EWEA 2011 BRUSSELS
EUROPE'S PREMIER WIND ENERGY EVENT

USE OF SCADA AND CMS SIGNALS FOR FAILURE DETECTION AND DIAGNOSIS OF A WIND TURBINE GEARBOX

Yanhui Feng, Yingning Qiu, Christopher J Crabtree, Hui Long, Peter J Tavner
Energy Group, School of Engineering and Computing Sciences, Durham University, UK.
yanhui.feng@durham.ac.uk

Abstract:

This paper has summarised the typical principal failure modes of WT gearbox and relevant SCADA & CMS measurements for health monitoring. Starting with the basics of heat and temperature, it derives the relationship between temperature, efficiency, and power output or rotational speed based on the first law of thermodynamics. This then leads to a new algorithm based on SCADA oil and bearing temperature measurements to detect gearbox failures. The second case study focuses on extracting diagnostic information from both the enveloped amplitude and oil debris particle count against energy generated of WT. The results show that the analysis of SCADA signals using simple algorithms can give early warning of failures in gearboxes and that analysis of CMS signals can locate and diagnose failures with detailed information. It is suggested that in future WT monitoring systems both SCADA and CMS signals should be used to detect faults and schedule maintenance.

Keywords: Gearbox failure, Wind turbine, SCADA, CMS

1 Introduction

From its inception the modern wind industry has experienced high gearbox failure rates due to design defects and an underestimation of operating loads [1]. Over the last two decades, lessons have been learnt in the industry to improve the gearbox reliability, one of the most costly subassemblies in the WT and most expensive to replace. These steady improvements in wind turbine (WT) reliability are confirmed by studies from public databases, which have shown that for a variety of WT configurations, gearboxes are a mature technology with a constant or slightly deteriorating failure rate with time [2][3]. Nevertheless, the public databases also show that the gearbox exhibiting one of the highest downtimes per failure of all the onshore WT subassemblies [4].

Some general principles on the reliability of a three stage gearbox, from a designer's view, are outlined as follows [7]:

- The high speed parallel stage is found to be the most unreliable module, due to its high speed operation.
- A parallel intermediate speed stage is more reliable than a planetary intermediate speed stage, due to fewer components compared to a planetary stage.
- The planetary intermediate speed stage appears to be less reliable than the planetary low speed stage due to the fact that the intermediate stage has a higher speed.
- The lubrication system has an important effect on reliability.

On the other hand, field observations have been made showing that most of the WT gearbox failures appear to initiate in the bearings rather than in the gears [1]. It is

Failure Modes of WT Gearbox	Planetary gear failure	Planetary bearing failure	Intermediate shaft bearing failure	High speed shaft bearing failure	Lubrication system malfunction

Table 1: Typical principal failure modes of WT gearbox from [1],[7],[8],[9] and [13].

reported that each bearing failure could result in an average downtime as high as 600 hours [13]. The hot spots of bearing failures are the high speed shaft bearing, planetary bearing and intermediate shaft bearing [9]. 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 bearing manufacturer. However, the broad or intimate knowledge of WT gearbox loads and responses that may be contributing to unpredicted bearing behaviours might not have been well understood.

Table 1 summarises the principal typical failure modes of WT gearboxes, based on the information collected from the literature [1],[7],[8],[9] and [13].

2 WT Gearbox Monitoring

A survey carried out by the UK Supergen Wind consortium shows that, among 18 commercially available Condition Monitoring Systems (CMS) for WTs, 12 systems provide vibration monitoring for the gearbox [10]. The majority of commercially available condition monitoring systems use Fourier transform or time domain analysis of vibration signals for gearbox fault diagnosis [10]. Information from other CMS or SCADA signals, such as oil debris counts, gear oil or high speed shaft bearing temperatures or alarms from the gearbox lubrication system, can be valuable to help diagnose WT gearbox faults and support maintenance decisions.

For a typical vibration monitoring system, sampling rate is 20k Hz and the whole data are stored for off-line analysis, while for SCADA system, data are normally averaged and stored in every 10 minutes; the data stored by CMS will be 12 million times of those stored by SCADA for a single acquisition channel. Therefore, wind industry is getting more and more interested in the studies using SCADA data to detect gearbox failure and some research results have proven their effectiveness for health monitoring. For example, the fault detection of Gearbox based on SCADA data is discussed in [11] with the anomaly-detection techniques. The techniques build up data models based on the available data and then use the models to detect abnormally high temperatures. In practice, there are two issues related to these techniques: firstly, they will generate poor models if the training data are noisy, which is true in SCADA data; secondly, it is not easy to convey information and interpret results to make them convinced to WT specialists and managers.

Table 2 has summarised some relevant SCADA data and CMS measurements could be useful for health monitoring of a WT

Failure Modes for Monitoring	Planetary gear failure	Planetary bearing failure	Intermediate shaft bearing failure	High speed shaft bearing failure	Lubrication system malfunction
SCADA data	Oil temperature signals	None	None	HSS bearing temperature signals	Oil pressure level, oil filter status
CMS signals	LSS end vibration signal; Oil debris counts of Non-Ferrous particles	LSS end vibration signal; Oil debris counts of Ferrous particles	LSS or HSS end vibration signals; Oil debris counts of Ferrous particles	HSS end vibration signals (vertical, transverse, axial); Oil debris counts of Ferrous particles	
Additional signals	Rotor speed; Generator speed; Nacelle temperature; Power output				

Table 2: Relevant SCADA & CMS measurements for Health Monitoring of WT Gearbox from [10],[11] and [12].

gearbox. With the setup of accelerometers in [12], the transducers are mounted as close as possible to the high speed and low speed end of gearbox to get the best quality of signals. In this case, the failure of an intermediate shaft bearing is quite difficult to detect.

3 Case Study on SCADA Signals

As a key component of the drive train of a wind turbine, the gearbox functions to transmit the kinetic energy received by the rotor to the generator through rotational speed and torque conversion. Gearbox designs for wind turbine applications differ from those used in conventional mechanical machines in that a variable load is imposed. This is considered as the main cause of fatigue in gears and bearings, affecting the lifetime of the gearbox. Root cause analysis of gearbox failures requires detailed understanding of the effects of the operating environment and the cumulative high cycle as well as low cycle fatigue damage. With all the considerations above and through analysis of the available SCADA data, detecting gearbox failure requires information provided by its neighbouring sub-assemblies such as the rotor and generator. Through detailed analysis of the physical procedure of kinetic energy transmission and dissipation, an algorithm monitoring the transmission efficiency by relating the temperature rise and the rotational speed on the different shaft stages is derived and used to detect failure of the gearbox.

3.1 Physical Description

It is assumed that the heat generated on a gear or bearing is proportional to the work done on them, which means:

$$Q \propto W \propto \Delta T \qquad (1)$$

in which *Q* is the heat generated from the gearbox gear or bearing, *W* is the work done on it, and ΔT is the temperature rise on the gearbox gear or bearing compared to the nacelle temperature.

The work done by the gear can be physically expressed as:

$$W = \frac{1}{2} I \omega^2 \cdot \qquad (2)$$

Supposing the gear efficiency is η_{Gear} and the bearing is efficiency η_{Brg}, the energy dissipated will be transferred as heat onto the gear or the bearing. Therefore:

$$Q_{Gear} = (1 - \eta_{Gear}) \frac{1}{2} I_{Gear} \omega_{Gear}^2 = k_{Gear} \Delta T_{Gear}, \qquad (3)$$

or:

$$Q_{Brg} = (1 - \eta_{Brg}) \frac{1}{2} I_{Brg} \omega_{Brg}^2 = k_{Brg} \Delta T_{Brg} \cdot \qquad (4)$$

Also written as:

$$1 - \eta_{Gear} = \frac{2 k_{Gear} \ \Delta T_{Gear}}{I_{Gear} \ \omega_{Gear}^2}, \qquad (5)$$

or:

$$1 - \eta_{Brg} = \frac{2 k_{Brg} \ \Delta T_{Brg}}{I_{Brgr} \ \omega_{Brg}^2}. \qquad (6)$$

As $2k / I$ is constant for a gear or bearing, the inefficiency of the gear $(1 - \eta_{Gear})$ or bearing $(1 - \eta_{Brg})$ is proportional to $\Delta T_{Gear} / \omega_{Gear}^2$ or $\Delta T_{Brg} / \omega_{Brg}^2$, respectively.

Assume that the rest of the kinetic energy transmitted through gearbox will be turned into power P_{out} by a generator such that:

$$P_{out} = W - Q_{Gear}, \qquad (7)$$

then:

$$P_{out} = \eta_{Gear} \frac{1}{2} I_{Gear} \omega_{Gear}^2 \cdot \qquad (8)$$

By comparing the two equations (3) and (8), we have:

$$\frac{1-\eta_{Gear}}{\eta_{Gear}} = k_{Gear}\frac{\Delta T_{Gear}}{P_{out}}, \tag{9}$$

or:

$$\Delta T_{Gear} = P_{out}\frac{1}{k_{Gear}}(\frac{1}{\eta_{Gear}}-1). \tag{10}$$

Equation (10) shows the temperature rise of the gear will be proportional to the power output P_{out}, provided the gear efficiency η_{Gear} has not changed. The efficiency η_{Gear} is sensibly constant for a healthy gearbox, therefore ΔT_{Gear} is proportional to power output P_{out} in ideal conditions. When a fault occurs in the gear, the efficiency decreases, so ΔT_{Gear} will have extra increase for a certain power output P_{out}.

3.2 Validation

Results using the algorithms above to detect a gearbox planetary gear failure are shown in the Figures below. The WT output power is normalized to the rated power PN. The gearbox oil temperature rise is assumed proportional to gear temperature rise. Figure 1 shows the gearbox oil temperature rise against relative power output (%) in three periods: 9 months, 6 months and 3 months before the known failure. Figure 2 shows the binning of average gearbox oil temperature rise for each 50kW increment of power output in those three corresponding periods. Figure 3 shows the histogram of gearbox oil temperature rise in the three periods. Figure 1 and 2 clearly show the rise in WT gearbox inefficiency in the 3 months before the failure. Observable trends are available 6 months before the failure, as confirmed by the histogram in Figure 3.

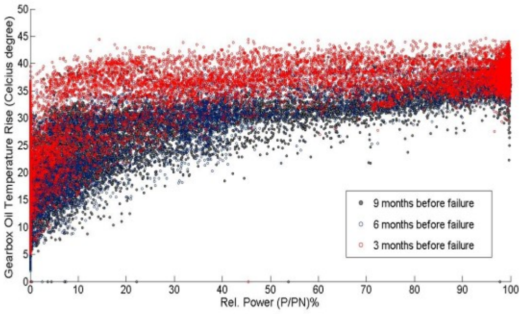

Figure 1: Gearbox oil temperature rise against relative power output.

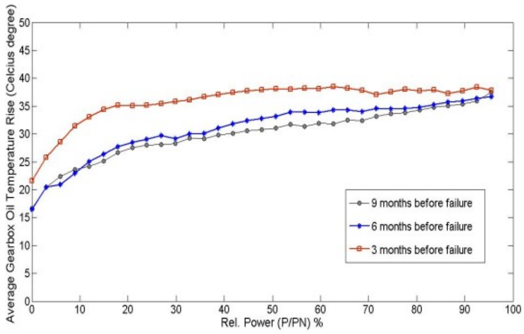

Figure 2: The trends of Gearbox oil temperature rise against relative power output.

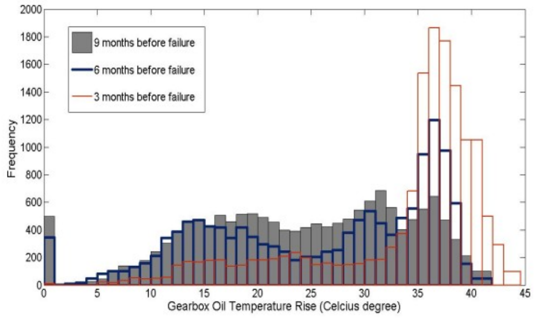

Figure 3: Histogram of Gearbox oil temperature rise.

4 Case Study on CMS Signals

Figure 4 shows the envelope amplitude of axial vibration at the High Speed Shaft (HSS) bearing of the gearbox, and oil debris particle count binned for each 50MWh increment of output energy generated, normalised to Energy Generated. This representation is similar to the information plotted against time domain but eliminates the effect of turbine stops, different power output conditions, and highlights vibration and oil debris rates of change.

In period 'A' vibration and debris particle count are both rising steadily, suggesting that although a fault may be present, it is not yet at a serious stage. Since the rate of generation of ferrous oil debris remains fairly constant, it might be assumed that the fault occurring on a bearing is not deteriorating too much. In contrast, during period 'B' the oil debris count rate is constantly increasing, as shown by the dashed lines. The same time there is a significant change in the vibration envelope, figure 4, appears to suggest that the faulty bearing began to deteriorate significantly between periods ‘A’ and ‘B’. It is believed that the decrease in vibration may be due to the breakdown of the vibration transmission path due to serious bearing damage and this is confirmed by the inspection during the maintenance. After inspection of the gearbox the intermediate shaft bearing was replaced and it was found that the bearing is serious damaged and, the cage is broken.

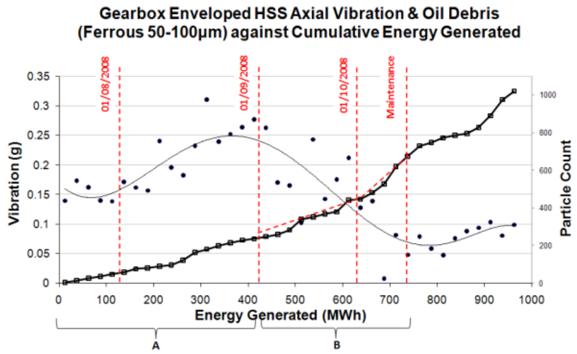

Figure 4: Gearbox enveloped HSS axial vibration (circle) & Ferrous 50-100 µm oil debris (square) against WT energy generated.

It can be seen from Figure 4 that a fault could be noticed at an early stage, during period ‘A’ and that the fault extends (i.e. bearing cage is broken) during period ‘B’ where two independent signals both show a simultaneous change. Since defect occurred to the inner race of an intermediate shaft bearing, the defect could hinder the gearbox to transmit torque from low speed shaft to high speed shaft, leading to the reduction of vibration at high speed end.

5 Discussion

These results show that the analysis of SCADA signals using simple algorithms can give early warning of failures in gearboxes and that analysis of CMS signals can locate and diagnose failures with detailed information. The suggestion is that in future WT monitoring systems both SCADA and CMS signals should be used to detect faults and schedule maintenance.

6 Conclusions

In summary, the following conclusions can be drawn:

- Typical WT gearbox failure modes include planetary gear failure, planetary bearing failure, intermediate shaft bearing failure, high speed shaft bearing failure and lubrication system malfunction.
- The physical explanations based on energy balance are described to support a detection algorithm based on SCADA oil and bearing temperature measurements.
- A case study on a 2 MW variable speed WT confirm that oil, bearing & nacelle temperatures and power output SCADA signals can be used to detect planetary gear failure providing 3 months warning.
- A case study on a 1.5 MW 2 speed WT also shows that the analysis of CMS oil debris particle count and vibration signals together and energy generated successfully diagnosed a gearbox ISS bearing fault providing 3 weeks warning.

Acknowledgements

This work was funded by the UK EPSRC Supergen Wind Energy Technologies Consortium EP/D034566/1 and the EU FP7 Project ReliaWind 212966. The authors would like to thank RELIAWIND and Supergen Wind project partners for their, discussion on practical experiences and for their suggestions on relevant work.

References

[1]. Musial, W., Butterfield, S., McNiff, B., Improving Wind Turbine Gearbox Reliability, EWEC 2007, Milan, Italy, May 7–10, 2007.

[2]. Spinato F., Tavner P.J., van Bussel G.J.W., Koutoulakos E. Reliability of wind turbine subassemblies, IET Renewable Power Generation, Vol. 3, Iss. 4, pp. 1–15, 2009.

[3]. Tavner P.J., Xiang J.P., Spinato F. Reliability analysis for wind turbines, Wind Energy, 10(1), July 2006.

[4]. Faulstich, S. et al.: Windenergie Report Deutschland 2008, Institut für solare Energieversorgungstechnik (Hrsg.), Kassel, 2008.

[5]. Tavner P.J., A review of condition monitoring of rotating machines, IET Electrical Power Applications, 2008, Vol. 2, No. 4, pp. 215–247.

[6]. Various Authors, Operations Report 2007, Document No. OWEZ_R_000_20081023, Noordzee Wind, October 2008.

[7]. Smolder K, Long H, Reliability Analysis and Prediction of Wind Turbine Gearboxes, EWEC 2010, Warsaw.

[8]. Strange Skriver, Determining a strategy for Managing Gearboxes and Spare Parts, Wind Farm O&M 2010, Glasgow, 16-17 June, 2010.

[9]. Don McVittie, Wind Turbine Gearbox Reliability: The Nature of the Problem, GRC 2008, USA.

[10]. Chris Crabtree, Survey of Commercially Available Condition Monitoring Systems for Wind Turbines (version 4), 24 May, 2010.

[11]. Zaher, A, McArthur, S, Infield, D, Patel, Online Wind Turbine Fault Detection through Automated SCADA Data Analysis, Wind Energy, 2009, DOI: 10.1002/we.319

[12]. C J Crabtree, Y Feng, P J Tavner, Detecting Incipient Wind Turbine Gearbox Failure: A Signal Analysis Method for On-line Condition Monitoring, EWEC 2010, Warsaw.

[13]. Gray C, Watson S, Physics of Failure Approach to Wind Turbine Condition Based Maintenance, Wind Energy, 2009.

[14]. Yang, W, Tavner, P. J, Crabtree, C. J, Wilkinson, M, Cost Effective Condition Monitoring for Wind Turbines, IEEE Transactions on Industrial Electronics, Vol. 57, No. 1, pp. 263-271, January 2010.