

# Condition Monitoring of Generators & Other Subassemblies in Wind Turbine Drive Trains

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**Abstract--Abstract--** Offshore wind turbines, incorporating electrical generators and converters, operate in locations where accessibility can lead to long mean times to repair. Conditionbased maintenance is therefore essential if cost-effective availability targets are to be reached. As yet the condition monitoring techniques appropriate for offshore wind turbines have not been resolved. Reliability studies have shown that the majority of failure modes in wind turbines are concentrated in drive train subassemblies, including the electrical generator and converter, and are heavily affected by wind conditions. A 30 kW test rig has been constructed, with features similar to a wind turbine drive train, to enable the development of the signal processing techniques necessary for this variable speed, high torque variation application. The test rig includes a low speed shaft, high speed shaft, gearbox and an electrical generator and can be driven by simulated wind conditions. The test rig can also be used to inform the selection of appropriate monitoring instrumentation for offshore wind turbines. A series of condition monitoring approaches have been investigated on this test rig, using measured torque, speed, shaft displacement and gearbox vibration to detect faults. By the use of appropriate signal processing techniques, changes to load conditions, properties of the gearbox and coil faults can be detected.

**Index Terms--** Fault diagnosis, monitoring, wind power generation.

## I. INTRODUCTION

WIND turbines are an established source of renewable electricity generation and are set to play an important role in the future energy supply in a number of countries. So far most wind energy converters (WECs) have been sited onshore, but in countries such as the UK there is increasing interest in exploiting the wind resource offshore. Siting turbines at sea has a number of advantages including improved wind conditions and reduced planning objections.

All generation sources connected to the grid are required by both suppliers and electricity consumers to maintain a high degree of security. Onshore wind turbines have consistently achieved availabilities in excess of 95%. However, the environment in which offshore wind turbines must operate is less benign and often extreme. The oil and gas industry has shown that operation offshore demands a higher integrity and reliability if costs are to be kept low. Experience with offshore wind turbines suggests that availabilities greater than 90% will be essential for economic viability.

Maintenance technicians need to access the tower by boat and then reach the nacelle by climbing, or alternatively be

landed directly onto the nacelle by a helicopter. The ability to carry out either of these procedures will be limited under extreme weather conditions. The first opportunity to carry out a visual inspection of a suspected fault may be several days or even weeks after its occurrence. Therefore, detecting root causes that lead to catastrophic failure modes and improving maintenance efficiency, assume high importance under these conditions.

## II. WIND TURBINE FAILURE DISTRIBUTION

Tavner et al. [1], [2] have produced a statistical reliability analysis of reported wind turbine failures and demonstrate that a major source of failures have root causes in subsystems centred on the drive train. This includes the main shaft and bearings, gearbox, rotor brake, blades, and generator. These results combined with the high mean time to repair (MTTR) and cost for these components make the drive train a valuable area to focus efforts for condition monitoring. These failure frequencies are demonstrated in Fig. 1, which considers two types of WEC, one direct and one indirect drive, over an 11 year period. The importance of the combined effect of the reliability of the main shaft, gearbox, generator and converter subassemblies can be seen. Further work by Tavner et al. [3] has analysed the effect of wind speed on WEC failure rates, to show a clear relationship between the failure frequency of a population of Danish wind turbines and the wind energy index averaged over Denmark. This is clearly of particular importance if turbines are to be sited offshore where the weather is more inclement than onshore.

Work by Jeffries et al. [4] has demonstrated that by measuring the power derived from the terminals of a WEC

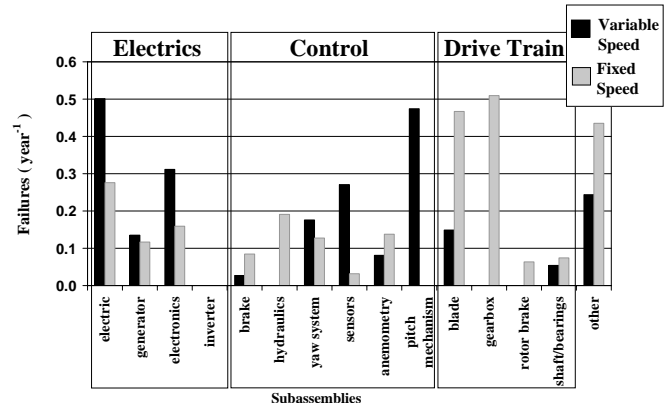


Fig. 1 Failure rate data for WEC subassemblies taken from Tavner [2] and averaged over a period of 11 years.

show it is possible to detect faults such as blade unbalance. The authors used bicoherence, a higher order technique. However, problems with the signal to noise ratio mean it is difficult to expand their approach.

More recent work by Caselitz & Giebhardt [5] has successfully used a statistical analysis of wind speed and power output of a WEC to monitor the turbine blade performance including increased blade surface roughness. They have also used spectral analysis methods on the nacelle oscillations to monitor mass imbalance and aerodynamic asymmetry due to blade faults. It is important to note that wind turbines operate at variable speed and defects initiate a complex array of harmonic effects in the drive train, which are in turn modulated by defects in the system. The work described here follows from Jeffries et al. and Caselitz & Giebhardt, but given the results of the reliability work described above, concentrates on the drive train. The aim is to develop a condition monitoring system that takes the machine's terminal quantities, but also uses information from selected additional sensors, as illustrated in Fig. 2.

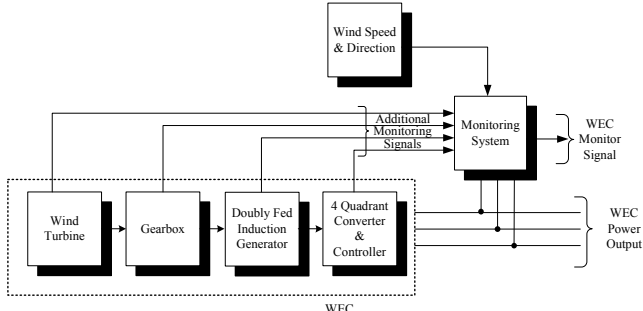


Fig. 2. Condition monitoring scheme for a WEC drive train.

### III. EXPERIMENTAL TEST RIG

The concept of the condition monitoring system as described above has been validated using a mechanical test rig, as shown in Fig. 3 and Fig. 4. This has enabled the development of fault detection algorithms and the selection of instrumentation appropriate for WEC drive trains. The main advantage of a test rig for this type of work is the ability to apply “fault-like perturbations” on demand. Conversely, in the field, with an operational wind turbine, researchers do not have any control over fault conditions and must wait for a fault to occur to test their hypotheses. Also, it can be difficult to obtain contractual agreement to fit sensors for experimental work without invalidating the manufacturer's warranty.

The rig comprises a variable speed drive, 50 kW DC drive motor, two stage gearbox and large diameter generator, based on the design of Spooner et al. [6]. Although unusual in design, the generator was used solely as a high inertia component to which electrical and mechanical faults could easily be applied. The test rig has been instrumented so that a variety of wind inputs can be applied, relevant data can be collected from the drive train and terminals of the generator, then correlated with the input conditions.

The test rig can simulate the torque input due to transient and gusting wind conditions by using the computer-controlled

DC drive system. The speed control comprised two interacting components: the wind input and the wind turbine. The wind model was constructed from the superposition of a mean velocity, ramps, gusts and turbulence. The mean wind speed varies with altitude and across the diameter of the blade swept area variations exist. This effect depends on the surface roughness and can be modelled effectively. The gusts and ramps were modelled with random duration and severity within standard levels [7]. The wind was then filtered through a rotational sampling model of the blades and connected to a Matlab Simulink 2 MW variable speed wind turbine, based work developed from [8]. The resulting data were used to control the drive through the speed feedback loop.

The drive train is instrumented with an accelerometer, torque transducer, eddy current displacement transducers, a tachometer and voltage and current transducers at the generator terminals. The torque transducer enables the shaft torque to be easily measured by the inductive measurement of a distorting shaft. In an operational wind turbine a strain gauge type transducer could be utilised, although the authors acknowledge that even this could be difficult to retro-fit. Therefore a secondary torque measurement was derived from the generator terminal voltage transducer (VT) and current transducer (CT) measurements; although this was found to give lower signal to noise ratio than the torque transducer. In an operational wind VT and CT measurements are readily available from the power converter and these measurements would be easy to retrofit. Lateral movement of the drive train shaft was obtained through horizontal and vertical non-contact displacement transducers. The accelerometer was located on the gearbox casing to measure meshing frequencies and changes to the gearbox condition. All signals from the sensors, except the accelerometer, were sampled at 1 kHz, which was sufficient to fulfil the Nyquist criterion for the highest identified rotor dynamic mode shapes of the test rig. The accelerometer was sampled at 20 kHz, which was sufficient for the highest predicted gearbox meshing frequency. It is important to note that for an operational wind turbine dealing with the large amounts of data acquired by these sampling rates would prove a challenge for the supervisory control and data acquisition (SCADA) systems



Fig. 3. The test rig, with the caged generator (left), driving DC motor (right).

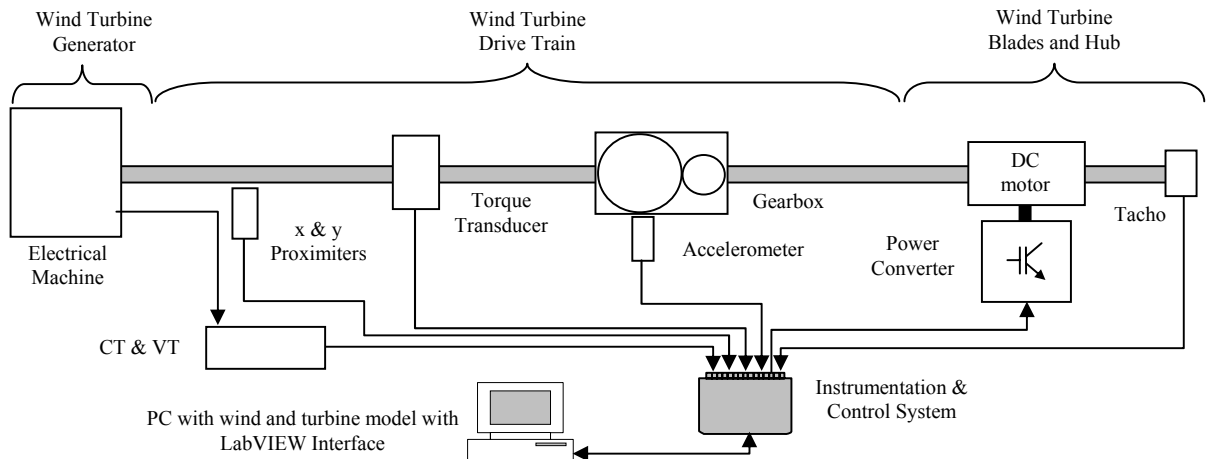


Fig. 4 A diagrammatic representation of the test rig, showing instrumentation and control.

that may sample only at 10 minute intervals. However we will show that if processing of the signals is conducted on the turbine, a lower sampling rate signal can be passed through the SCADA. A LabVIEW program has been designed to manage the speed control and data acquisition. This allows different wind profiles to be presented to the drive train, while simultaneously giving the system state presented in a graphical format and saving the data to hard disk.

The generator and drive train are harmonic rich and the natural frequencies were measured through instrumented hammer mobility testing. Several orders of modes in lateral, axial, radial and torsional directions were measured directly and form a basis for normal operation. This was compared with measurements from the test rig running under wind excited control.

Various fault-like perturbations have been applied to the rig:

- (i) Shorted Coils. The generator comprises 84 coils on the stator and remote relays were installed to enable either one, two or three coils to be connected normally or shorted. This is analogous to generator winding faults in a wind turbine generator.
- (ii) Load Conditions. Various load conditions have been applied to investigate the operational regime under which the strongest detectability level may be obtained.
- (iii) Rotor Unbalance. Masses were added to the rotor of the generator, giving torsional pulsations analogous to the effects observed from unbalanced blades in operational wind turbines.

#### IV. FAULT DETECTION ALGORITHMS

A number of methods have been investigated for the detection of the “fault-like perturbations” through the various sensors. The level of detectability,  $S_{det}$ , was established for each perturbation, by each sensor, processed by each method. A number of different fault detection algorithms have been investigated. The two most effective, giving the highest signal to noise ratio, are described below:

##### A. Torque Speed Variation

The drive train’s torque speed curve was established under normal conditions. Commutation noise present in the DC tachometer speed signals,  $\omega$ , was reduced by smoothing with a window of 100 samples (0.1 s). Faults on the drive train cause either a torsional oscillation of the type illustrated in Fig. 5, or a shift in the  $T/\omega$  ratio. By monitoring this ratio certain fault conditions can be detected.

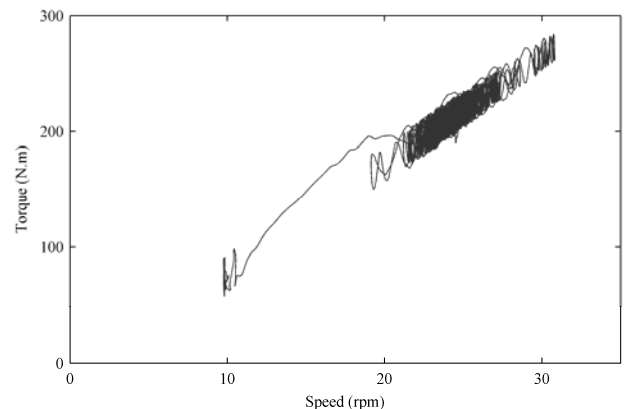


Fig. 5. Variations in the  $T/\omega$  curve resulting from rotor mass unbalance.

##### B. Spectral Methods

The Fourier transform is widely used to determine the spectral content of steady state signals, but this is not appropriate for non-stationary signals such as those encountered in a variable speed wind turbine. The spectrogram, is the short time observation of a signal  $x(t)$  through a window  $h$  with local frequency analysis, giving the power spectral density (PSD)

$$P_{x,spec}(\tau, f) = \left| \int_{-\infty}^{+\infty} x(t) h^*(t - \tau) e^{-j2\pi f t} dt \right| \quad (1)$$

where  $\tau$  is the time at which each analysis is performed. The Wigner Ville transform can also be used, which can provide greater frequency resolution when required, for example to focus on a particular known frequency:

$$P_{x,wv}(\tau, t) = \int_{-\infty}^{+\infty} x\left(t + \frac{\tau}{2}\right) x^*\left(t - \frac{\tau}{2}\right) e^{-j2\pi f t} d\tau \quad (2)$$

A time-frequency plot of the drive train shaft torque measurement after being excited by a variable wind speed signal is shown in Fig. 6. The first order torsional mode can be observed at about 2.1 Hz and this is modulated by a time dependent perturbation. A condition monitoring fault detection signal,  $S_{det}$ , can be derived by taking the energy in a band around the drive train's torsional natural frequency and normalising for the variable energy input from the wind. Temporal blocks,  $\Delta\tau$ , of the signal are integrated to give  $S_{det}$ , shown here for the torque signal:

$$S_{det} = W \sum_{t=0}^{t_f} \frac{\int_t^{t+\Delta\tau} \int_{f_0-\Delta f}^{f_0+\Delta f} P_x(T) df dt}{\int_t^{t+\Delta\tau} \int_{f_1}^{f_2} P_x(\omega) df dt} \quad (3)$$

where  $P_x(T)$  is the shaft torque PSD,  $P_x(\omega)$  is the wind input PSD,  $W$  is a normalisation factor,  $f_0$  is the drive train natural frequency,  $\Delta f$  is the drive train half power frequency and  $f_2 - f_1$  is the half power bandwidth of the input wind.

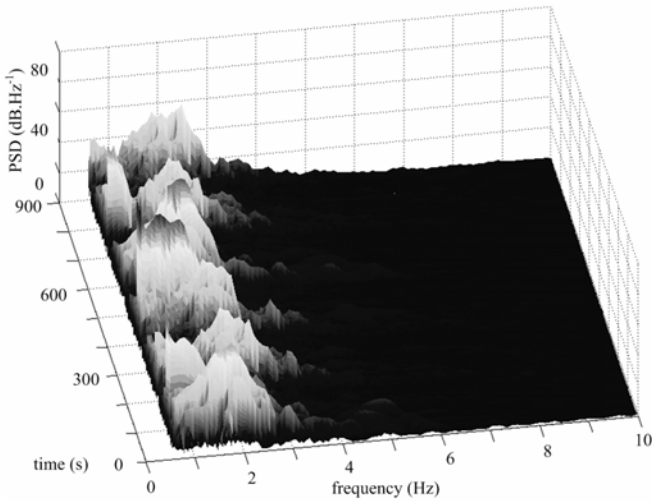


Fig. 6. The power spectral density showing the torsional energy in the drive train

## V. FAULT DETECTION RESULTS

The detectability of the various “fault-like perturbations” has been assessed and some of the more interesting results are presented below:

### A. Shorted Coils

The effect of shorting generator coils can be seen in Fig. 7. The fault signal, Fig. 7(d), is time-dependent with Fault Level = 0 indicating normal connection and Fault Level = 1 indicating 3 shorted coils. Observing the PSD of the shaft torque, Fig. 7(b), reveals speed dependent features that, when correlated with the smoothed shaft speed signal, Fig. 7(b), give a strong detectability,  $S_{det}$ , signal, Fig. 7(a).

With 1 or 2 shorted coils a similar result was obtained, although  $S_{det}$  was reduced as the effect of the condition was reduced.

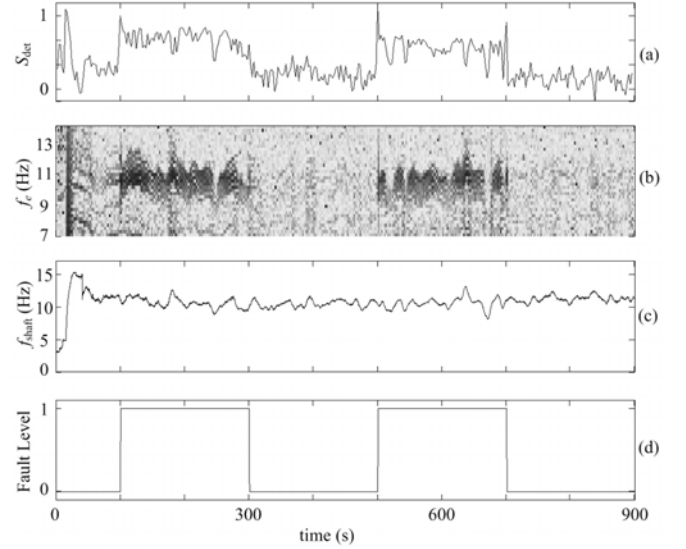


Fig. 7. Detectability of coil faults. (a)  $S_{det}$  for 3 shorted coils, (b) torsional PSD with speed-dependent features, (c) smoothed speed signal, (d) fault level.

### B. Load Conditions

Changes to the generator load conditions were applied by switching load bank resistances. The detectability of all “fault-like perturbations” was improved at higher load. Fig. 8 shows the detectability in the shaft torque under different load conditions. Fig 8(c) shows the 3 shorted coil fault level, as described previously, with the resulting  $S_{det}$  with the generator loaded to 1 kW, Fig 8(a), and 0.1 kW, Fig 8(b). It can clearly be seen that the higher load condition leads to a stronger detectability signal.

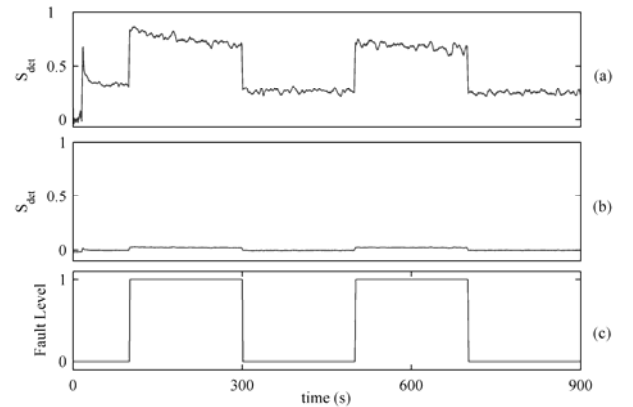


Fig. 8. The effect of load conditions on detectability. (a)  $S_{det}$  for 3 shorted coils with 1 kW load, (b) 0.1 kW load, (c) fault level.

### C. Rotor Mass Unbalance

Various masses were added to the rotor of the generator, giving torsional pulsations analogous to the effects observed from unbalanced blades in operational wind turbines. The effect can be described by an effective mass,  $m_e$ , at an effective radius,  $r_e$ , resulting in the centrifugal force

$$F_e = m_e r_e \omega \quad (4)$$

In the rotational frame this is a transverse wave that can be measured in the shaft displacement and also manifests itself as torsional oscillations visible in the  $T/\omega$  ratio.

Fig. 9(a) shows the detectability of unbalance in the

proximeter measurement of the shaft displacement in  $\mu\text{m}$ . The unbalance conditions, Fig. 9(b), are with no mass, 1 kg and 1.8 kg added at 1 m radius. The oscillations in  $r$  are the result of an eccentric measuring track on the shaft.

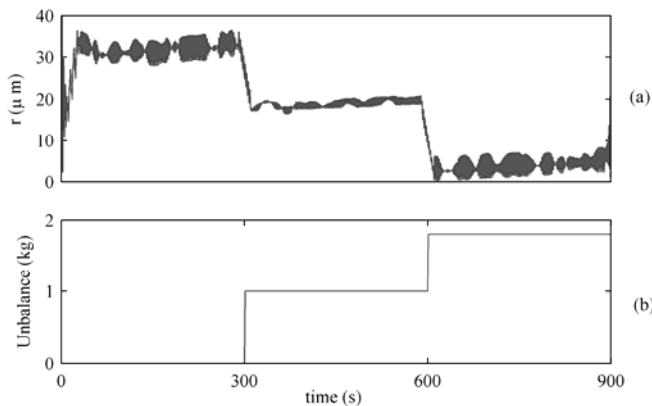


Fig. 9. Detectability of torque speed variations resulting from unbalanced mass.

## VI. CONCLUSIONS

A test rig has enabled the suitability of different sensors and signal processing techniques to be assessed for use in wind turbine condition monitoring. A shaft torque transducer is a convenient method for obtaining torque in a laboratory situation, but would be costly to install and is thus impractical for operational WECs. Deriving the torque through VT and CT measurements can easily be retrofitted and has been demonstrated to be successful, although the signal to noise ratio is lower than from the shaft torque transducer. The proximeters were successful for measuring shaft movement and vibration. They would be easy to retro fit, although could be damaged by collision with the shaft under strong transient conditions and therefore could potentially be unreliable. The DC tacho-generator gave a noisy signal for condition monitoring purposes, although good results were still obtained after appropriate filtering. The accelerometer proved useful for measuring gearbox conditions although perturbations in other subassemblies could not be detected through this sensor.

The detectability of all perturbations applied to the test rig increased with load. This has significance for the condition monitoring of turbines in highly variable wind conditions.

Torque, shaft displacement and gearbox vibration can be combined and weighted according to their importance to provide valuable signals for monitoring a variable speed WEC.

The information provided by the system described can ultimately be interfaced with the WEC supervisory control and data acquisition (SCADA) system, using a low sampling rate detectability signal, to provide offshore wind turbine operators with condition monitoring information to organise maintenance schedules for preventative maintenance.

Further work needs to be conducted to further improve the detection algorithms. Experimental work is also underway to investigate how these techniques can be applied to a more standard wound rotor induction machine.

## VII. ACKNOWLEDGEMENTS

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## VIII. REFERENCES

- [1] P.J. Tavner, J. Xiang, and F. Spinato, "Reliability Analysis for Wind Turbines", *Wind Energy*, Vol. 10, pp. 1-18, 2007.
- [2] P.J. Tavner, G.J.W van Bussel, and F. Spinato, "Machine and Converter Reliabilities in Wind Turbines", 3rd International IEE Conference, Power Electronics Machines and Drives, Dublin, April 2006, 6pp.
- [3] P.J. Tavner, C. Edwards, A. Brinkman, F. Spinato, "Influence of Wind Speed on Wind Turbine Reliability". *Wind Engineering*, Vol. 30, No. 1, pp.55-72, 2006.
- [4] W.Q. Jeffries, J.A. Chambers, and D.G. Infield, "Experience with bicoherence of electrical power for condition monitoring of wind turbine blades". *Proc IEE, Vision Image & Signal Process*, Vol. 145, No. 3, pp. 141-148, 1998.
- [5] P. Caselitz and J. Giebhardt, "Rotor condition monitoring for improved operational safety of offshore wind energy converters", *Journal of Solar Energy Engineering-Transactions of the ASME*, vol. 127, pp. 253-261, 2005.
- [6] E. Spooner, P. Gordon, J.R. Bumby, and C.D. French, "Lightweight Ironless-Stator PM Generators for Direct Drive Wind Turbines", *IEE Proc.-Electr. Power Appl.*, Vol. 152, No. 1, pp. 17-26, January 2005.
- [7] W. Bierbooms, "A gust model for wind turbine design", *JSME International Journal Series B-Fluids and Thermal Engineering*, vol. 47, pp. 378-386, 2004.
- [8] W. E. Leithead and B. Connor, "Control of variable speed wind turbines: dynamic models", *International Journal of Control*, vol. 73, pp. 1173-1188, 2000.

## IX. BIOGRAPHIES



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