACLab	HYDAC Filtertechnik GmbH (Germany)	It is a system for monitoring the particles (including air bubbles) in hydraulic and lubrication systems.	It is used mainly for monitoring the gearbox of the wind turbine.
19	BLADEcontrol	IGUS ITS GmbH (Germany)	BLADEcontrol is a system dedicatedly designed for monitoring wind turbine blades by comparing spectra with historic spectra obtained from normal blades.	Accelerometers are bonded directly to the blades and a hub measurement unit transfers data wirelessly to the nacelle.
20	FS2500	FiberSensing (Portugal)	This is also a fibre optic system designed for monitoring wind turbine blades with the aid of Fibre Bragg Grating sensors.	This system can be potentially applied to wind turbine blade monitoring, but at the moment it has not been extensively deployed.
21	Oil Condition Monitoring System	Rexroth Bosch Group (Germany)	It us a system for the early detection of gearbox damages and the monitoring of oil cleanliness. High dissolving sensors for the measurement of particles and water content in the lubricating oil are available. Both permit an estimate of the remaining life time of the lubricating oil.	This system not only improves the reliability of wind turbines but also the efficient operation by predictable maintenance.
22	Gearbox oil condition monitoring	Intertek (UK)	Intertek oil condition monitoring services include testing of gearbox oils and lubricants, helping clients extend runtimes for expensive turbines, windmills and other equipment, while minimizing down-time and costly repairs.	This is an offline oil analysis system.
23	Icount System and IcountPD particle Detector	Parker (Finland)	Parker's system is an all-in-one system to determine whether or not system oil is contaminated and the best way to detect particles online or offline.	IcountPD is a particle detector; while Icount system provides early warning of any unwanted changes in hydraulic or lubrication oil quality. Thus increasing the availability of the machinery by reducing the need for unnecessary down-time.

Figure Caption:

Fig.1 Evolution of modern wind turbines in diversity and size

Fig.2 Schematic diagram of a typical WF SCADA system

Fig.3 Outline of a typical vibration-based WTCMS

Fig.4 The transverse vibration of a perfect shaft under varying loading conditions

Fig.5 Temperature of generator bearing against ambient temperature and generator power

Fig.6 Correlation between WT output power and generator bearing temperature

Fig.7 Failure rate proportions attributable to geared-drive onshore WT sub-assemblies

Fig.8 Software interface of SKF WindCon3.0 (Observer software)

Fig.9 Performance monitoring by the correlation with neighbouring WTs

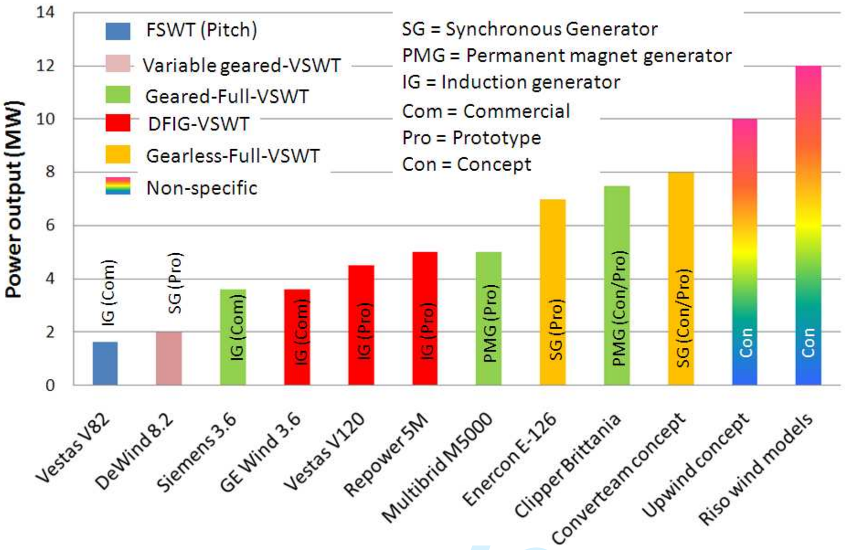


Fig.1 Evolution of modern wind turbines in diversity and size

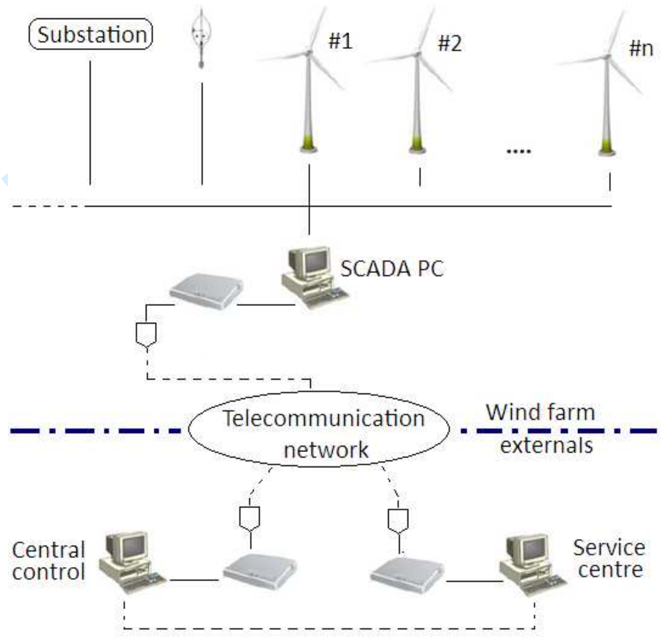
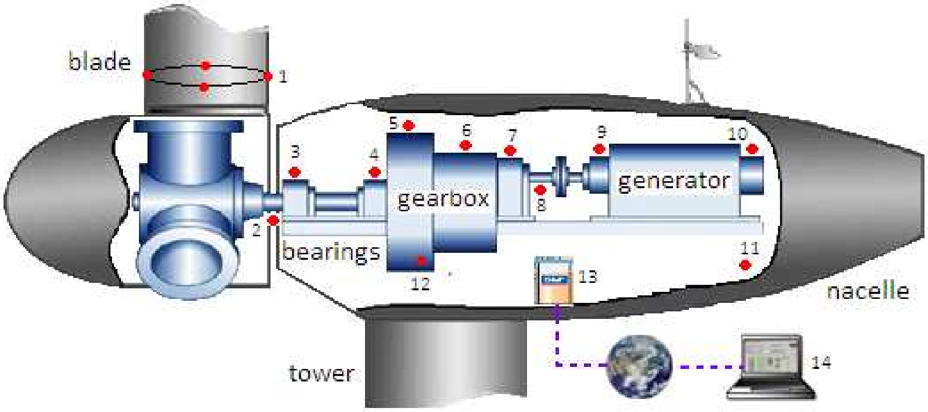


Fig.2 Schematic diagram of a typical WF SCADA system



1 --- fibre optic transducers; 2, 8 --- speed transducers; 3, 4, 5, 6, 7, 9, 10, 11 --- accelerometers; 12 --- oil debris counter; 13 --- online CMS; 14 --- PC at control center.

Fig.3 Outline of a typical vibration-based WTCMS

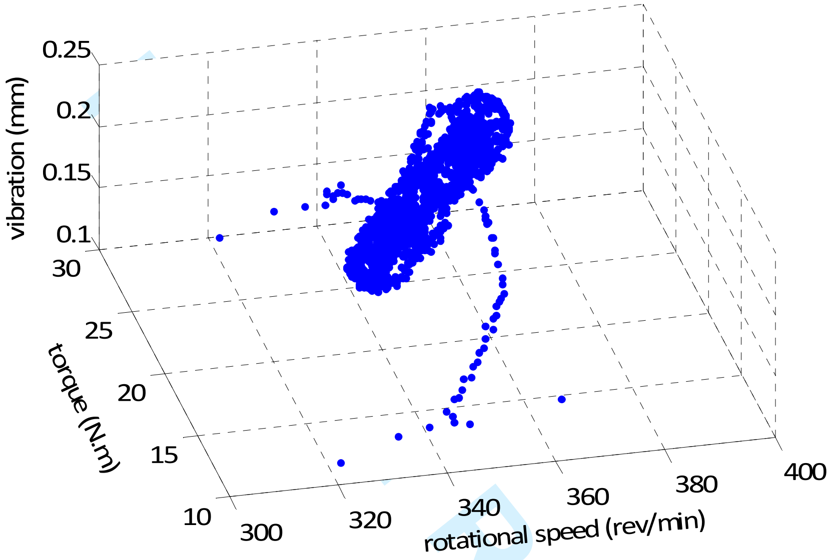


Fig.4 The transverse vibration of a perfect shaft under varying loading conditions

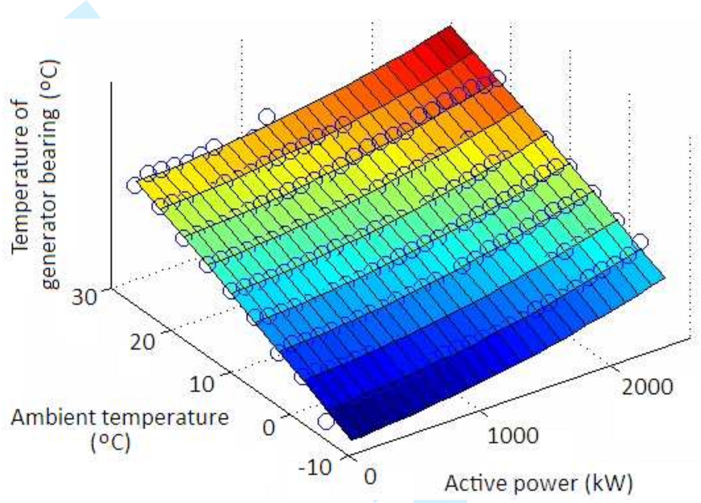


Fig.5 Temperature of generator bearing against ambient temperature and generator power

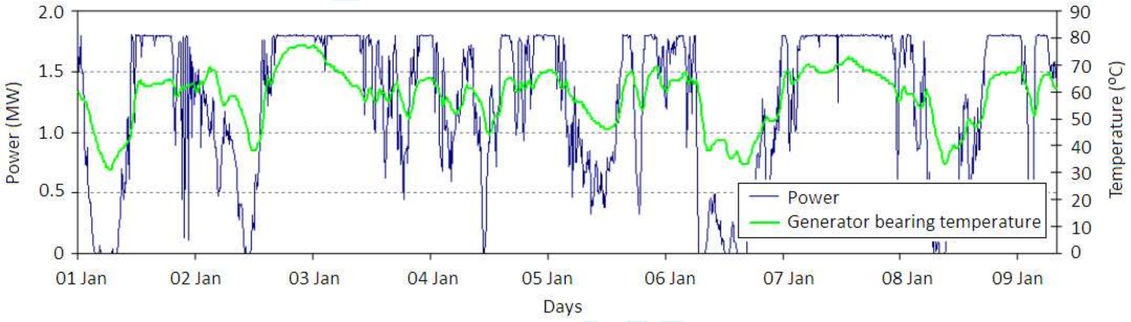


Fig.6 Correlation between WT output power and generator bearing temperature

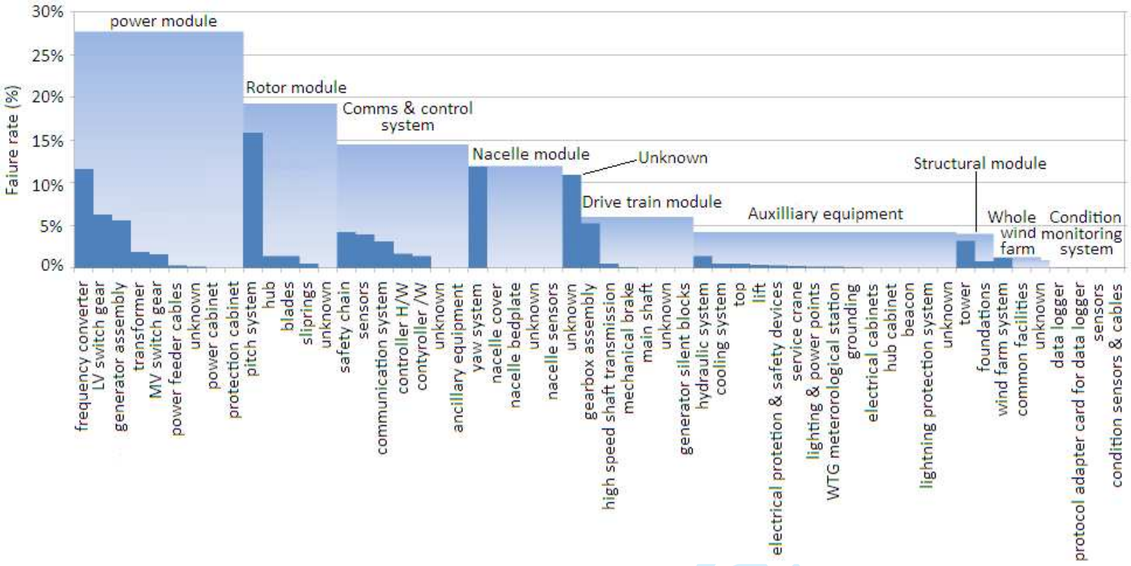
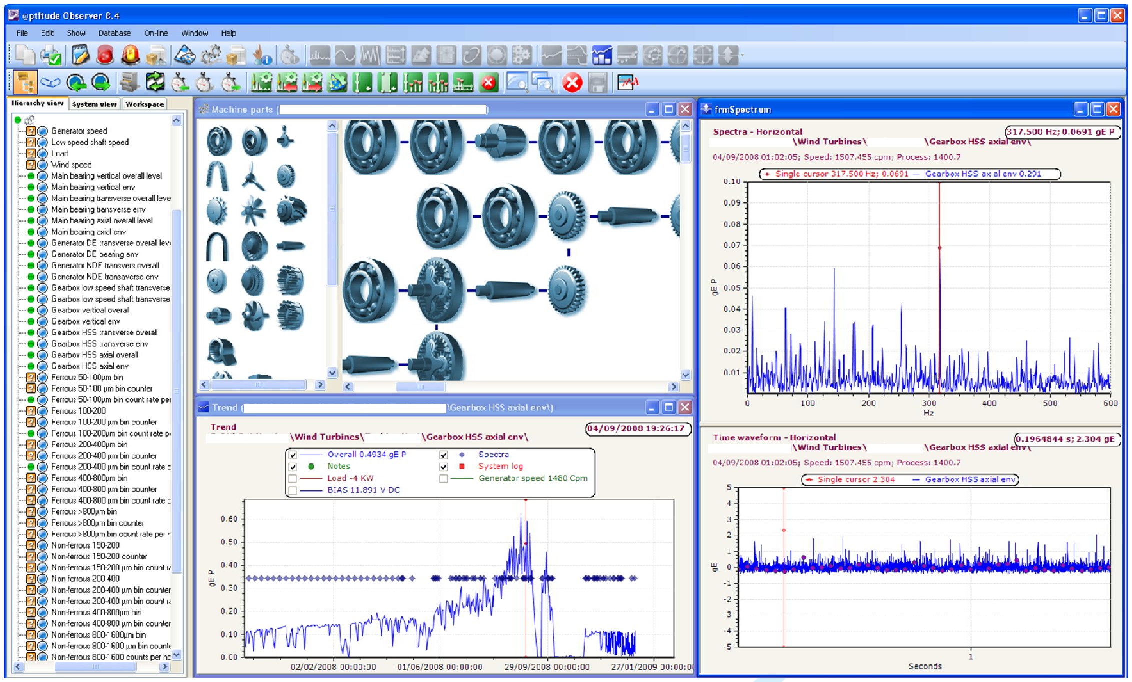


Fig.7 Failure rate proportions attributable to geared-drive onshore WT sub-assemblies



☑ Overall 0.4934 gE P
☑ Notes
☐ Load -4 KW
☐ BIAS 11.891 V DC
☑ Spectra
☑ System log
☐ Generator speed 1480 Cpm

04/09/2008 01:02:05; Speed: 1507.455 cpm; Process: 1400.7

Single cursor 317.500 Hz; 0.0691 — Gearbox HSS axial env 0.291

04/09/2008 01:02:05; Speed: 1507.455 cpm; Process: 1400.7

Single cursor 2.304 — Gearbox HSS axial env

Fig.8 Software interface of SKF WindCon3.0 (Observer software)

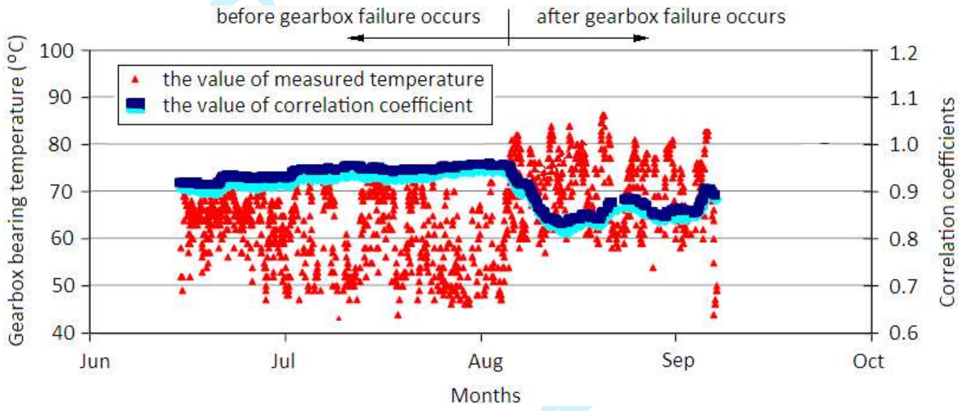


Fig.9 Performance monitoring by the correlation with neighbouring WTs

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Table Caption:

Table1: CM Techniques and Features

Table 2: 24 hr unplanned down-time cost, 500MW fossil-fired unit compared to 3MW WT

Table 3: Cost justification for WTs onshore, offshore or in an offshore WF

Table 4: Technologies being researched for WT CM

Table1: CM Techniques and Features

No.	CM Techniques	Cost	Online CM	Fault diagnosis	Deployment	WT components
1	Thermocouple	Low	Y	N	Already used	Bearings Generator Converter Nacelle Transformer
2	Oil Particle Counter	Low	Y	N	Already used	Gearbox Bearing
3	Vibration Analysis	Low	Y	Y	Already used	Main shaft Main bearing Gearbox Generator Nacelle Tower Foundation
4	Ultrasonic Testing	Low to Medium	Y	N	Being tested	Tower Blades
5	Electric Effects (e.g. discharge measurement)	Low	Y	N	Already used	Generator
6	Vibro-Acoustic Measurement	Medium	Y	N	N	Blade Main bearing Gearbox Generator
7	Oil Quality Analysis	Medium to High	N	Y	N	Gearbox Bearing
8	Acoustic Emission Transducers	High	Y	N	N	Blade Main bearing Gearbox Generator Tower
9	Torsional Vibration (Encoder based)	Low	Y	N	Being tested	Main shaft Gearbox
10	Fibre Optic Strain Gauges	Very High	Y	N	Already used	Blade
11	Thermography	Very High	Y	N	N	Blade Main shaft Main bearing Gearbox Generator Converter Nacelle Transformer
12	Shaft Torque Measurement	Very High	Y	N	Being tested	Blades Main shaft Main bearing
13	Shock Pulse Method (SPM)	Low	Y	N	N	Bearing Gearbox

Table 2: 24 hr unplanned down-time cost, 500MW fossil-fired unit compared to 3MW WT

	500MW Unit	**3MW WT**
Machine capacity	500MW	3MW
Cost of saleable energy	£36/MWh	£76/MWh
Capacity Factor	0.45	0.27
Cost of 24hrs unplanned down-time, at given Capacity Factors	£194,400	£1,477
Approximate number of CMSs paid for by avoiding a 24hr unplanned outage	14	0.11

Table 3: Cost justification for WTs onshore, offshore or in an offshore WF

	3MW Onshore WT	**3MW Offshore WT**	**Scroby Sands Offshore WF**
Turbine capacity	3MW	3MW	2MW
Number of turbines in study	1	1	30
Capacity Factor	0.30	0.27	0.27
Price of saleable energy	£50/MWh	£76/MWh	£76/MWh
Gearbox failure rate (failures/turbine/year)	0.15	0.20	0.20
Down-time per failure (days)	30	41	41
Failures per year	0.15	0.20	6.00
Annual down-time (days)	4.5	8.2	246.0
Annual cost of maintenance, A	£180	£840	£25,200
Annual cost of lost energy, B	£3,240	£6,998	£242,300
Annual cost of replacement gearbox, C	£25,500	£34,000	£1,020,000
Total annual cost of failure, $T = A+B+C$	£28,920	£41,838	£1,287,500
Annual cost of replacement bearings assuming failure is avoided, D	£375	£500	£15,000
Approximate number of CMSs paid for by early detection of a gearbox fault including bearing replacement $(T-D)/CMS_{\text{cost}}$	2	3	91

Table 4: Technologies being researched for WT CM

No.	Technique	Advantages	Disadvantages	Online CM	Fault diagnosis
1	High order spectrum [53]	Able to detect the nonlinear relationships between different orders of the harmonics contained in the signal.	It is still a tool for processing linear signals, not ideal for analysing WT CM signals.	N	N
2	Continuous wavelet transform [31,41,54]	Able to analyse non-stationary signals satisfactorily.	It involves intensive calculation and is still a tool for processing linear signals. However, WT CM signals are often nonlinear.	N	Y
3	Discrete wavelet transform [30,55]	Able to analyse non-stationary signals efficiently.	Unable to analyze nonlinear WT CM signals correctly, and unable to locate a desired frequency range flexibly.	N	Y
4	Empirical mode decomposition [56,57]	An ideal tool for processing non-stationary and nonlinear signals, like WT CM signals.	Unable to locate a desired frequency range flexibly.	N	Y
5	Energy tracking [42]	An efficient tool for analysing WT CM signals.	It inherits the disadvantages of wavelet transforms and the accuracy of its results is highly dependent on the correctness of WT speed.	Y	Y
6	Wigner-Ville Distribution [58]	Able to analyse non-stationary signals satisfactorily.	Unable to analyse nonlinear WT CM signals correctly.	N	Y
8	Neural network [29]	An ideal tool for developing real time CMS. It takes all CM information into account, however is able to process them efficiently.	Difficult to train the neural network.	Y	Y
9	Data driven technique [56,57,59]	Attributed to 'natural' decomposition of original signal and the use of phase information, it is ideal to detect incipient mechanical and electrical defects occurring in WTs.	Complex computation and manual selection of interested intrinsic mode functions make it difficult to use online.	N	Y
10	Genetic programming [60]	Able to simulate complex problem mathematically.	The physical mean of the obtained mathematical model is unknown.	Y	Y