To be presented at ICEM
Chania, Crete, Greece,
September 2006

Condition Monitoring of Wind Turbine Drive Trains

Michael. R. Wilkinson and Peter. J. Tavner

***Abstract*—Condition-based maintenance for offshore wind turbines will improve reliability and increase the availability and hence the cash return for operators. Reliability studies and failure modes and effects analysis give an indication about which areas are most important. A test rig has been used to act as a model for a wind turbine and enable the development of a condition monitoring system concentrating on the drive train. This paper presents results from the test rig that shows the identification of harmonic content of the drive train, the detection of faults and the effect of different load conditions.**

***Index Terms*—Condition monitoring, Reliability, Drive Train, Wind Turbine.**

I. INTRODUCTION

RENEWABLE sources are forming an increasingly important component of electricity generation as a result of national and international targets for the reduction of CO_2 emissions. As the most developed renewable generation technology, wind turbines are increasing in prevalence and size. Offshore locations offer a number of advantages compared with onshore including a smoother, less turbulent wind and the ability to build larger turbines due to reduced concerns over visual impact. Turbines are now available with ratings of 4.5 MW and above, with rotor diameters greater than 120 m. These large turbines are ideally suited to offshore where foundation and cabling costs require a high energy yield per turbine. Fig. 1 shows a typical wind energy converter (WEC) arrangement with a doubly-fed induction generator (DFIG) arrangement.

A. *Reliability and Failure Modes*

A quantitative analysis of real wind turbine failure data has shown important features of failure rate values and trends [1][2]. This work has demonstrated that the reliability of onshore turbines is increasing and a significant part of this improvement has come from regular and frequent maintenance. The same data does not exist for offshore turbines, however it is clear that in an offshore environment, reliability becomes even more important as a result of two main factors: firstly, reduced accessibility of the site, especially in the winter periods, dramatically decreases the energy harvest in the case of a severe failure; secondly, the cost of specialized personnel and equipment is substantially higher, for example crane vessels required for heavy maintenance operations. Improvements in offshore reliability therefore require a condition based approach to allow efficient scheduling of maintenance, such as that demonstrated by Caselitz [3].

Failure Mode and Effects Analysis (FMEA) is a qualitative method, which identifies failure modes and assign risk priority numbers (RPNs) to the various subassemblies. RPNs include:

- Severity: To what extent the failure affects the capital operation of the system.
- Occurrence: How likely the failure mode is to initiate.
- Detection: How likely failure is to be detected using current condition monitoring and inspection techniques.

FMEA enables the prediction of wind turbine failure rates, giving manufacturers a better idea as to how reliable new or existing wind turbine designs will be. FMEA is also useful as a logical process to identify failure modes and initiating causes that are most likely to lead to faults in the turbine.

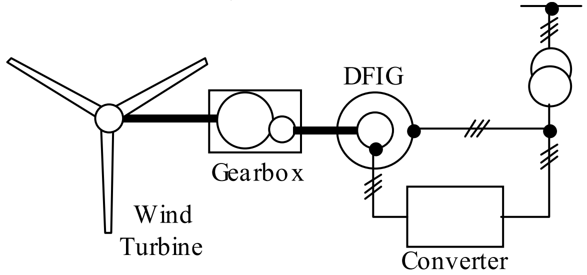

Fig. 1. Wind Energy Converter with DFIG arrangement.

B. *Condition Monitoring*

It has been recognised for a number of years [4] that the magnetic field of the machine is modulated by many of the defect mechanisms that precede an electrical machine failure. Ran, Yacamini and Smith [5] [6] have also shown that defects in an mechanical drive train connected to the electrical machine can be detected at the terminals of the machine. Jefferies [7] used this principle to detect the presence of unbalance and defects in the blades of a small wind turbine by measuring the power spectrum density at the terminals of the turbine's generator.

Manuscript received June 30, 2006. This work was funded by under the Engineering Doctorate Programme by EPSRC and FKI PLC.

M. R. Wilkinson is at the School of Electrical, Electronic and Computer Engineering, University of Newcastle upon Tyne, UK, conducting research at School of Engineering, Durham University, Durham, DH1 3LE, UK (phone: +44 191 3342469; fax: +44 191 3342408; e-mail: m.r.wilkinson@durham.ac.uk).

P. J. Tavner, is with the School of Engineering, Durham University (e-mail: peter.tavner@durham.ac.uk).

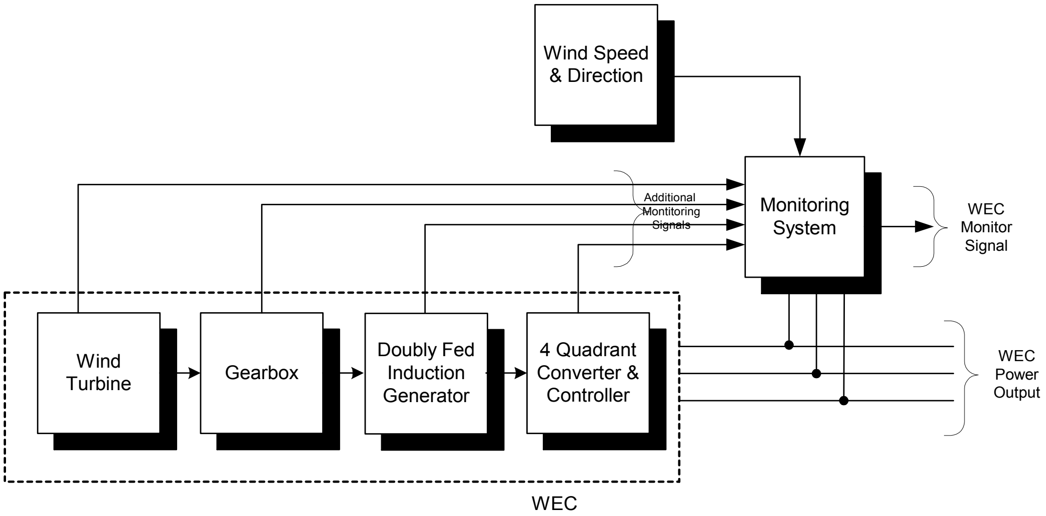

Fig. 2. Architecture of a wind energy converter (WEC) condition monitoring scheme.

The advantage of such an approach is that the terminal quantities of an electrical machine are easily accessible during operation, the current via a current transformer, the voltage via a voltage transformer and the power by computation.

Condition monitoring equipment, whether retro-fitted or in new-build, must be of low cost if it is to be taken up by operators. This can be achieved by minimising the number of additional sensors and utilising existing sensors, such as current and voltage transducers. Money and effort can be expended on the development of algorithms that can be rolled out with relatively low-cost processing across many sites. The paper will summarise work to develop a system along the lines of that shown in Fig. 2, through careful and appropriate design from an understanding of wind turbine failure modes.

II. TEST RIG

A mechanical test rig has been established to act as a model for a small wind turbine. This incorporates low and high speed shafts, a gearbox and components to represent the low inertia of the turbine and the generator conversion system. The test rig, shown in Fig. 3, comprises a variable speed drive, DC drive motor rated at about 50 kW, gearbox, shaft torque transducer and generator. The generator is a permanent magnet, spoked, air-cored generator, as descried by Spooner et al. [8]. Although this generator is of unusual topology, it is harmonic rich with modes that have been calculated and confirmed by extensive modal testing. The rig can be controlled with real and simulated wind speed data. It is important to note that in common with most wind turbines the rig operates at variable speed and the acceleration and deceleration of the wind excites a complex array of harmonics in the generator and drive train as a whole.

A. Instrumentation

The test rig has been instrumented with a number of sensors, as illustrated in Fig. 4. The lag between demanded and actual speed becomes more important at higher frequencies and the transfer function of the power converter was unknown, so a tachometer was provided to measure of the actual speed of rotation for the rig.

Accelerometers are positioned at various points on the gearbox. An inductive torque transducer operating on the principle of a voltage transformer with a variable coupling factor is located on the shaft between the gearbox and the generator. Two displacement sensors are positioned to measure the horizontal and vertical movement of the shaft at this location.

Displacement transducers are appropriate for measuring low frequency oscillations where the required mass of an accelerometer would be inappropriate for the application. Accelerometers provide a localised point measurement in terms of amplitude, but a global frequency measurement. These input signals are conditioned and measured at appropriate rates through data acquisition boards.

Fig. 3. Condition monitoring test rig and instrumentation showing generator (left), instrumentation (centre) and DC drive motor (right).

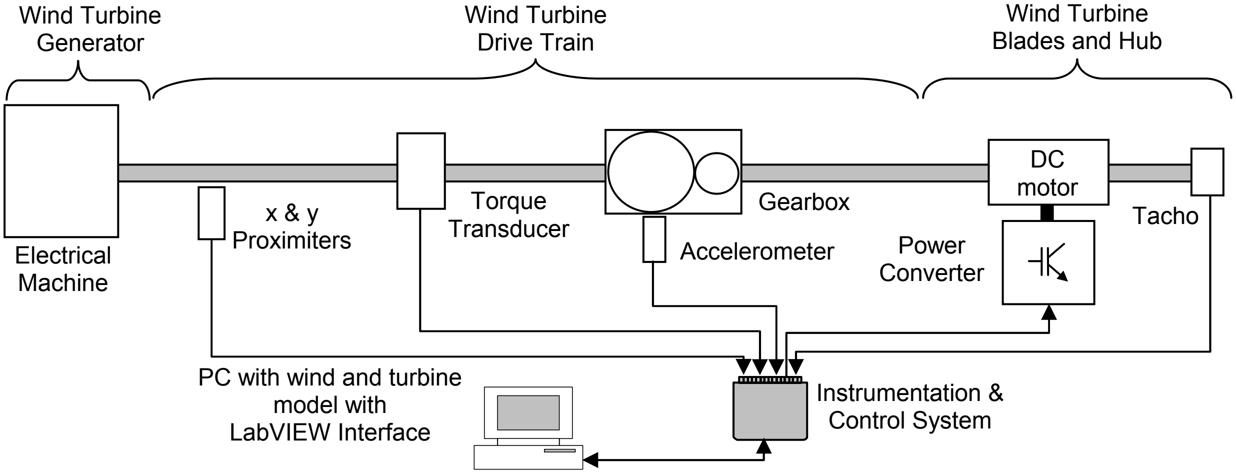

Fig. 4. Schematic showing the test rig and instrumentation.

B. Control

A simple wind model has been developed that combines random turbulence and various ramps, gusts and baseline level. This enables a range of wind data to be constructed of different severity according to the Germanischer Lloyd wind turbine classes. A variety of real wind data was also used that was measured from a small Wind Harvester turbine at Rutherford Labs. The turbine's rating is ~25 kW, which is similar to the test rig rating. The raw data is a power measurement from the turbine, which was scaled to give a corresponding shaft speed in rpm of DC motor end of the test rig. A LabVIEW program has been developed to control the test rig and to run tests by applying these different wind types. The program also measures the input signals, displays them in real time and writes them to a file for offline analysis. MATLAB signal processing and wavelet toolboxes have been used to enable the signals to be manipulated and changes in levels quantified.

III. RESULTS & DISCUSSION

A. Drive Train Frequencies

A simple calculation of the first order natural frequency of the generator/gearbox/drive motor system indicated a resonance at around 2 Hz. This is under the assumption that the generator operates in a rigid rim mode, which is appropriate for low order modes. By driving the rig with speed signal that comprises a DC level with a low amplitude sinusoidal oscillation superimposed, it is possible to measure the system's natural frequency. Because of concerns about its lighter structure compared to other, more conventional, machines the amplitude of the drive speed signal was kept below approximately 100 rpm. It was possible to drive through the first torsional resonance at a frequency in close agreement with the calculation. The Q-factor in this case is about 0.7, suggesting a high degree of energy absorption in the generator structure, which is to be expected considering the spoked nature of the machine. This is illustrated in Fig. 5.

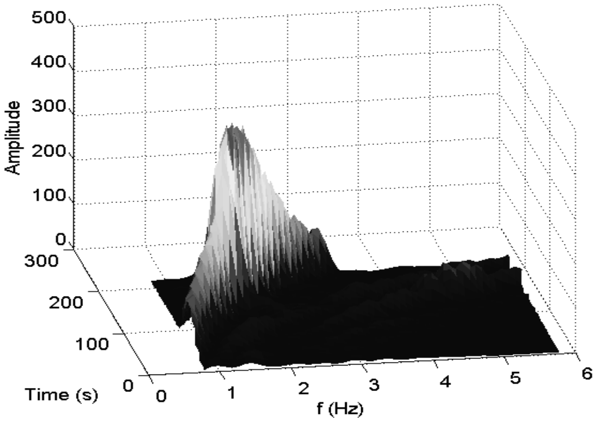

Fig. 5. The torsional response to an oscillating speed frequency sweep.

Driving the test rig with wind speed data excites the harmonic rich generator and drive train, as illustrated, for example, in Fig. 8. This also shows the main resonance at 2.1 Hz. Modal testing of the test rig reveals a torsional natural frequency that is in agreement with the value measured from the rig of 2.1 Hz. A number of axial and lateral modes have also been identified. There is a cross-coupling effect between the torsional and lateral frames and this can be measured through the torque transducer and shaft displacement sensors.

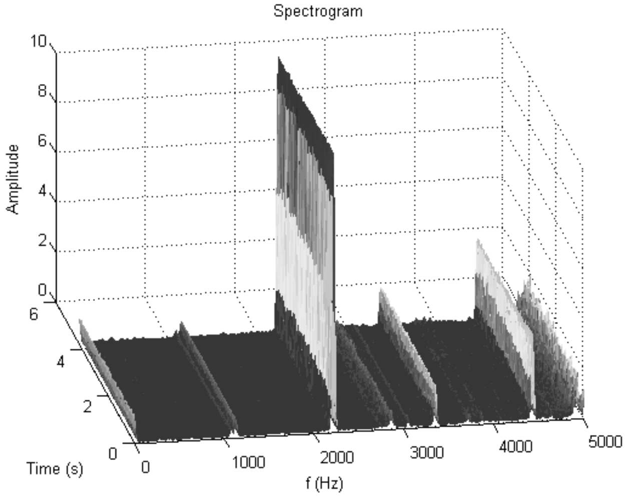

Fig. 6. Gearbox accelerometer measurements.

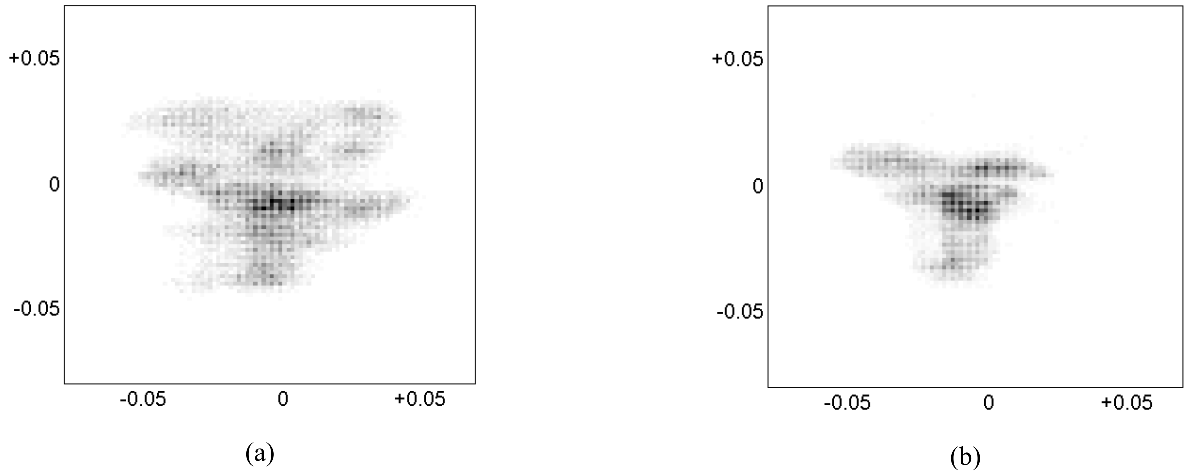

Fig. 7.Density plots of shaft displacement (mm) about the centre point with generator (a) not loaded and (b) loaded.

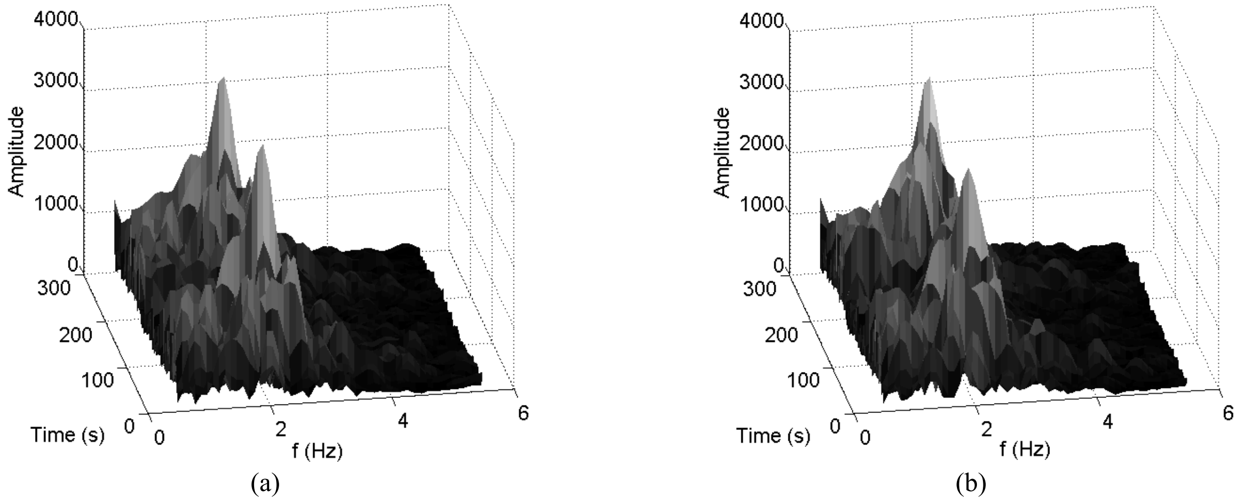

Fig. 8. The torsional effect of the generator loaded (a) under normal conditions and (b) with a single coil fault. Arbitrary, but consistent, amplitude units.

The gearbox frequencies are also excited by the wind speeds. Fig. 6 shows the signal from the accelerometer readings. To analyse data recorded under these conditions, a normal FFT is inappropriate because of the long time duration of the measurements and non-stationary nature of the wind. Instead, a spectrogram is used, which is a short time FFT. This yields a three dimensional representation of the frequency response of the rig with time.

B. Generator Load Conditions

Shaft displacement signals are represented in Fig. 7 by means of a three dimensional histogram. The area is split into 100 × 100 bins and the number of occurrences when the centre of the shaft is located in each segment is recorded. The result is that the lighter the display colour, the more time the centre of the shaft spends in that position. Comparing Fig. 7(a) and Fig. 7(b) shows the effect on the rig radial position of the drive train shaft as 136 W load is applied to the generator.

C. Generator Faults

The generator used for these experiments has 84 armature air-cored coils on the stator. A single coil was shorted while the generator was excited by wind speeds and the remaining coils connected to a load bank. Fig. 8 shows the result of this transform on the shaft torque under normal and faulted conditions. These plots also show the natural frequency of the test rig, which is excited by the harmonic content of the wind speed. This natural frequency is modulated by the fault and the effect of one coil short circuited out of 84 can clearly be detected by analysing the difference between these two plots.

The load of the generator affects how the fault modulates the harmonics and this can be measured accordingly. With the generator unloaded and open circuit the fault is most evident. With increasing load, the fault becomes less clear as a result of the increased damping from the coil currents.

IV. CONCLUSIONS

A test rig has been developed to model the effects of faults on a small wind turbine drive train. The test rig has been excited by wind speed data and subjected to a number of load and fault conditions.

The generator and drive train are harmonic rich and the natural frequencies have been measured through mobility tests. Driving the rig with wind speed data excites these harmonics, which can be measured through the drive train torque and displacements and vibrations of the drive train.

Load and faults on the drive train modulate these harmonics. The effect of generator load on the drive train can measured. Increased load damps the generator, causing lateral and torsional vibrational levels to decrease. Shorting a single coil on the generator can detect the effect of a single coil fault

The information provided by the system described can ultimately be interfaced with the wind turbine SCADA (supervisory control and data acquisition) system to provide the operators of an offshore wind turbine with condition monitoring information to organise maintenance schedules for preventative maintenance.

REFERENCES

[1] P. J. Tavner, J. Xiang, F. Spinato, "Reliability Analysis for Wind Turbines", Journal of Wind Energy, to be published 2006.
[2] P. J. Tavner, G. J. W. van Bussel, F. Spinato, "Machine and converter reliabilities in wind turbines", Proc. PEMD, Dublin, Ireland, 2006
[3] P. Caselitz and J. Giebhardt, "Advanced condition monitoring for wind energy converters". Proc. European Wind Energy Conference, Nice, France, 2002.
[4] P. J. Tavner, B. G. Gaydon, D. M. Ward, "Monitoring generators & large motors". Proc. IEE Pt. B, 1986, 133(3), pp 169-180.
[5] R. Yacamini, K. Smith, L. Ran, "Monitoring torsional vibrations of electromechanical systems using stator currents", ASME Journal of Vibration & Acoustics, January, 1998, 120, pp 72-79.
[6] Ran L., Yacamini R. and Smith K., Torsional vibrations in electrical induction motor drives during start-up, ASME Journal of Vibration and Acoustics, Vol. 118, April, 1996, pp 242-251.
[7] W. Q. Jeffries, J. A. Chambers, D. G. Infield, "Experience with bicoherence of electrical power for condition monitoring of wind turbine blades". Proc IEE, Vision Image & Signal Process, 1998, 145(3), pp 141-148.
[8] E. Spooner, C. French, P. Gordon, "Lightweight ironless-stator permanent magnet generators for direct drive wind turbines", Proc. PEMD, Edinburgh, UK, 2004.