Wind Turbine Condition Monitoring and Fault Diagnosis using Wavelet Transforms

Wenxian Yang[1),] **Peter J. Tavner**[1)]

[1)] New & Renewable Energy Group, School of Engineering, Durham University,
Durham DH1 3LE, United Kingdom

ABSTRACT

Some large wind turbines use a synchronous generator directly-coupled to the turbine. This paper considers condition monitoring and diagnosis of mechanical and electrical faults in such a variable speed machine. The application of wavelet transforms is investigated because of the disadvantages of conventional spectral techniques in processing instantaneous turbine signals. In this paper a new condition monitoring technique is proposed which removes the negative influence of variable wind in machine condition monitoring. The diagnosis of rotor imbalance in the wind turbine will be done, heralding the detection of wind turbine electromechanical faults by power analysis.

KEYWORDS

Synchronous generator, wind turbine, condition monitoring, fault diagnosis, wavelet transforms.

1 INTRODUCTION

With advances in wind turbine technology and government decisions that are favourable to ‘green’ or renewable power, wind turbines are becoming an increasingly economically viable alternative to conventional fossil-fuelled power generation. In some countries, notably Germany and Denmark they have been playing a vital role in the power network **Error! Reference source not found.**, although not without some problems. However, wind turbines because of their variable load condition and aggressive operating environment, wind turbines can be subject to relatively high failure rates, although they are beginning to show a reliability that is better than some other forms of power generation, for example diesel generators **Error! Reference source not found.**. So developing economic condition monitoring and fault diagnosis techniques for them would be highly desirable. SCADA techniques are being applied very widely to wind turbines but the data rate, once every 5-10 mins, is too slow for most rotating machine fault diagnosis. There are many condition monitoring techniques developed in electric power production, aerospace, marine propulsion, and other process

Email: Wenxian.yang@durham.ac.uk

industries which could be applied to wind turbines but the results have not proved satisfactory to date due to the peculiarities of the wind turbine, that is slow and variable speed, at least for the larger types. In recent years, some efforts have been made to improve this situation **Error! Reference source not found.**. However, the majority of wind turbine condition monitoring and fault diagnosis techniques proposed **Error! Reference source not found.-Error! Reference source not found.** have used Fourier Transform (FT) techniques, which are less capable of solving the problem due to its shortcomings dealing with non-stationary signals. In view of this, in this paper the potential application of the wavelet transform to the condition monitoring and fault diagnosis of wind turbines is investigated. This paper carries forward the previous work described in [6]. The Discrete Wavelet Transform (DWT) is used for noise cancellation as the signals from the wind turbine contain noise which is difficult to remove by using a conventional filter with fixed cut-off frequencies. The Continuous Wavelet Transform (CWT) is used for feature extraction purpose. A new technique, inspired by the torque-speed data obtained from a series of load and no-load experiments on a wind turbine, is proposed for assessing the running condition of the wind turbine. The effectiveness of the technique is validated by the detection of generator winding and rotor imbalance faults on the test rig. Experimental results show that the application of the DWT dramatically enhances the viability of this technique for wind turbines. In order to further simplify and reduce the cost of wind turbine condition monitoring and fault diagnosis, the possibility of detecting wind turbine mechanical faults by analysis of the power signal is also investigated. The CWT plays a vital role in extracting faulty features from the power signal.

2 TEST RIG FOR SYNCHRONOUS GENERATOR WIND TURBINES

In order to simulate the effects of wind turbines working under different conditions and develop the new condition monitoring and fault diagnosis techniques, a wind turbine test rig was built, as shown in Fig.1.

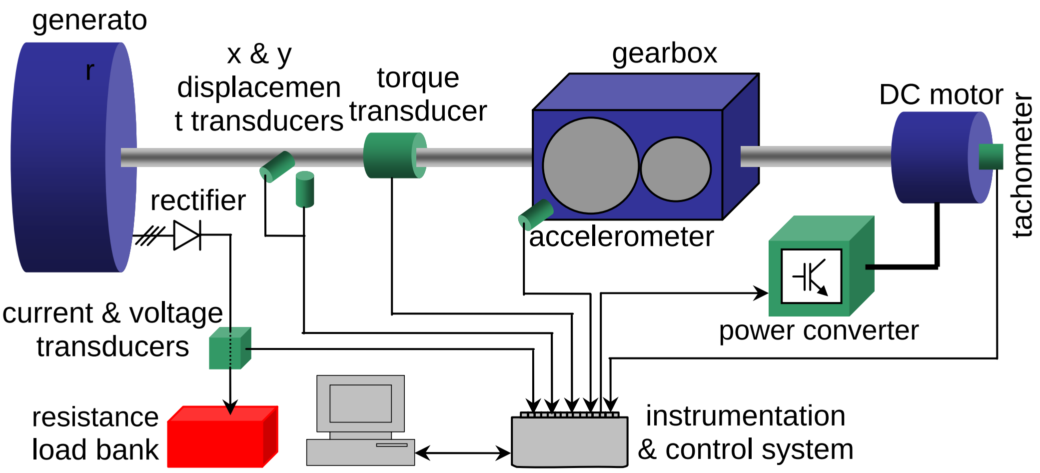


Figure 1: Wind turbine test rig and the transducers fitted to it

The test rig comprises a 50kW DC variable speed drive controlled motor, a two-stage gearbox and a three-phase synchronous permanent-magnet generator. The generator has 84 coils on the stator, 108 permanent-magnets on the rotor and each coil was rectified, then coupled to a DC bus and fed to a resistance load bank.

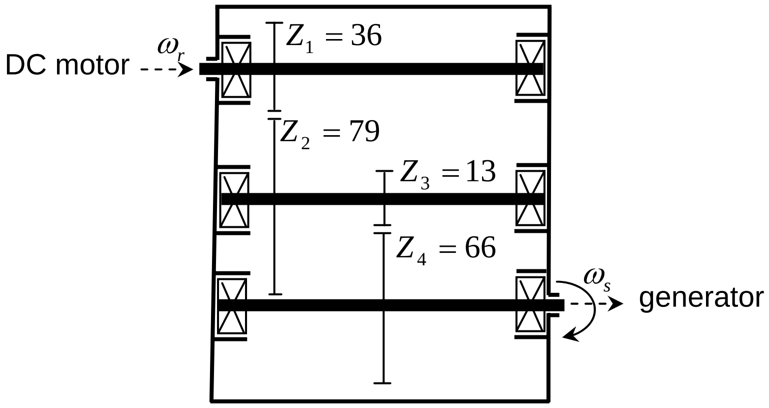
The test rig is controlled by LabVIEW so that a variety of wind speed inputs can be applied and the relevant signals can be collected from the drive train and terminals of the generator. As shown in Fig.1, a number of transducers are fitted to the rig to measure the shaft rotational speed, torque and vibration. The load DC current and voltage are measured at the terminals of the generator with the aid of data acquisition equipment installed in control cabinet of the test rig. In the experiments, the speed of the DC motor is controlled by an external model, in which both the properties of natural wind and the mechanical behaviour of turbine rotor are incorporated. In the investigations, both generator electrical and wind turbine mechanical faults were simulated on the test rig as follows:

- A generator stator winding fault was simulated by simultaneously shorting the load bank to ground;
- A full short circuit fault was simulated by connecting one of the phase terminals of the generator and resistance bank to ground;
- A rotor imbalance fault was simulated by attaching a mass to the outer surface of the generator rotor.
- A drive train mechanical fault was simulated by an eccentricity fault in the test rig gearbox.

The diagram of the test rig gearbox is shown in Fig.2, from which the gear ratio can be easily obtained, i.e.

$$r_g = \frac{\omega_r}{\omega_s} = \frac{Z_2}{Z_1}\cdot\frac{Z_4}{Z_3} = \frac{79}{36}\cdot\frac{66}{13} = 11.14 \tag{1}$$

where ω_r represents the rotational speed of the DC motor, ω_s stands for the rotational speed of the synchronous generator, and Z_i (i=1~4) indicate the tooth numbers of the gears.



Email: Wenxian.yang@durham.ac.uk

Figure 2: Diagram of the gearbox used in the test rig

3 CONDITION MONITORING TECHNIQUE

In order to develop an effective technique for monitoring the running condition of synchronous generator wind turbines, a series of full and half load tests were conducted on the test rig. Different loads and fault conditions were applied to the rig during the experiments. The shaft torque and rotational speed data measured in the different cases are plotted in Fig.3. The polynomial equations fitting to these data are also derived with the aid of the polynomial curve fitting technique **Error! Reference source not found.**. In Fig.3, the fitting curves and the corresponding polynomial equations are given as well for facilitating analysis.

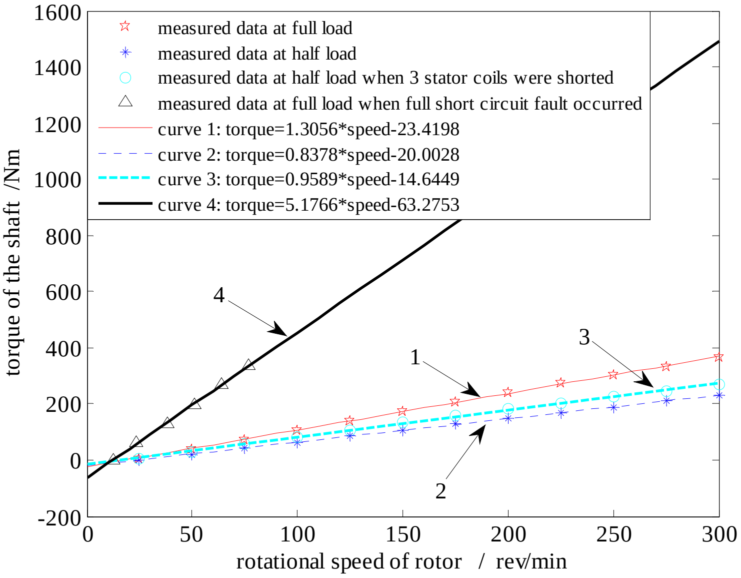


Figure 3: The shaft torque and speed data measured in the full and half load tests

From Fig.3, it can be seen that the generator exhibits different torque-speed characteristics under different load and fault conditions. Most interestingly, the generator shows a significant change in torque-speed characteristic when faults occur, regardless of the load condition. This suggests that the torque-speed curve could be a sensitive indicator of the running condition of a synchronous generator wind turbine. Inspired by this idea, a new condition monitoring technique will be developed in this paper. According to Eq.(1), have

$$\omega_s = \frac{\omega_r}{r_g} \qquad (2)$$

Henceforward, the rotational speed used in this paper will be that of the generator ω_s .

According to **Error! Reference source not found.**, the following relations exists for the relationship between the torque and speed of a synchronous generator wind turbine:

Email: Wenxian.yang@durham.ac.uk

$$\begin{cases} T \propto \dfrac{\omega_s}{X_a} \\ T_{pm} \approx T \end{cases} \tag{3}$$

where X_a stands for the synchronous reactance of the generator, and T_{pm} represents the mechanical torque created by wind force.

With the aid of Eq.(3) the proposed technique will use a criterion C as a versatile function for monitoring the running condition of the wind turbine:

$$C = \frac{T}{\omega_s} \tag{4}$$

where T is the torque and ω_s the generator rotational or synchronous speed, both measured on the generator shaft. It should be noted that the rotational speed shown in Fig.3 is the DC motor speed ω_r measured by using a tachometer mounted on the motor. *C* can be used not only to monitor the presence of a drive train mechanical fault, but also can be employed to detect the occurrence of a generator electrical fault because a drive train mechanical fault will have response in T_{pm} and a generator electrical fault will have response in X_a. One more advantage of criterion *C* is that it is independent of the variable wind demonstrated by the linear relationship between the shaft torque T_{pm} and rotational speed ω_r shown in Fig.3.

4 WAVELET TRANSFORMS

The mechanical and electrical signals from wind turbines comprise complex instantaneous information in both time and frequency domains. The shaft torque and speed signals are also very noisy. Therefore wavelet transforms have been employed to process the data in this paper, the DWT is applied to remove noise and the CWT to extract time-frequency features. In conception, wavelets are a family of functions obtained by the dilation and translation of a mother wavelet $\psi(t)$. The daughter wavelets $\psi_{a,b}(t)$ at scale a and translation b may be expressed as

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \tag{5}$$

The CWT of a signal $x(t)$ is implemented by following the equation

$$CWT_{a,b}(t) = \int_{-\infty}^{\infty} x(t)\psi_{a,b}(t)dt \tag{6}$$

The dyadic discrete wavelet transform, DWT, is a special form of the CWT with dilation $a = 2^j$ and translation $b = 2^j n$, i.e.

$$DWT_{j,n}(t) = CWT_{2^j,2^j n}(t) = \frac{1}{\sqrt{2^j}}\int_{-\infty}^{\infty} x(t)\psi\left(\frac{t}{2^j} - n\right)dt \qquad (j, n \in Z) \tag{7}$$

Email: Wenxian.yang@durham.ac.uk

By using the DWT, the signal being investigated is decomposed into a series of sub-signals with different frequencies, i.e.

$$x(t)=\sum_{n=-\infty}^{\infty}a_{0,n}(t)g_{0,n}(t)+\sum_{j=0}^{\infty}\sum_{n=-\infty}^{\infty}d_{j,n}(t)h_{j,n}(t) \tag{8}$$

where $g(t)$ is a low-pass filter and $h(t)$ is a high-pass filter. Therefore, the first term in Eq.(8) with high frequencies and shows the 'details' of the signal; the second term with low frequencies and shows the 'approximations' of the signal.

The de-noised signal $\hat{x}(t)$ is reconstructed by using the same equation but with the trimmed wavelet coefficients $\hat{a}_{0,n}(t)$ and $\hat{d}_{j,n}(t)$, i.e.

$$\hat{x}(t)=\sum_{n=-\infty}^{\infty}\hat{a}_{0,n}(t)g_{0,n}(t)+\sum_{j=0}^{\infty}\sum_{n=-\infty}^{\infty}\hat{d}_{j,n}(t)h_{j,n}(t) \tag{9}$$

Currently, two thresholding approaches are popularly used to trim the wavelet coefficients. They are

- Hard thresholding:

$$\hat{d}_{j,n}(t)=\begin{cases}d_{j,n}(t) & if\quad |d_{j,n}(t)|>\theta\\ 0 & if\quad |d_{j,n}(t)|\le\theta\end{cases} \tag{10}$$

- Soft thresholding **Error! Reference source not found.**:

$$\hat{d}_{j,n}(t)=\begin{cases}d_{j,n}(t)-\theta & if\quad d_{j,n}(t)>\theta\\ 0 & if\quad |d_{j,n}(t)|\le\theta\\ d_{j,n}(t)+\theta & if\quad d_{j,n}(t)<\theta\end{cases} \tag{11}$$

In the equations, the threshold θ is estimated by following equation (9)

$$\theta=\sigma\sqrt{2\,log(N)} \tag{12}$$

where σ is an estimate of the noise level, N is the number of wavelet coefficients in the current level.

The calculation of $\hat{a}_{0,n}(t)$ is similar as that of $\hat{d}_{j,n}(t)$. Both the aforementioned thresholding strategies have advantages and disadvantages of their own. In this paper, the soft thresholding approach is adopted so that the smoothness of the de-noised signal can be guaranteed.

5 CONDITION MONITORING OF THE WIND TURBINE

In order to verify the effectiveness of the proposed technique in wind turbine condition monitoring, two illustrative examples are given in the following. One is detecting a stator winding fault in the generator; another is detecting a rotor imbalance fault in the wind turbine.

Email: Wenxian.yang@durham.ac.uk

5.1 Stator Winding Fault in the Generator

A stator winding fault in the generator was simulated on the test rig by simultaneously shorting 3 coils installed on the stator of the generator. As shown in Fig.4, the 3 coils are equally distributed on the stator by a spherical angle 37^o. They are well connected or shorted with the aid of remote relays connected to them. When the connection state of the coils was alternated periodically, the torque and rotational speed signals were collected from the generator shaft. The time-waveforms of the signals are shown in Fig.5.

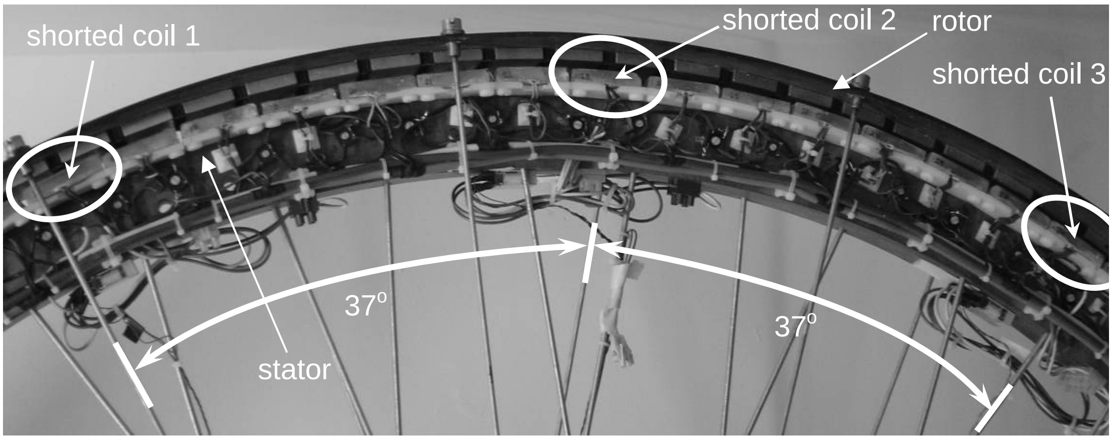


Figure 4: Arrangement on the generator for simulating a stator winding fault by shorting coils

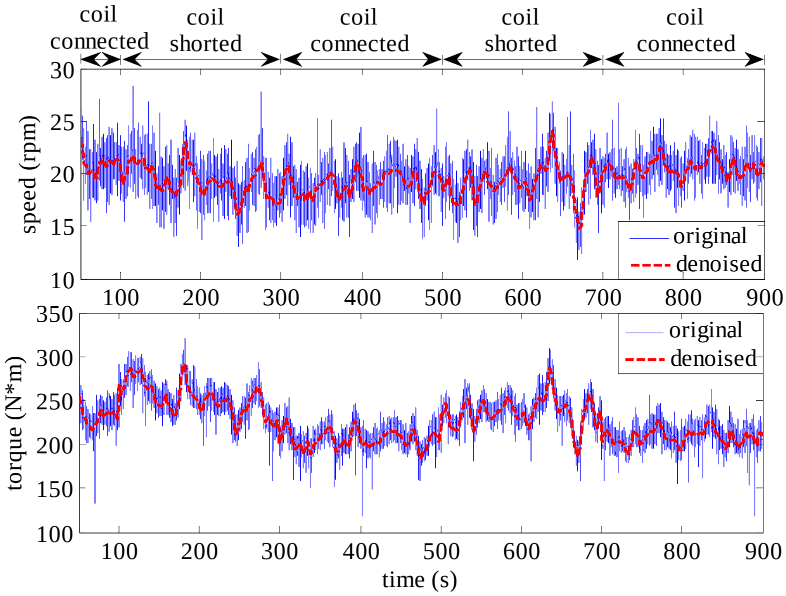


Figure 5: The torque and speed signals when the coils are well connected and shorted

From Fig.5, it can be seen that the shaft torque and rotational speed are indeed very noisy as stated above. So a de-noising process is essential to perform before using them to calculate criterion *C*. By using the wavelet-based de-noising technique depicted in Section 4, the signals are de-noised and plotted in Fig.5. From Fig.5, it is clearly seen that the noise contained in the original torque and speed signals has been successfully removed. Then, the criterion *C* is calculated and the results are shown in Fig.6, in which the results obtained from the original signals are also shown for comparison.

Fig.6 shows that the criterion increases sensibly when the coils are shorted, and returns to normal when the coils are well-connected. Clearly, the stator winding fault in the generator has been successfully detected using the proposed technique. The corresponding decrease of the synchronous reactance X_a of the generator when the coils are shorted accounts for the increase of *C*. In other words, when the coils are shorted, X_a decreases and therefore the torque T created at the same speed ω_r increases. In consequence, the value of *C* increases accordingly.

5.2 Rotor Imbalance Fault

One more proof for demonstrating the effectiveness of the proposed technique in wind turbine condition monitoring can be given by the detection of a rotor imbalance fault. It is known that wind turbine rotors are prone to unbalance due to [4~5]:

- Water in the blade,
- Icing on the blade surface,
- Impact damage to the blade.

Once the rotor is imbalanced a strong vibration at the shaft rotational frequency will be introduced into the system. It travels along the wind turbine drive train, and finally arrives at the generator and a dynamic air-gap eccentricity fault is introduced into the generator. The characteristic frequency of this type of fault will be the rotational frequency of the shaft where the imbalance happens.

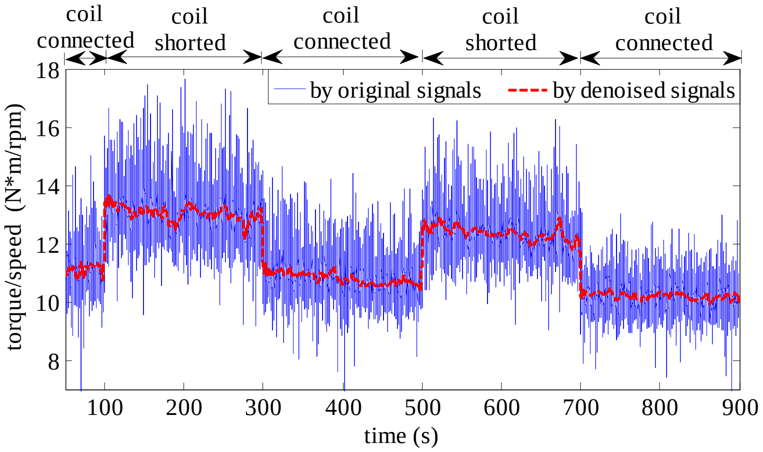


Figure 6: Criterion *C* derived in the case of generator winding fault

A rotor imbalance fault was simulated on the test rig by directly attaching a 1.027kg weight mass to the outer surface of the generator rotor, as shown in Fig.7, which introduced a periodic air-gap fluctuation between the stator and rotor of the generator. The shaft torque and rotational speed signals collected before and after the attachment of the unbalance mass are shown in Fig.8.

The DWT was applied to remove the noise before performing the calculation of criterion *C*. The de-noised signals are also plotted in Fig.8, from which a significant fluctuation of shaft torque due to the unbalance mass is clearly observed. This indicates that the balance condition of the rotor does have a significant influence on the stability of the whole wind turbine. By using the de-noised signals, the criterion *C* is calculated and the calculation results are shown in Fig.9, in which the results derived directly from the original signals are shown for comparison.

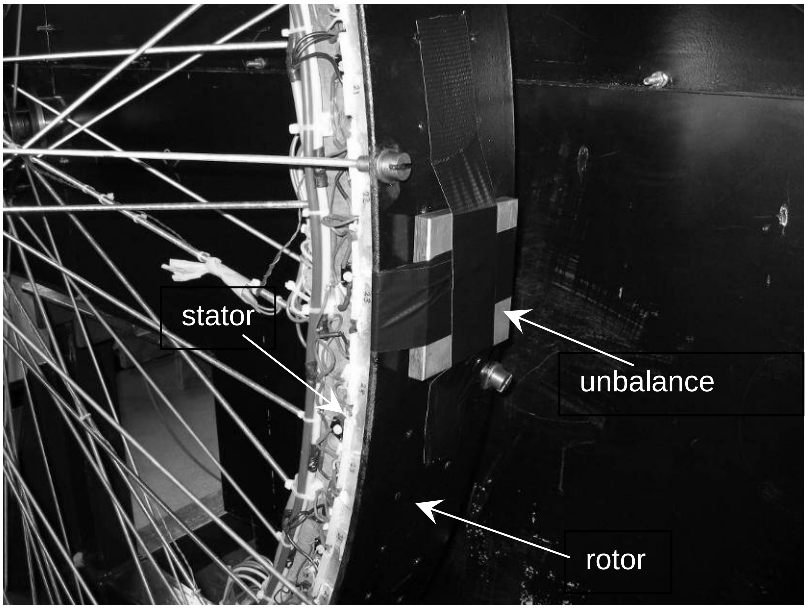


Figure 7: Simulation of a rotor imbalance fault

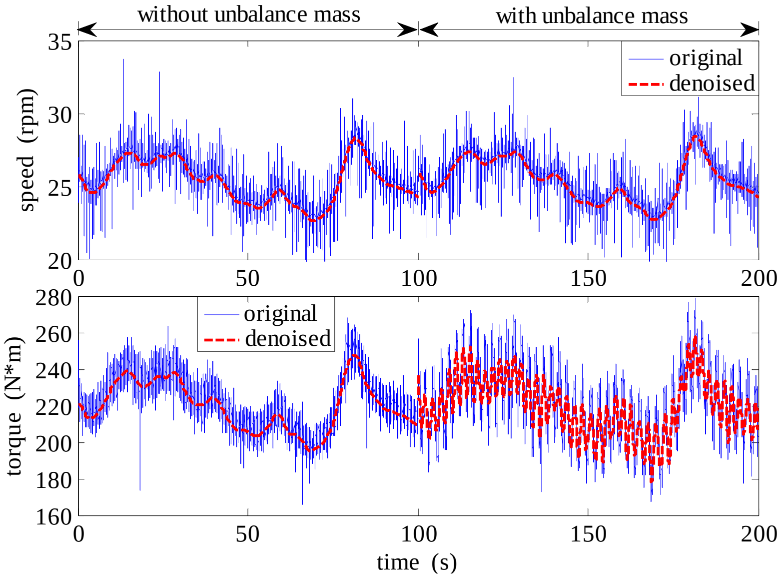


Figure 8: The torque and speed signals in the case of rotor imbalance fault

Email: Wenxian.yang@durham.ac.uk

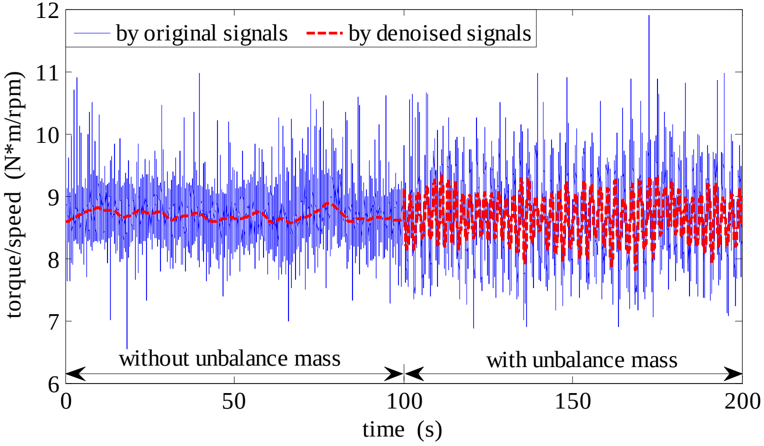


Figure 9: Criterion *C* in the case of rotor imbalance fault

From Fig.9, it is found that criterion *C* shows a large fluctuation when the unbalance mass is attached, becoming stable again as soon as the unbalance mass is removed. Thus, it can be concluded that rotor imbalance can be successfully detected using the proposed technique.

Both Figs.6 and 9 reveal that the application of wavelet-based de-noising strengthens the application of criterion *C* to the condition monitoring of wind turbines.

6 DIAGNOSING MECHANICAL FAULTS BY POWER SIGNAL ANALYSIS

The vibro-acoustic approach is currently popular for diagnosing the mechanical faults presented in the rotor blade, gearbox, bearing, pitch control system and the nacelle of the wind turbine **Error! Reference source not found.**. However, this approach involves the use of a number of transducers and a consequent cost, for example a system recently developed by Bently Nevada **Error! Reference source not found.** includes measurement of:

- Power,
- Shaft torque,
- Wind speed,
- Accelerometers in 8 locations (2 for the nacelle, 1 for the main bearing, 3 for the drive train and 2 for the generator),
- Displacement transducers in 2 locations,
- A keyphasor transducer.

The motion transducers are not able to work independently and must be connected to a dedicated data acquisition/processing device known as a Dynamic Scanning Module (abbreviated as DSM) mounted in control cabinet in the nacelle. This sort of condition monitoring systems is sophisticated and costly and probably cannot be justified except for the most high risk locations. Moreover, the compact nature of the wind turbine nacelle means that installation of the transducers is not easy. Reducing the number of transducers required for condition monitoring is strongly recommended. In the above sections the proposal to condition monitor a wind turbine by using its shaft torque and rotational speed signals has been discussed in detail. Subsequently, the possibility of detecting the wind turbine mechanical faults using power signal analysis will be investigated. If this works, the number of transducers fitted to a wind turbine could be significantly reduced. There is no doubt that a novel condition monitoring and fault diagnosis system consisting only of power, torque and wind velocity transducers, will be much cheaper than a scheme such as proposed in **Error! Reference source not found.** and will therefore be more favourable to wind turbine users.

To prove the feasibility of reducing the number of transducers, a rotor imbalance fault will be diagnosed using the terminal power signal of the generator, this was an approach first advocated by **Error! Reference source not found.** . As depicted in Section 5.2, the unbalanced rotor was simulated by attaching an unbalance mass to the rotor (see Fig.7). Before and after the unbalance mass was attached, the phase current, voltage and power signals were monitored and their time-waveforms are shown in Fig.10.

From Fig.10, no significant difference is visible between the signals collected before and after the unbalance mass was attached. But according to the predictions given in Section 5.2, a characteristic frequency component should occur when the imbalance happens. For the present experiment, this characteristic frequency is at the rotational frequency of the generator rotor. In order to detect this faulty feature CWT is applied to the power signal shown in Fig.10, and the calculation results are shown in Fig.11.

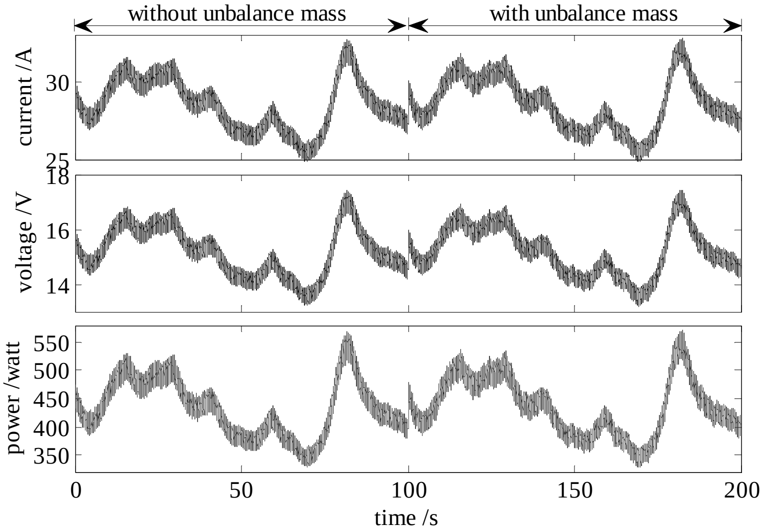


Figure10: Electrical signals in the case of rotor imbalance fault

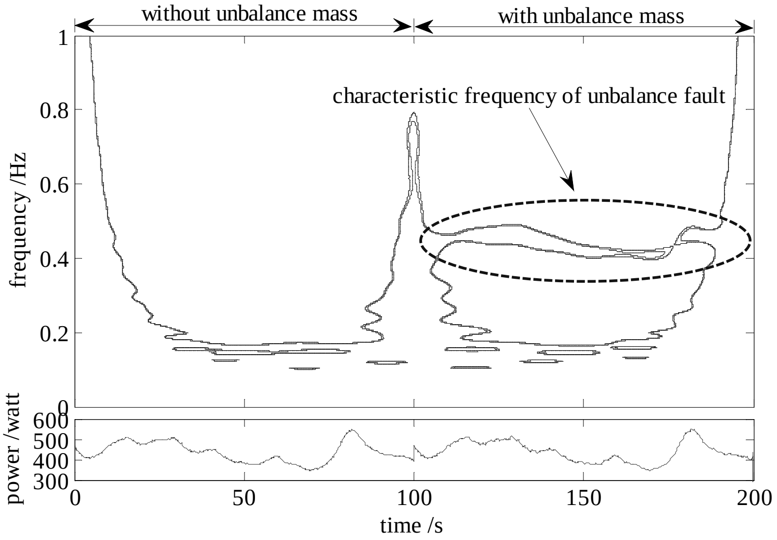


Figure 11: The CWT map of the power signal shown in Figure10

From Fig.11, it is clearly seen that when the imbalance occurs a characteristic frequency appears at about 0.44Hz, corresponding to the rotational speed of 26 rev/min (see Fig.8). The feature extracted by the CWT from the power signal is in accordance with the theoretical prediction thus demonstrating that the detection of mechanical faults by analyzing generator terminal power signal is feasible for a wind turbine. The experiment also proved the value of the CWT for in analyzing non-stationary signals and a faulty feature, created by imbalance, was explicitly identified, though the unbalance mass was light compared to the generator rotor mass.

7 CONCLUSIONS

Condition monitoring and fault diagnosis techniques were investigated in this paper for a wind turbine with a synchronous generator. Firstly, a new condition monitoring technique was proposed based on the phenomena observed in a series of full and half load experiments. Then, the proposed technique was verified by detecting generator winding and rotor imbalance faults. In order to meet the need of developing a simpler and cheaper wind turbine condition monitoring and fault diagnosis system, the possibility of detecting a wind turbine mechanical fault by power signal analysis was investigated with the aid of the CWT. It has been concluded from these preliminary investigations that:

- When the condition monitoring test rig suffered a generator electrical or mechanical fault, the change of running condition was correctly detected using the condition monitoring technique proposed, based upon the criterion $C = \frac{T}{\omega_s}$, rather than by using traditional vibration signals.

- The DWT has a powerful denoising capability for wind turbine signals. The application of the DWT strengthens the viability of the proposed technique in detecting changes of wind turbine running condition.
- The feasibility of detecting a wind turbine mechanical fault through analyzing the generator power signal using the CWT technique has been demonstrated.

It should also be possible, using wind velocity and power transducers, to develop a simple and cheap wind turbine condition monitoring and fault diagnosis system, without resorting to costly vibro-acoustic transducers.

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Email: Wenxian.yang@durham.ac.uk