Monitoring wind turbine gearboxes

Article *in* Wind Energy · July 2013

DOI: 10.1002/we.1521

Yanhui Feng
Nanjing University of Science and Technology

Yingning Qiu
Nanjing University of Science and Technology

Christopher Crabtree
Durham University

Hui Long
The University of Sheffield

WIND ENERGY
Wind Energ. (2012)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/we.1521

RESEARCH ARTICLE

Monitoring wind turbine gearboxes

Yanhui Feng[1], Yingning Qiu[1], Christopher J. Crabtree[2], Hui Long[3] and Peter J. Tavner[2]

[1] School of Energy and Power Engineering, Nanjing University of Science and Technology, Nanjing, China
[2] School of Engineering and Computing Sciences, Durham University, Durham, UK
[3] Department of Mechanical Engineering, The University of Sheffield, Sheffield, UK

ABSTRACT

Concerns amongst wind turbine (WT) operators about gearbox reliability arise from complex repair procedures, high replacement costs and long downtimes leading to revenue losses. Therefore, reliable monitoring for the detection, diagnosis and prediction of such faults are of great concerns to the wind industry. Monitoring of WT gearboxes has gained importance as WTs become larger and move to more inaccessible locations. This paper summarizes typical WT gearbox failure modes and reviews supervisory control and data acquisition (SCADA) and condition monitoring system (CMS) approaches for monitoring them. It then presents two up-to-date monitoring case studies, from different manufacturers and types of WT, using SCADA and CMS signals.

The first case study, applied to SCADA data, starts from basic laws of physics applied to the gearbox to derive robust relationships between temperature, efficiency, rotational speed and power output. The case study then applies an analysis, based on these simple principles, to working WTs using SCADA oil temperature rises to predict gearbox failure.

The second case study focuses on CMS data and derives diagnostic information from gearbox vibration amplitudes and oil debris particle counts against energy production from working WTs.

The results from the two case studies show how detection, diagnosis and prediction of incipient gearbox failures can be carried out using SCADA and CMS signals for monitoring although each technique has its particular strengths. It is proposed that in the future, the wind industry should consider integrating WT SCADA and CMS data to detect, diagnose and predict gearbox failures. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS

wind turbine; gearbox; condition monitoring; reliability; SCADA; oil temperature; vibration; oil debris

Correspondence

Dr. Yanhui Feng, School of Energy and Power Engineering, Nanjing University of Science and Technology, Nanjing, China.
E-mail: yanhui.feng@njust.edu.cn; fongyanfai@hotmail.com

Received 6 July 2011; Revised 12 April 2012; Accepted 19 April 2012

1. INTRODUCTION

The modern wind industry has experienced high gearbox failure rates compared to other wind turbine (WT) sub-assemblies for a variety of reasons[1] including the following:

- Underestimation of true operating loads.
- Unexpected overloads due to unusual operating conditions.
- Defective gearbox component design.
- Poor maintenance.

Wind turbine gearboxes are designed to IEC standards for a life of 20 years; however, most experience shorter lives. Over the last 2 decades, many lessons have been learnt by the industry to improve the reliability of gearboxes, one of the most expensive WT sub-assemblies. These steady improvements are confirmed by public database studies of WT reliability[2], but an LWK study shows that gearbox technology is mature and that WT gearboxes have a constant or slightly deteriorating service reliability due to wear and fatigue.[3] From a WT maintenance viewpoint, however, WT operators are concerned with gearbox reliability due to the following:

- High replacement costs following failure: the gearbox cost is about 13% of overall WT cost.
- High cost of removal of the gearbox from the WT and reinstallation because of the need for a crane.

- Complex repair procedures.
- High revenue losses due to long downtime between failure and repair completion.

The public surveys WMEP[4] and LWK, referred to by Spinato *et al.*,[3] showed that the gearbox exhibits the highest downtime per failure among all onshore WT sub-assemblies, whereas Gray and Watson[5] pointed out that the gearbox alone could be responsible for up to one-third of all lost WT availability. Data for a Netherlands offshore wind farm over a 3 year period have shown that once gearbox failures occurs, the downtime can be as high as 55.2% of the annual total and energy loss as high as 52.0% of annual production.[6–8] Reports for offshore wind farms in the UK have also shown some serious gearbox problems during early operation.[9] One of the factors contributing to the long WT gearbox downtime is that gearbox repair procedures are complex, particularly offshore, requiring not only special logistics such as a maintenance support vessel and crane ship, but also favourable weather conditions in order that the work can be carried out safely.

For large gear-driven WTs, most manufacturers use a three-stage design with a complex configuration as shown in Figure 1. The low-speed shaft (LSS) planetary gear stage comprises the planetary gears in a planet carrier coaxial with a sun gear and a ring gear. The planet gears rotate at the constant centres of the planet carrier. The low-speed input is from planet carrier driving motion via the planet gears to the sun gear. The intermediate-speed shaft (ISS) stage uses parallel helical gears as does the high-speed shaft (HSS), which is then coupled to generator drive end.

The benefit of any monitoring must be to provide detection, diagnosis and prognosis for an incipient fault, allowing time for the fault to be mitigated by maintenance, repair or replacement, as shown in Figure 2. This must be the purpose of any monitoring applied to WTs, including to the WT gearbox.

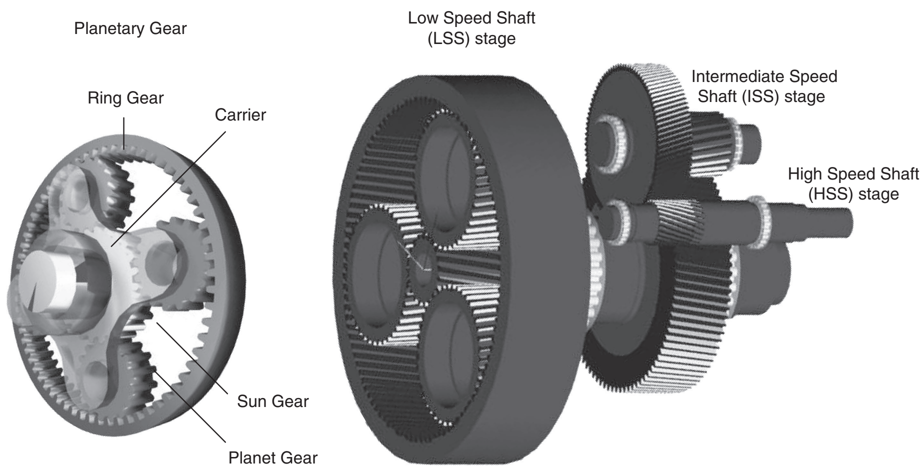

Figure 1. Three-stage WT gearbox with one planetary and two parallel stages.

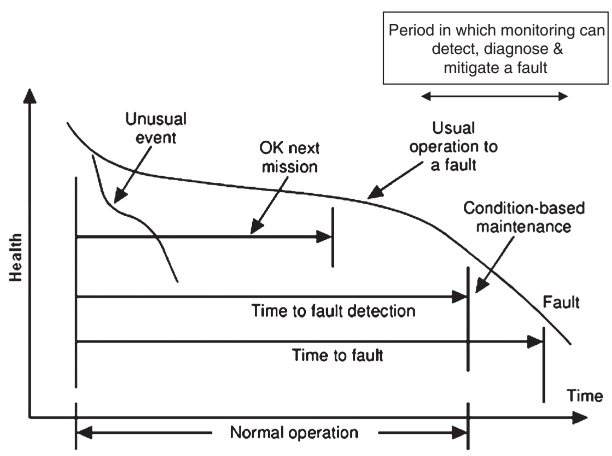

Figure 2. Progression of machinery to a failure showing monitoring benefit.

In response to gearbox reliability concerns, collaborations have been established between WT, gearbox and bearing original equipment manufacturers (OEMs), consultants and lubrication engineers to improve gearbox load prediction, design, manufacture and operation, for example, the gearbox reliability collaborative in the US.[1] Considering the potential costs and maintenance difficulties, WT OEMs and operators are adopting preventative maintenance strategies for WT gearboxes. Gearbox monitoring has therefore become an essential part of the whole WT condition monitoring (CM) programme to support the strategy, with vibration monitoring being the most popular CM approach for gearboxes despite technical challenges.[10–12]

A multi-parameter approach for CM electrical machinery was suggested by Tavner[13] to increase CM detection confidence and reduce false alarms, using the relationships between different signals. Additionally, proper analytical tools for these signals are also essential to extract signatures with the greatest impact on the diagnostic task. Feng and Schlindwein[14] showed that a two-dimensional diagnostic scheme based on two parameters (i.e. relative wavelet packets energy, total wavelet packets entropy) extracted from a signal had reduced errors when discriminating between several faults. There has been research into sub-assembly physics of failure, to generate good analytical models for CM. Recent WT research has focused attention on the most critical WT sub-assemblies, including the gearbox, generator, converter and pitch system; for example, Gray and Watson[5] predicted WT bearing failure based on a gearbox physics of failure model, Peng *et al.*[15] predicted the WT generator failure based on a non-linear state estimate technique. Qiu *et al.*[16] proposed and demonstrated two methods of SCADA alarm analysis, i.e. time-sequence and probability-based, to diagnose pitch and converter systems.

This paper concentrates on the gearbox, firstly by reviewing WT gearbox reliability and summarizing typical failure modes. It then reviews two measurement case studies, using first supervisory control and data acquisition (SCADA) and then condition monitoring system (CMS) data from WT gearboxes with known faults.

2. RELIABILITY OF WT GEARBOXES

To understand better the reliability of WT gearboxes, studies including reliability prediction and failure mode, effects and criticality analysis (FMECA) can be carried out. A good reliability prediction for WT gearboxes could only be achieved through collaboration between wind farm operators, WT, gearbox and bearing OEMs. General reliability principles for a three-stage gearbox were given by Smolders *et al.*[17] as follows:

- The high-speed parallel stage is found to be the least reliable gearbox module.
- A parallel intermediate-speed stage is more reliable than a the planetary intermediate-speed stage.
- A planetary intermediate-speed stage appears less reliable than a planetary low-speed stage.
- The lubrication system has an important effect on reliability.

On the other hand field observations have shown that most WT gearbox failures appear to initiate in the bearings rather than in the gears.[18] It was reported by Gray and Watson[5] that each gearbox bearing failure could result in an average downtime as high as 600 h. The most significant bearing failures are in the HSS, planetary and ISS bearings.[19] A major factor contributing to the complexity of the issue is related to the gearbox design process. Much of the bearing design–life assessment process is proprietary to the gearbox OEM and their bearing manufacturers. However, an intimate knowledge of WT loads and gearbox responses, contributing to unpredicted bearing behaviours, may not be well understood. Based on information collected from literature[1,17–19] including some FMECAs, five prominent WT gearbox failure modes are summarized as follows:

- Planetary gear failure.
- Planetary bearing failure.
- ISS bearing failure.
- HSS bearing failure.
- Lubrication system malfunction.

3. REVIEW OF METHODS FOR MONITORING WT GEARBOXES

In the early days of modern large WTs, they were not monitored apart from regular inspections. To monitor general operation of WTs, such as performance, SCADA systems were then installed. When WTs became large and expensive, complex CMS were added to improve protection of costly assets. Nowadays, many CMS systems focus on vibration signal interpretation to indicate WT gearbox health. A survey carried out by the UK Supergen Wind Energy Technologies Consortium[8] shows that out of 20 commercially available WT CMS, 14 systems provide gearbox vibration monitoring. Some experienced WT operators have successfully used these vibration-based techniques to detect incipient gearbox damage, ultimately avoiding gearbox failure. In contrast to SCADA systems, however, CMS are still not standardized. Hence, industry is trying to extend the application of standardized SCADA systems into component CM.

3.1. Review of SCADA signal analysis methods

The detection of WT gearbox faults using SCADA data was investigated by Zaher *et al.*[20] using anomaly detection. The technique was used to detect abnormally high temperatures based on data models. In practice, there were two problems related to these techniques: firstly, they generated poor models as the SCADA training data was noisy; secondly, it was not easy to convey information and interpret results making them unconvincing to WT specialists and managers. A physics of failure approach was proposed by Gray and Watson[5] for gearbox bearing failures. Theoretical damage models were developed to describe the relationship between WT operating environment, applied loads and the rate at which damage accumulated. Accurate estimates were then made in real time concerning the probability of specific failure modes or component failures.

Supervisory control and data acquisition system data is averaged and stored every 10 min. With a CMS sampling frequency up to 20 kHz, the raw data transmitted could be up to 12 million times the size of that stored by SCADA for a single acquisition channel. Large amount of CMS data collected from WTs are posing challenges to operators in aspects of data communications, processing, storage and interpretation. More details are explained in the next section. Complementary solutions, such as using SCADA data of slow sampling rate to analyse and predict gearbox faults, are useful to alleviate the task of manual analysis of CMS data. Once converted into algorithms, such analyses can be integrated into the SCADA system software, to provide efficient online monitoring at central SCADA locations, such as the wind farm control room.

3.2. Review of CMS signal analysis methods

The majority of commercially available CMS use time-domain or Fourier transform analysis of vibration signals for gearbox fault diagnosis.[11,12] Time and frequency-domain methods have certain limitations affecting their applicability to WT CMS, which are a direct result of WT operating conditions. Typical vibration monitoring sampling rates are around 10-20 kHz. Some CMS transmit complete time-domain signals for offline analysis in the operator database. However, a more common and lower bandwidth approach is to analyse signals locally in the WT CMS and only convey the resultant spectra or minute-averaged trends to the operator database. For machines operating at fixed speed and power, traditional time-trending is valid and allows users to examine deterioration accurately. For WTs operating at variable speed and power, signals such as vibration and gearbox oil debris particle counts that are related to variable power may not yield a clear result in time domain.

To counter this challenge, some CMS allow the operator to define power output and speed conditions at which signal spectra are recorded. As spectra are only recorded when these restricted conditions are met, signals are effectively stationary during analysis, resulting in comparable spectra over time. CMS can also create trend figures where the magnitude of fault-related frequencies are extracted and plotted over time. Once a vibration spectrum has been recorded, the CMS applies speed information to an established machine model to generate drive train specific cursors to overlay on the spectrum. This allows the user to relate fault-related spectral peaks to specific drive train components. However, even with diagnostic plots to reduce manual analysis, a large number of faults require the examination of complete spectra to see sidebands or harmonic trends that would otherwise be discounted. Once monitoring is carried out on large WT populations, the amount of manual examination increases dramatically and would be impractical for operators or maintainers unless the process is simplified further. In addition, the processing power required to calculate spectra for large WT populations becomes so significant that data handling and storage becomes an issue.

One major limitation of these and many other CMS techniques, however, is that interpretation relies on a single type of signal, with the potential for false alarms. Therefore, other signals collected from SCADA or CMS, such as oil debris counts, gear oil temperature or bearing temperatures, could be valuable in raising confidence in WT gearbox fault diagnosis and reducing false alarms. This is particularly relevant in circumstances where a manager needs to decide whether to shutdown a WT for specific maintenance action or launch a special investigation, which would lead to increased downtime.

3.3. SCADA and CMS measurement set-up

Wind turbine operators, or the WT OEM if the WT is still under warranty, continuously monitor SCADA alarms in real time, and SCADA signal data, normally sampled at high frequency then averaged over 10 min. Common gearbox-related SCADA measurements are as follows:[20]

- Gearbox sump oil temperature.
- Gearbox oil pressure.
- HSS bearing temperatures.

DOI: 10.1002/we

Common gearbox-related SCADA alarms are as follows:

- Gearbox bearing and oil temperatures.
- Running of the gearbox electrical oil pump.
- Filter status.

Gearbox oil pressure and oil filter status are related, for example, to the gearbox oil pump. Its pressure and the lubrication filters and are all monitored by SCADA. When the pump stops or the oil pressure is low or an oil filter choked, SCADA must trigger alarms to the operator because such failures can lead to catastrophic gearbox damage.

Wind turbine gearbox-related CMS signals come from two sources: vibration transducers and oil debris counters. The accelerometer positions for gearbox monitoring vary however an experienced WT operator, using the SKF WindCon CMS, records signals from four gearbox accelerometers[21,22] in positions that seem common among many vibration-based CMS:

- LSS end, transverse.
- HSS end, vertical.
- HSS end, transverse
- HSS end, axial.

A gearbox oil debris counter can be fitted to record both ferrous and non-ferrous particles of different sizes being circulated in the gearbox lubrication oil system. These particles are then filtered by the oil circulation system. By examining counts from ferrous and non-ferrous particle transducers, useful information for diagnosing whether a fault is developing

Table I. Relevant SCADA and CMS monitoring signals from a WT gearbox.

Monitorable failure modes	Planetary gear failure	Planetary bearing failure	ISS bearing failure	HSS bearing failure	Lubrication system malfunction
SCADA signals	Oil temperature	Oil temperature	Oil temperature	HSS bearing temperature	Oil pressure level, oil filter status
CMS signals	LSS vibration; non-ferrous particle oil debris counts	LSS vibration signal; ferrous particle oil debris counts	LSS or HSS vibration signals; ferrous particle oil debris counts	HSS vibration signals (vertical, transverse, axial); ferrous particle oil debris counts	
Additional signals	Rotor speed; generator speed; nacelle temperature; power output				

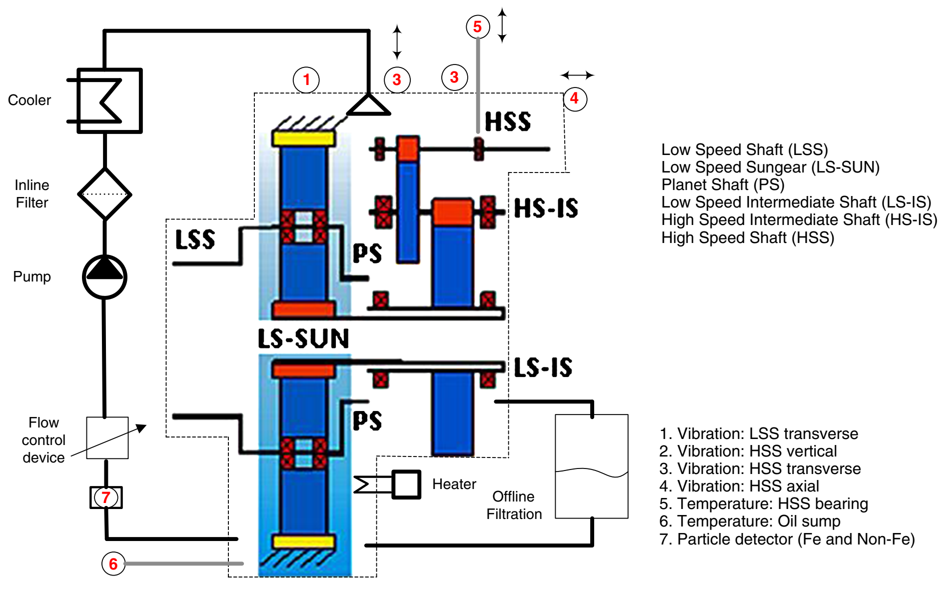

Figure 3. Arrangement of a WT gearbox showing measurement set-up.

in bearing rollers, bearing cages or gears could be found. However, detailed interpretation of oil particle data is tricky, and there are some practical difficulties in selecting suitable sampling size of particle.

Table I summarizes the commercial SCADA and CMS measurements useful for monitoring a WT gearbox. With the accelerometer set-up by Crabtree *et al.*[21] and by Feng *et al.*,[22] the transducers were mounted as close as possible to the gearbox HSS and LSS to get the best quality signals. The gearbox arrangement and transducer diagram is depicted in Figure 3. In this case, intermediate-shaft bearing failure is difficult to detect because of the lack of a local transducer.

4. FAILURE DETECTION AND PREDICTION FROM SCADA SIGNALS

As a key component of the WT drive train, the gearbox transmits kinetic energy from the turbine rotor to the generator by rotational speed and torque conversion. WT gearbox operation differs from that of conventional mechanical systems in that a stochastically varying torque is imposed. This is considered to be a major root cause for gear and bearing fatigue, driving gearbox failure modes and affecting gearbox life. Root cause analysis of gearbox failures requires detailed understanding of the effects of the operating environment and cumulative high and low cycle fatigue damage, using information from the gearbox and its neighbouring sub-assemblies, the rotor and generator, by analysis of kinetic energy transmission and heat losses. This can be simply achieved by monitoring the transmission efficiency and rotational speed, and relating them to the temperature rise to predict gearbox failure.

Based on the first law of thermodynamics, the input kinetic energy E to the gearbox can be physically expressed as the sum of output kinetic energy P_{GB}, and heat loss Q_{GB} multiplied by the duration $\bar{T}_i$ as shown in Figure 4:

$$E - Q_{\mathrm{GB}}\bar{T}_i = P_{\mathrm{GB}}\bar{T}_i \tag{1}$$

in which output kinetic energy from gearbox $P_{\mathrm{GB}}\bar{T}_i$ is approximately equal to output energy from generator $P_{\mathrm{Generator}}\bar{T}_i$, where $\bar{T}_i$ is a period of duration.

Supposing the gearbox efficiency is η_{GB}:

$$E = \frac{1}{\eta_{\mathrm{GB}}} P_{\mathrm{GB}}\bar{T}_i \tag{2}$$

Substituting equation (2) into equation (1) gives

$$Q_{\mathrm{GB}}\bar{T}_i = \left(\frac{1}{\eta_{\mathrm{GB}}} - 1\right) P_{\mathrm{GB}}\bar{T}_i \tag{3}$$

Since

$$Q_{\mathrm{GB}} = U_{\mathrm{GB}}\Delta T \tag{4}$$

where Q_{GB} the heat is generated from the gearbox, ΔT is the temperature rise of gearbox compared with nacelle temperature and U_{GB} is a compound heat transfer coefficient. Substituting equation (4) into equation (3) gives

$$\Delta T = \frac{1}{U_{\mathrm{GB}}}\left(\frac{1}{\eta_{\mathrm{GB}}} - 1\right) P_{\mathrm{GB}} \approx \frac{1}{U_{\mathrm{GB}}}\left(\frac{1}{\eta_{\mathrm{GB}}} - 1\right) P_{\mathrm{Generator}} \tag{5}$$

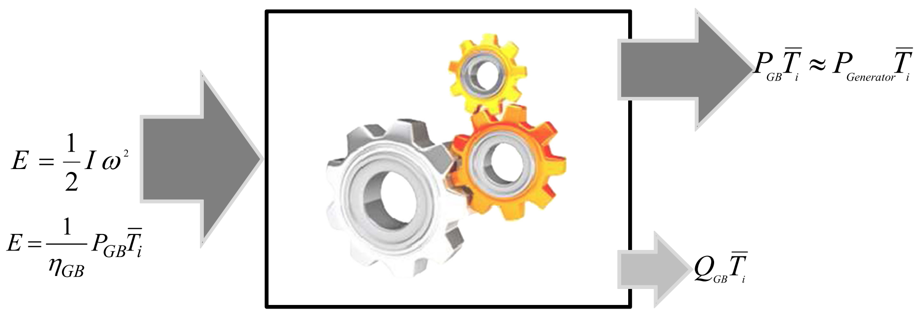

Figure 4. WT gearbox energy balance.

Equation (5) shows that the temperature rise of gearbox will be proportional to the generator power output $P_{\mathrm{Generator}}$, given an unchanged gear stage efficiency η_{GB}. At a certain power output, the efficiency η_{GB} for a healthy gearbox in ideal conditions is fixed; therefore, ΔT is proportional to $P_{\mathrm{Generator}}$. When a fault occurs in gearbox, equation (5) shows that ΔT should increase for the same power output $P_{\mathrm{Generator}}$ in response to an efficiency reduction.

Also, the rotational kinetic energy of a gearbox at planetary stage E with angular velocity ω_{Gear}, equal to rotor velocity, can be expressed in terms of the gear's moment of inertia I_{Gear} , combining equations (2) and (5):

$$E = \frac{1}{2} I_{\mathrm{Gear}} \omega_{\mathrm{Gear}}^2 \approx \frac{1}{\eta_{\mathrm{GB}}} P_{\mathrm{GB}} \bar{T}_i = \Delta T \frac{U_{\mathrm{GB}}}{1-\eta_{\mathrm{GB}}} \bar{T}_i \tag{6}$$

so that

$$\Delta T = \frac{I_{\mathrm{Gear}}}{2\bar{T}_i U_{\mathrm{GB}}} \omega_{\mathrm{Gear}}^2 (1-\eta_{\mathrm{GB}}) \tag{7}$$

Since I_{Gear}, U_{GB}, $\bar{T}_i$ for a gearbox stage are constants, then equation (7) shows that gear stage inefficiency $1-\eta_{\mathrm{GB}}$ will be proportional to $\Delta T / \omega_{\mathrm{Gear}}^2$. When a fault occurs in a gear stage, ΔT should increase in response to an efficiency reduction.

In the following, these equations have been used on retrospective SCADA data from a 2 MW class variable-speed WT in three successive identical length periods: 9 months before a failure, 6 months before the failure and 3 months before the failure. In this case, according to the maintenance record, a catastrophic WT gearbox planetary gear failure occurred at the time of breakdown. The WT output power was normalized to the rated power as P_N and assumed proportional to the

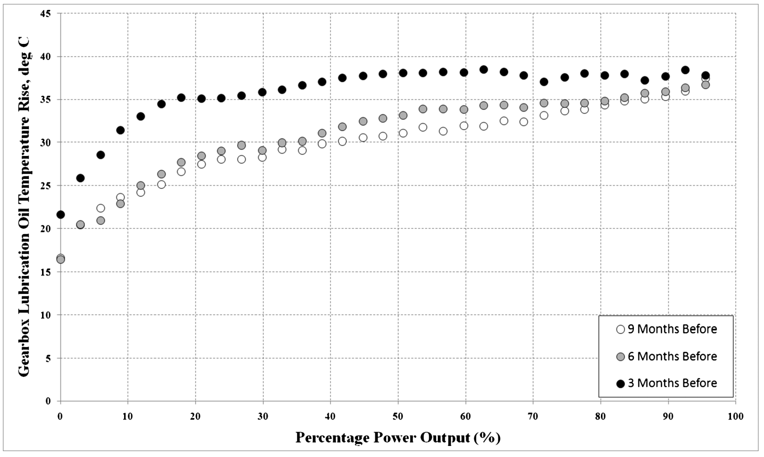

Figure 5. Gearbox oil temperature rise trend, ΔT, versus relative power output.

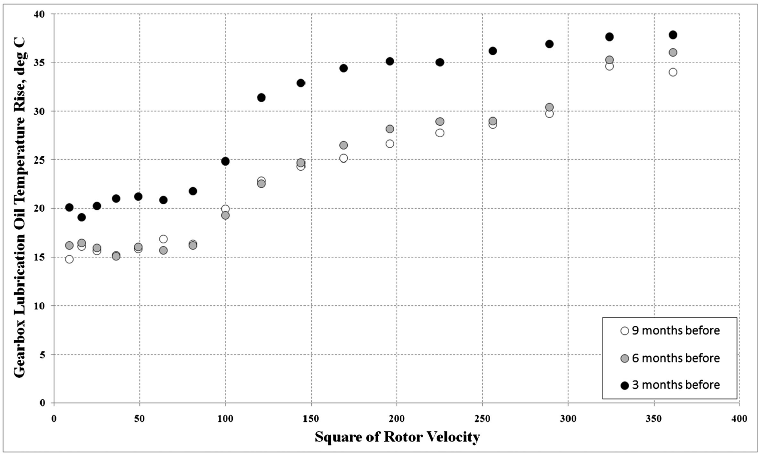

Figure 6. Gearbox oil temperature rise trend, ΔT, versus square of rotor velocity, ω_{gear}^2.

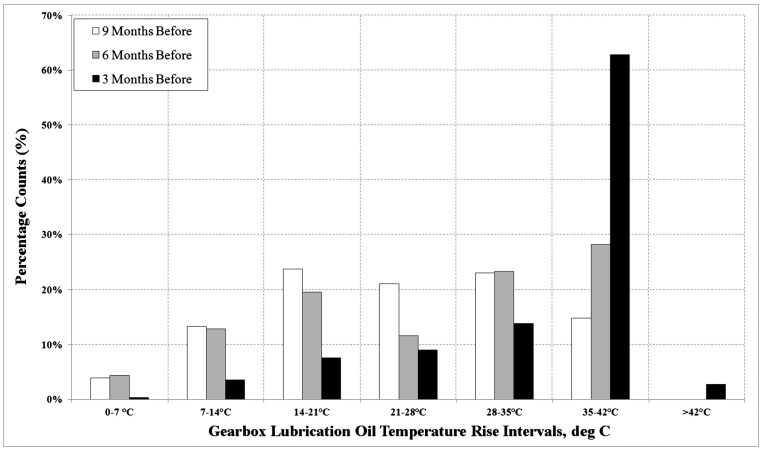

Figure 7. Histogram of frequencies of gearbox oil temperature rises, ΔT.

gear temperature rise ΔT according to equation (5). Figure 5 shows the gearbox oil temperature rise against relative power output (%). In this figure, the binning average of gearbox oil temperature rise was taken for each 50 kW power output increment in those three periods. The binning average means data collected at the same period and power output range are aggregated and averaged.

Figure 6 shows the binned average of temperature rise ΔT plotted against the square of rotor velocity ω_{Gear}^2 at the time the SCADA measurement was made. The use of variable ω_{Gear}^2 along x-axis in figure is explained in equation (7). In Figure 6, the data for the 3 months period preceding the breakdown show a worsening situation, which agrees with the prediction made by equation (7).

Figure 7 shows the histogram of gearbox oil temperature rise for the three periods. Both Figures 5 and 7 clearly show a rising gearbox inefficiency in the 9 months before failure with a worsening trend presented 3 months before failure. The results in Figure 6 are showing good agreement to the theoretical prediction based on equation (7), which has demonstrated clearly that slow speed SCADA data is perfectly suitable for the long-term detection of gearbox problems.

5. FAILURE DIAGNOSIS FROM CMS SIGNALS

In this case study, an operator deployed the WindCon CMS on its 1.3 MW two-speed WT fleet and achieved success in detecting a number bearing faults in both gearboxes and generators. In one example, the operator detected a gearbox ISS bearing fault using spectral analysis, triggered by a change in vibration envelope amplitude, that is obtained by amplitude demodulation of the raw, time-domain, vibration signal. The results below were again taken retrospectively from the CMS to show how a fault can be detected using multiple signals to improve detection confidence and using cumulative energy instead of the conventional signal time axis.

Figure 8 shows the gearbox-enveloped HSS axial vibration amplitude signal plotted against time and energy, respectively. There are two major points to notice. Firstly, the fault developed over a period of 90 days, which is 3 months. Secondly, periods of zero generation, apparent in Figure 8(a), for example, during bearing replacement, are removed when plotted against energy. These zero generation periods reduce to a single point, allowing changing vibration trends to be clearer making overall trends more defined, simplifying signal interpretation.

Figure 9 shows that the effect is more pronounced for the particle generation rate, represented by the gradient in the figure, which does not necessarily change instantaneously for a WT operating at variable load. This is because the particle generation rate may be masked by periods of high, low or zero load. Since more particles are generated at higher than lower load, it is useful to plot oil debris counts against energy generated as in Figure 9(b). This figure shows smoother trends and can be compared directly with vibration signals, such as Figure 8 without the issues associated with variable load operating conditions.

Figure 10 shows the energy domain plot of gearbox HSS axial vibration envelope and oil debris count. Three distinct regions are marked in Figure 10(a); during period ‘A’, the enveloped vibration increases with the energy generated. This appears to give a clear indication that a fault is present; however, confidence is reduced as the WT passes into period ‘B’ when vibration decreases, suggesting that the fault may have disappeared. Depending on how alarms are set, it is possible for an inexperienced operator to assume that the signal is simply subject to high variability; therefore, to be sceptical of taking a maintenance decision based on this single signal or simple alarm rule. The verification of other signals would

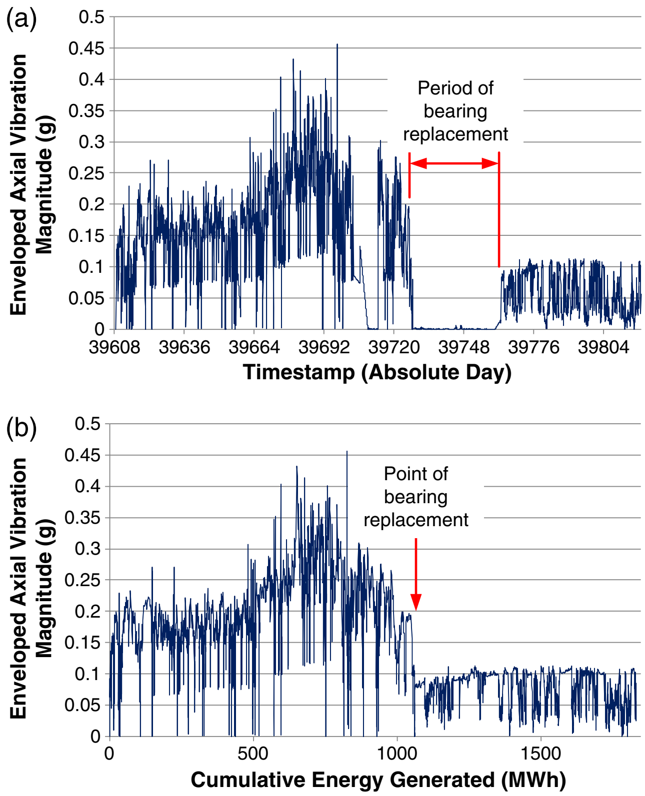

Figure 8. Gearbox HSS axial vibration amplitude envelope against (a) absolute date stamp and (b) cumulative energy generated.

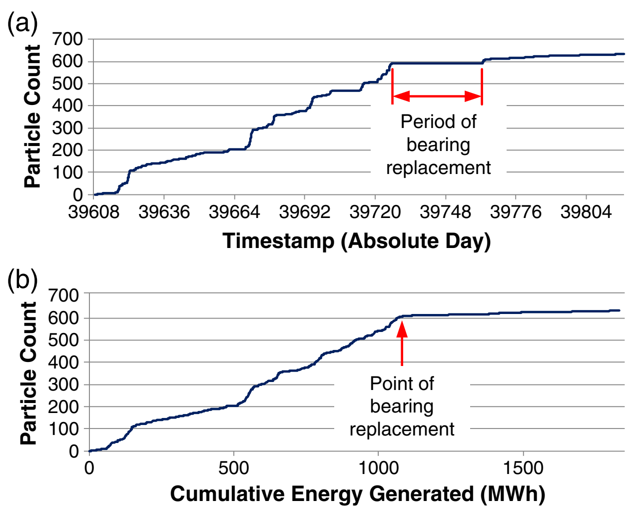

Figure 9. Gearbox cumulative oil debris count for ferrous particles 100–200 μm plotted against (a) absolute date stamp and (b) cumulative energy generated.

be advantageous. Figure 10(b) shows the 50–100 μm ferrous particles counted in the gearbox oil system and a noticeable increase in the average rate of particle generation can be seen, corresponding with vibration decrease during period 'B'. The cumulative particle counts of 100–200 μm and 200–400μm ferrous particles, Figure 10(c),(d), respectively, both indicate a marked increase in particle generation rate in period 'B' (i.e. at increasing gradient) suggesting that a fault is still present and has become more serious.

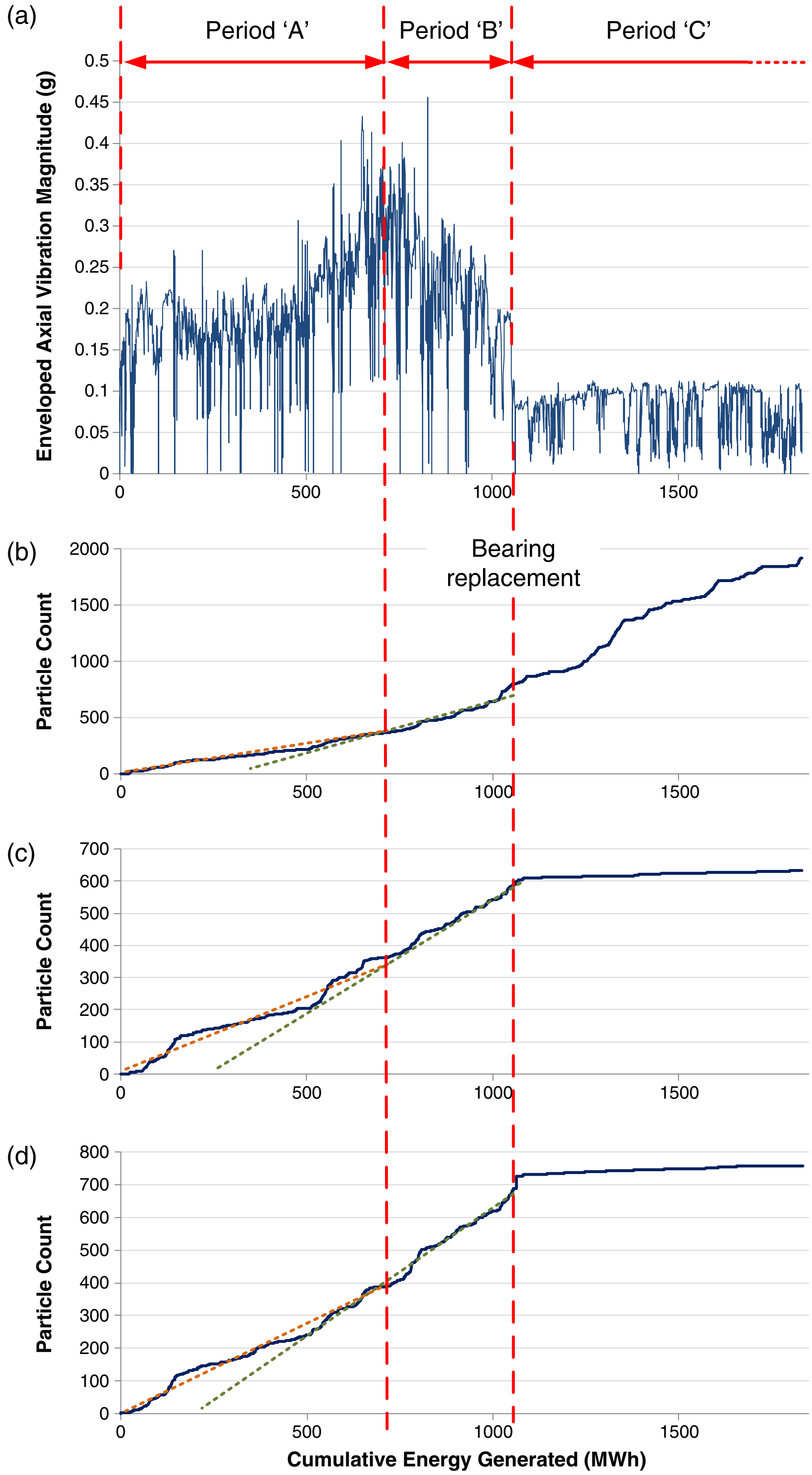

Figure 10. (a) Gearbox-enveloped high-speed end axial vibration and gearbox cumulative oil debris count for ferrous particles (b) 50–100 μm, (c) 100–200 μm, (d) 200–400 μm plotted against cumulative energy generated.

The increasing particle generation rate and vibration in period 'A' may provide an early indication of the fault from independent signals, and the diagnosis is confirmed when entering period 'B' because of the fact that independent signals change simultaneously. The increasing rate of large particle generation in period 'B' suggests significant material breakout from the ferrous part of the bearing, rollers and bearing races. The corresponding decrease in enveloped vibration suggests that the vibration transmission path is deteriorating, indicating bearing deterioration due to material breakout.

This hypothesis was confirmed by a subsequent visual inspection, leading to the replacement of the gearbox ISS bearing. A large amount of surface pitting and material breakout had occurred from the ISS bearing inner race. The post-incident root cause analysis of the failure mechanism was useful here to improve understanding. Since the failure occurred to the ISS bearing, breakout from the inner race would hinder torque transmission from the LSS to HSS shafts, contributing to the HSS axial vibration envelope reduction.

Period 'C' of Figure 10(a) shows that the vibration envelope magnitude reduced significantly following maintenance. The cumulative 100–200 μm and 200–400 μm ferrous particle counts, Figure 10(c),(d), also reduced during period 'C' in line with the vibration decrease. However, the 50–100 μm ferrous particle count increased during the same period, probably as a result of particle generation during the new bearing wear-in period. This analysis suggests that the 100–200 μm particle counts are probably more useful than the smallest particle counts, 50–100 μm, when examining the development of gearbox bearing failures.

6. DISCUSSION

Previous work has shown that gearbox monitoring should concentrate on the following:

- Planetary, ISS and HSS stage bearings.
- Planetary stage gears.
- Lubrication system.

Two case studies on retrospective data from two different large WT types, 2 MW class variable-speed and 1.3 MW two-speed, have shown that faults in gearboxes and their bearing can be detected using both SCADA and CMS data many days or even months before failure.

One issue around SCADA or CMS data interpretation is that relying on a single signal or analysis method could lead to false alarms from the monitoring process. Temperature, vibration and oil debris all reflect the condition of a WT gearbox from different viewpoints, and there are both pros and cons concerning their use for gearbox health interpretation. For example, the oil temperature rise of a WT gearbox is not only related to transmission efficiency, but also those of heaters, coolers and pumps. The failure of those components could be a gearbox failure root cause. Similarly, vibration is sensitive to dynamic changes in local rotating components, so signal quality depends heavily on the mounting location of the transducer. Modern WT gearboxes may have a highly integrated design, so it is not always easy to find the 'best' location for transducer mounting. Oil debris could indicate early failures, but the signal is poor for the locating of failures or tracing the root cause.

It would be sensible to consider both SCADA and CMS data together to support a comprehensive WT gearbox monitoring strategy. However, this may prove difficult due to the fact that CMS and SCADA systems currently store data independently and in their own formats. CM specialists then find it hard to gain access to both datasets and obtain a complete solution. Difficulties also arise because of confidentiality conflicts between operators and WT OEMs, especially during the warranty period.

In the longer term, these issues must be resolved by the industry in order to achieve greater integration of data coming from WTs allowing the industry to benefit from increased WT availability and a reduced cost of energy.

7. CONCLUSIONS

This paper has presented analyses of SCADA and CMS monitoring signals of WT gearboxes in case studies on retrospective data from 2 MW class variable speed and 1.3 MW two-speed WTs with gearbox faults, with the following conclusions:

- Prominent WT gearbox failure modes include planetary gear and bearing failure, intermediate-shaft bearing failure, HSS bearing failure and lubrication system malfunction.
- The SCADA signal case study on a 2 MW class variable-speed WT has shown that by monitoring gearbox oil temperature rise, power output and rotational speed, a gearbox planetary stage failure could be predicted and detected.
- The CMS signal case study using vibration, oil debris and power signals from a 1.3 MW, two-speed WT showed that analysis of large oil debris particle counts and vibration signals plotted against cumulative energy generated was able to diagnose a gearbox ISS bearing failure.

- Since the use of multiple signals or analyses can support accurate diagnosis, the approaches developed in the two case studies could be used alongside one another to raise confidence in the diagnostic conclusions made and reduce false alarms.
- Early WT gearbox fault mitigation is enhanced by the integration of SCADA and CMS data aimed at detecting root causes.

ACKNOWLEDGEMENTS

This work was funded by the EU FP7 Project RELIAWIND 212966 and the UK EPSRC Wind Energy Technologies Consortium, EP/D034566/1. The authors would like to thank RELIAWIND and Supergen Wind project partners, anonymous reviewers for useful discussions and suggestions.

REFERENCES

1. Musial W, Butterfield S, McNiff B. Improving wind turbine gearbox reliability, *EWEC 2007*, Milan, May 2007; 7–10.
2. Tavner PJ, Xiang JP, Spinato F. Reliability analysis for wind turbines. *Wind Energy* January 2007; **10**(1): 1–18.
3. Spinato F, Tavner PJ, van B G J W, Koutoulakos E. Reliability of wind turbine subassemblies. *IET Renewable Power Generation* 2009; **3**(4): 1–15.
4. Faulstich S *et al.* Windenergie Report Deutschland 2008, Institut für solare Energieversorgungstechnik (Hrsg.), Kassel, 2008. http://windmonitor.iwes.fraunhofer.de/wind/download/Windenergie_Report_2008_de.pdf, Access 1 January 2012.
5. Gray C, Watson S. Physics of failure approach to wind turbine condition based maintenance. *Wind Energy* July 2010; **13**(5): 395–405.
6. Noordzee Wind Various Authors. Operations Report 2007. Document No. OWEZ_R_000_20081023, October 2008, http://www.noordzeewind.nl/wp-content/uploads/2012/02/OWEZ_R_000_20081023-Operations-2007.pdf, accessed on May 2012.
7. Noordzee Wind Various Authors. Operations Report 2008. Document No. OWEZ_R_000_ 200900807, August 2009, http://www.noordzeewind.nl/wp-content/uploads/2012/02/OWEZ_R_000_20090807-Operations-2008.pdf, accessed on May 2012.
8. Noordzee Wind Various Authors. Operations Report 2009. Document No. OWEZ_R_000_20101112, November 2010, http://www.noordzeewind.nl/wp-content/uploads/2012/02/OWEZ_R_000_20101112_Operations_2009.pdf, accessed on May 2012.
9. Feng Y, Tavner P, Long H. Early experiences with UK round 1 offshore wind farms. *Proceedings of the ICE - Energy* 01 November 2010; **163**(4): 167–181.
10. Crabtree CJ. Survey of commercially available condition monitoring systems for wind turbines. Version 5, 2 November 2010, http://www.supergen-wind.org.uk/docs/Survey%20of%20commercially%20available%20CMS%20for%20WT.pdf, accessed on 1 January 2012.
11. Crabtree CJ. *Condition monitoring techniques for wind turbines*, PhD thesis, Durham University. Febuary 2011, http://etheses.dur.ac.uk/652/1/2011-Christopher_Crabtree_PhD.pdf?DDD10, accessed on 1 January 2012.
12. Yang W, Tavner PJ, Crabtree CJ, Feng Y, Qiu Y. Wind turbine condition monitoring: technical and commercial challenges. *Wind Energy* 2012; DOI: 10.1002/we.1508.
13. Tavner PJ. A review of condition monitoring of rotating machines. *IET Electrical Power Applications* 2008; **2**(4): 215–247.
14. Feng Y, Schilindwein FS. Normalized wavelet packets quantifiers for condition monitoring. *Mechanical Systems and Signal Processing* April 2009; **23**(3): 712–723.
15. Guo P, Infield D, Yang X. Wind turbine generator condition-monitoring using temperature trend analysis. *IEEE Transactions on Sustainable Energy* January 2012; **3**(1): 124–133.
16. Qiu Y, Feng Y, Tavner PJ, Richardson P, Erdos G, Chen BD. Wind turbine SCADA alarm analysis for improving reliability. *Wind Energy* 2011. DOI: 10.1002/we.513.
17. Smolders K, Long H, Feng Y, Tavner P. Reliability analysis and prediction of wind turbine gearboxes, *Proceedings of the Scientific Track of the European Wind Energy Conference*, Warsaw, 20-23 April EWEC 2010; 162–165.
18. Skriver S. Determining a strategy for Managing Gearboxes and Spare Parts. *Wind Farm O&M 2010, Glasgow* 16–17 June 2010.

19. McVittie D. Wind turbine gearbox reliability: the nature of the problem, GRC 2008. USA, http://windpower.sandia.gov/2006reliability/tuesday/14-brianmcniff.pdf, assessed on 1 January 2012.
20. Zaher A, McArthur SDJ, Infield DG, Patel Y. Online wind turbine fault detection through automated SCADA data analysis. *Wind Energy* September 2009; **12**(6): 574–593.
21. Crabtree CJ, Feng Y, Tavner PJ. Detecting incipient wind turbine gearbox failure: a signal analysis method for on-line condition monitoring, *Proceedings of the Scientific Track of the European Wind Energy Conference*, Warsaw, 20-23 April EWEC2010; 154–156.
22. Feng Y, Qiu Y, Crabtree CJ, Long H, Tavner P J. Use of SCADA and CMS signals for failure detection and diagnosis of a wind turbine gearbox, *Proceedings of the Scientific Track of the European Wind Energy Association Conference*, Brussels, 14-17 March EWEA2011; 17–19.