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Wind Turbine Condition Monitoring and Fault Diagnosis Using both Mechanical and Electrical Signatures

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Abstract **– Some large wind turbines use a synchronous generator, directly-coupled to the turbine, and a fully rated converter to transform power from the turbine to the mains. This paper considers condition monitoring and diagnosis of mechanical and electrical faults in such a variable speed machine. A new condition monitoring technique is proposed in this paper, which removes the negative influence of variable wind in machine condition monitoring. This technique has a versatile function, able to detect both the mechanical and electrical faults in the wind turbine. Its effectiveness is validated by the experiments on a wind turbine condition monitoring test rig. Furthermore, a potential approach for diagnosing wind turbine drive-train mechanical faults using wind turbine generator electrical signals is introduced. The diagnosis of rotor imbalance in the wind turbine will be used as an illustrative example, heralding the detection of wind turbine electromechanical faults by power analysis. The paper offers a simpler and cheaper condition monitoring and fault diagnosis system for wind turbines.**

Index Terms – wind turbine, condition monitoring, fault diagnosis.

I. INTRODUCTION

With advances in wind turbine technology and government decisions that are favourable to 'green' or renewable power, wind turbines are an increasingly viable economic 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 [1], although not without some problems. However, because of the variable load of wind turbines and the aggressive operating environment, wind turbines are subject to relatively high failure rates and their condition monitoring signals are highly variable and subject to large dynamic range. However, wind turbines are beginning to show a reliability that is better than some other forms of power generation, for example diesel generators [2]. So developing economic condition monitoring and fault diagnosis techniques for them would be highly desirable. SCADA techniques are being widely applied 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 industries which could be applied to wind turbines but the results have not proved entirely 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 [3]. However, the majority of wind turbine condition monitoring and fault diagnosis techniques proposed [4]-[5] have used Fourier Transform (FT)-based techniques, which are less capable of solving the problem due to its shortcomings dealing with non-stationary signals. Recently, wavelet analysis has been attempted to detect wind turbine blade and bearing faults[6,7]. However, further research on wind turbine condition monitoring and fault diagnosis is still needed if the problems of signal variability and dynamic range are to be overcome. All techniques available today are for the detection of local faults in wind turbine components. Diagnosis of the whole machine needs the signals from many transducers, which is costly and difficult to install. To date a low cost technique for the diagnosis of the whole machine has not been achieved. Experience has also shown that currently vibration-based techniques may be unsatisfactory as they frequently give false alarms because of the variable nature and dynamic range of the monitoring signals.

So, a further effort is required to develop a simpler but more inclusive wind turbine condition monitoring technique. For this purpose and in the meantime in order to carry forward the previous work described in [8], a new wind turbine condition monitoring criterion is investigated in this paper, and a potential approach of diagnosing wind turbine mechanical faults from generator electrical signals is researched, preliminarily with the aid of wavelet analysis. Techniques are validated on a wind turbine test rig using a three-phase permanent-magnet synchronous generator loaded with aerodynamic forces from a drive motor controlled by an external model, incorporating the wind and turbine rotor behaviour. Through this research, a simpler, cheaper but effective wind turbine condition monitoring and fault diagnosing technique is heralded. More details about this research are depicted in the following sections.

II. 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.

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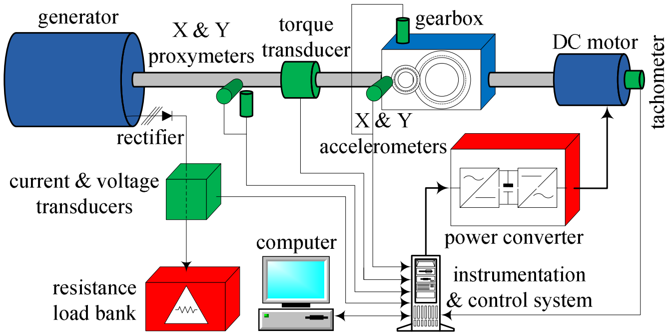

Fig.1 Wind turbine test rig and the transducers fitted to it

The test rig comprises a 50kW DC variable speed drive controlled motor, a two-stage gearbox with gear ratio 11.14:1 and a three-phase synchronous permanent-magnet generator. The generator has 84 coils installed on the stator and 108 permanent magnets on the rotor. Each coil was rectified and 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 the 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 directly 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.

III. CONDITION MONITORING TECHNIQUE

In order to develop a more effective technique for monitoring the running condition of synchronous generator wind turbines, a series tests were conducted on the test rig. Different fault conditions were applied to the rig under a fixed load condition. Part of experimental results obtained when simulating generator stator winding fault are given in Fig.2, in which both the data obtained in the experiments and the polynomial curves derived by using the data fitting technique depicted in [9] are illustrated for facilitating analysis.

From Fig.2, it can be seen that the generator exhibits different torque-speed characteristics under different running conditions. This suggests that the torque-speed curve could be a potential indicator of the running condition of a synchronous generator wind turbine. Experiments also showed that its sensitivity to the fault was relatively insensitive to the change of the load applied to the generator. Inspired by this idea, a new condition monitoring technique is developed in this paper.

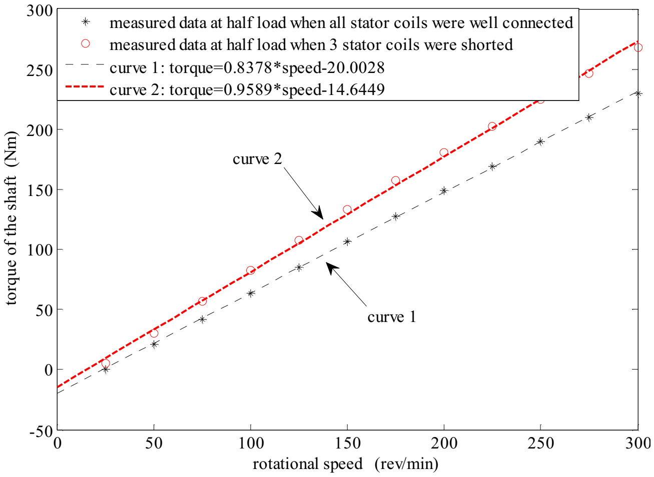

Fig.2 The shaft torque and speed data measured in the full and half load tests

According to [10], the electromagnetic torque produced by a three-phase non-salient pole synchronous machine can be expressed as

$$T_{em}=3\frac{\left|\bar{E}_a\times\bar{V}_a\right|}{\omega_s X_a}=3\frac{E_a\times V_a}{\omega_s X_a}\sin\delta \tag{1}$$

where $\bar{E}_a$ refers to the phasor per-phase induced emf in the winding, $\bar{V}_a$ is the phasor per-phase terminal voltage, X_a is the synchronous reactance, and δ represents the load angle between $\bar{V}_a$ and $\bar{E}_a$.

Generally, the circuit equation can be formularized as

$$\bar{V}_a=\bar{E}_a-(jX_a+R_a)\bar{I}_a \tag{2}$$

where $\bar{I}_a$ is the phase current and R_a is the winding resistance.

As the winding resistance R_a in large synchronous generators is much smaller than the synchronous reactance X_a, have

$$T_{em}=3\frac{\left|\bar{E}_a\times\left(\bar{E}_a-jX_a\bar{I}_a\right)\right|}{\omega_s X_a}=3\frac{E_a\cdot\left|\bar{E}_a-jX_a\bar{I}_a\right|}{\omega_s X_a}\sin\delta \tag{3}$$

For a phase winding with N turns in series, the induced emf, from Faraday's law is

$$E_a=-Nk_w\frac{d\phi}{dt} \tag{4}$$

where k_w is the winding factor, which includes the distribution and pitch factors. $\phi=\hat{\phi}\sin(\omega_{se}t)$ is the flux per pole of a round rotor revolving at angular velocity ω_s, where ω_{se} refers to the electrical supply frequency and $\omega_s=\omega_{se}/p$ and p is the number of pole pairs.

As the flux revolves, the emf in the phase winding can be expressed as

$$E_a=-Nk_w\omega_{se}\hat{\phi}\cos(\omega_{se}t) \tag{5}$$

and

$$E_a\cdot\left|\bar{E}_a-jX_a\bar{I}_a\right|\propto E_a^2=N^2k_w^2\omega_{se}^2\hat{\phi}^2\cos^2(\omega_{se}t) \tag{6}$$

Then submit (5) into (2), have

$$T_{em}(t) \propto 3\frac{N^2 k_w^2 \omega_{se}^2 \hat{\phi}^2 \cos^2(\omega_{se} t)}{\omega_s X_a}\sin\delta = 3\frac{N^2 k_w^2 \omega_s \hat{\phi}^2 \cos^2(\omega_{se} t)}{p^2 X_a}\sin\delta \quad (7)$$

When load, δ, and flux ϕ are constant, then the following relations exist between the shaft torque T and the speed ω_s of a synchronous generator wind turbine

$$\begin{cases} T_{em} \propto \dfrac{\omega_s}{X_a} \\ T \approx T_{em} \end{cases} \quad (8)$$

so

$$T \propto \frac{\omega_s}{X_a} \quad (9)$$

Obviously, the correctness of the experimental results shown in Fig.2 has been fully demonstrated by (9). Inspired by the relation expressed by (9), a versatile function is proposed for monitoring the running condition of the wind turbine, i.e.

$$C = \frac{T}{\omega_s} \quad (10)$$

It should be noted that the rotational speed shown in Fig.2 is the DC motor speed ω_r measured by using a tachometer mounted on the motor. Before conducting the calculation of (10), ω_r needs to be converted to be ω_s by taking gear ratio into account.

From (9) and (10), it is inferred that 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 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 and rotational speed ω_s shown in Fig.2.

IV. BRIEF REVIEW OF WAVELET ANALYSIS

The mechanical and electrical signals from wind turbines comprise complex instantaneous information in both time and frequency domains. The shaft torque signals are also very noisy. Therefore wavelet analysis has been used to process the data in this paper, the Discrete Wavelet Transforms (DWT) are applied to removing noise and the Continuous Wavelet Transforms (CWT) to extracting 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

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \quad (11)$$

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

$$CWT_{a,b}(t) = \int_{-\infty}^{\infty} x(t)\psi_{a,b}(t)dt \quad (12)$$

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.

$$DWT_{j,n}(t) = CWT_{2^j,2^j n}(t) = \frac{1}{\sqrt{2^j}}\int_{-\infty}^{\infty} x(t)\psi\left(\frac{t}{2^j} - n\right)dt \quad (j,n \in Z) \quad (13)$$

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

$$x(t) = \sum_{n=-\infty}^{\infty} a_{0,n}(t)g_{0,n}(t) + \sum_{j=0}^{\infty}\sum_{n=-\infty}^{\infty} d_{j,n}(t)h_{j,n}(t) \quad (14)$$

where $g(t)$ is a low-pass filter and $h(t)$ is a high-pass filter. Therefore, the first term in (14) 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.

$$\hat{x}(t) = \sum_{n=-\infty}^{\infty} \hat{a}_{0,n}(t)g_{0,n}(t) + \sum_{j=0}^{\infty}\sum_{n=-\infty}^{\infty} \hat{d}_{j,n}(t)h_{j,n}(t) \quad (15)$$

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

- Hard thresholding:

$$\hat{d}_{j,n}(t) = \begin{cases} d_{j,n}(t) & if \quad |d_{j,n}(t)| > \theta \\ 0 & if \quad |d_{j,n}(t)| \le \theta \end{cases} \quad (16)$$

- Soft thresholding [11]:

$$\hat{d}_{j,n}(t) = \begin{cases} d_{j,n}(t) - \theta & if \quad d_{j,n}(t) > \theta \\ 0 & if \quad |d_{j,n}(t)| \le \theta \\ d_{j,n}(t) + \theta & if \quad d_{j,n}(t) < \theta \end{cases} \quad (17)$$

with

$$\theta = \sigma\sqrt{2\log(N)} \quad (18)$$

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 is guaranteed.

V. 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.

A. 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.3, 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.4.

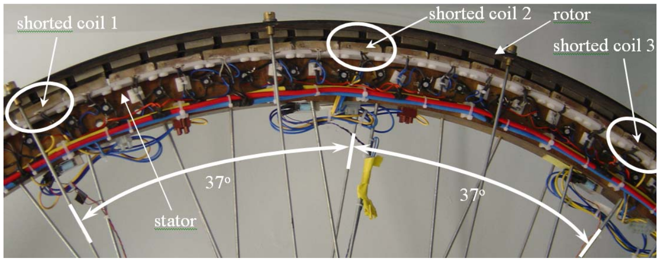

Fig.3 Simulating a stator winding fault by shorting coils.

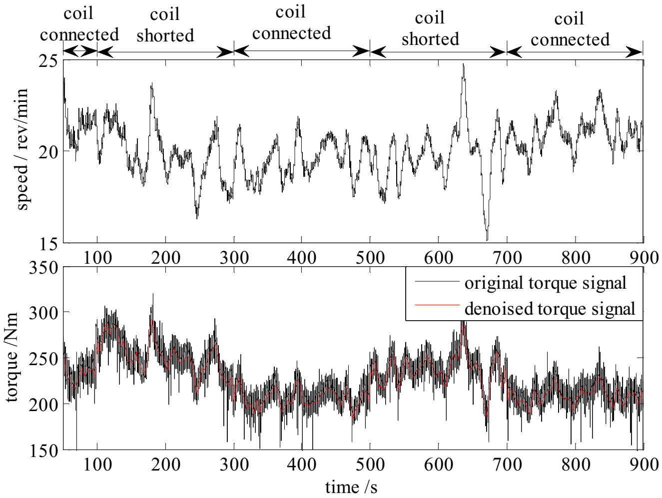

Fig.4 The torque and speed signals when the coils are connected and shorted

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

Fig.5 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.

B. Rotor Imbalance Fault

One more proof for demonstrating the effectiveness of the proposed criterion *C* 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,
- Unequal icing on the blade surface,
- Impact/fatigue damage to the blade.

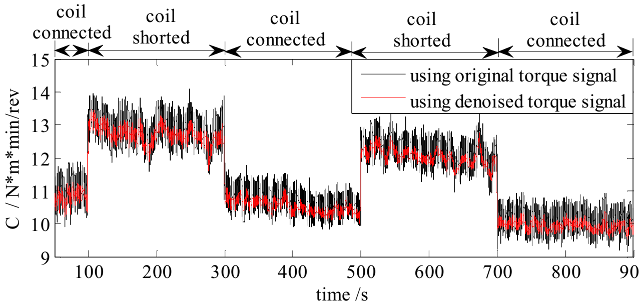

Fig.5 Criterion *C* derived in the case of generator winding fault

Once the rotor is unbalanced a strong vibration at the shaft rotational frequency will be introduced. It travels along the wind turbine drive train, and finally arrives at the generator. Consequently, 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 on which the unbalance happens.

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.6, 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.7.

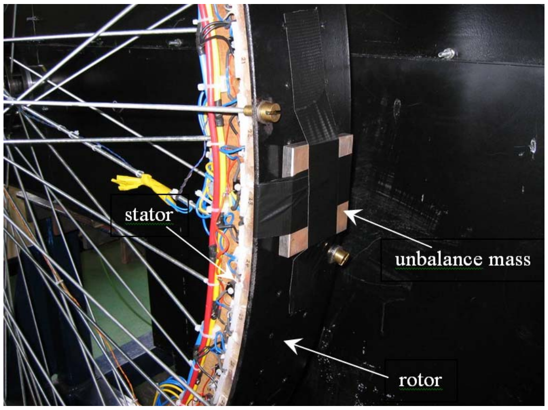

Fig.6 Simulation of a rotor imbalance fault

Likewise, the DWT was applied to remove the noise before performing the calculation of criterion *C*. The de-noised torque signal is also plotted in Fig.7, 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 wind turbine. Subsequently, the criterion *C* is calculated and the calculation results are shown in Fig.8, in which the result derived using the original torque signal is also shown for comparison.

From Fig.8, it is found that criterion *C* shows a large fluctuation when the unbalance mass is attached, becoming stable immediately as soon as the unbalance mass is removed. Thus, it can be concluded that rotor imbalance can be successfully distinguished by using the proposed technique.

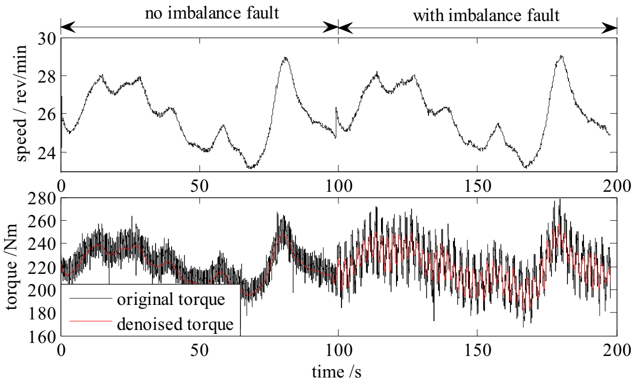

Fig.7 The torque and speed signals in the case of rotor imbalance fault

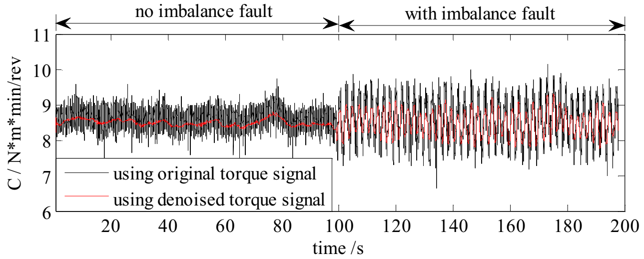

Fig.8. Criterion *C* in the case of rotor imbalance fault

Both Figs.5 and 8 reveal that criterion *C* is an effective and versatile measure for detecting both the mechanical and electrical changes in wind turbine with synchronous generator and the application of wavelet-based de-noising technique further strengthens it.

VI. DIAGNOSING WIND TURBINE DRIVE-TRAIN MECHANICAL FAULTS BY GENERATOR ELECTRICAL SIGNAL ANALYSIS

The vibro-acoustic analysis 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 [4]. However, this approach involves the use of a number of transducers and a consequent high capital cost, for example a system recently developed by Bently Nevada [12] 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 (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 situations. Thus, 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 approach 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 [12] 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 [5] . As depicted in Section 5.2, the unbalanced rotor was simulated by attaching an unbalance mass to the rotor (see Fig.6). 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.9.

From Fig.9, 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 and the calculation results are shown in Fig.10.

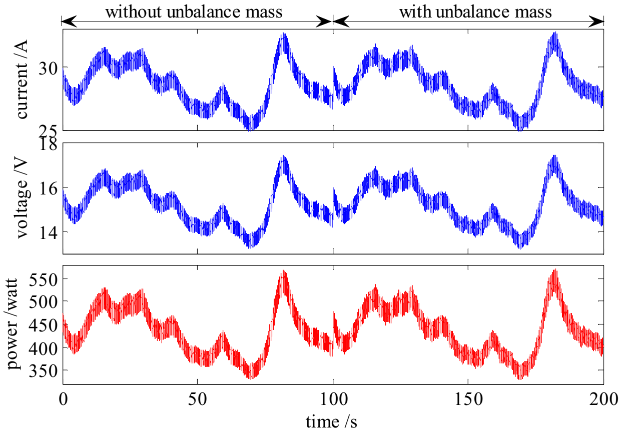

Fig.9 Electrical signals in the case of rotor imbalance fault

From Fig.10, it is clearly seen that when the imbalance fault occurs a characteristic frequency appears at about 0.44Hz, corresponding to the rotational speed of 26 rev/min (see Fig.7). Obviously, 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 in analyzing non-stationary signals. With the aid of it, the faulty feature, created by the imbalance fault, was explicitly identified, though the unbalance mass was light compared to the generator rotor mass.

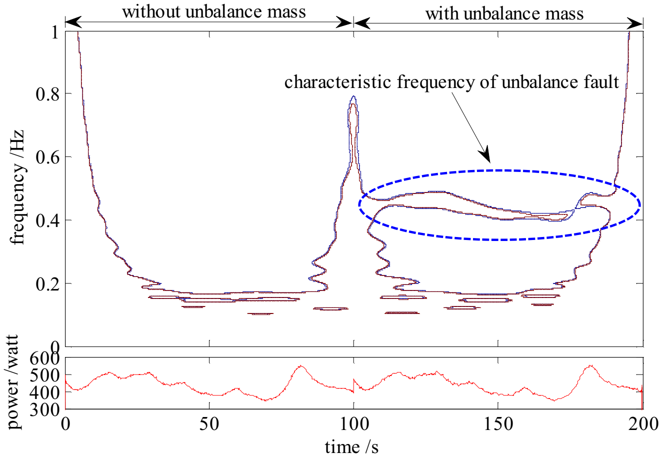

Fig.10 The CWT map of the power signal shown in Fig.9

VII. 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 torque-speed 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 investigations that:

- When the condition monitoring test rig suffered a generator electrical or mechanical fault, the change of its running condition was correctly detected by using the condition monitoring technique proposed, based upon the criterion C, rather than resorting to traditional vibration analysis.
- 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 the 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.
- Further work will be required to develop these techniques and also to consider the effects on the method not only of variations in the turbine output but also in the grid conditions to which the turbine is connected.

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