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Condition Monitoring and Fault Diagnosis of a Wind Turbine with a Synchronous Generator using Wavelet Transforms

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Abstract

Some large wind turbines use a low speed synchronous generator, directly-coupled to the turbine, and a fully rated converter to transform power from the turbine to mains electricity. This paper considers the 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 information in turbine signals derived from the wind, which is variable and noisy. A new condition monitoring technique is proposed which removes the negative influence of variable wind in machine condition monitoring. The technique has a versatile function to detect mechanical and electrical faults in the wind turbine. Its effectiveness is validated by experiments on a wind turbine condition monitoring test rig using a permanent-magnet synchronous generator, which can be driven by aerodynamic forces from a drive motor controlled by an external model, representing wind and turbine rotor behaviour. Within the technique wavelet transforms are employed for noise cancellation and are extended to diagnose faults by taking advantage of their powerful capabilities in analysing non-stationary signals. The diagnosis of wind turbine rotor imbalance in the will be used as an illustrative example, heralding the possibility of detecting a wind turbine mechanical faults by power signal analysis.

1 Introduction

The development of wind turbine technology has benefited from the government decisions favourable to 'green' or renewable power. Wind turbines are becoming economically a viable alternative to conventional fossil-fuelled power generation. In some countries, notably Germany and Denmark, wind turbines have been playing a vital role in the power network, although not without some problems [1]. However, wind turbines do experience failures [2], due to their variable load condition and aggressive operating environment, however, turbines are beginning to show a reliability that is better than other forms of power generation, for example diesel generators. So developing economic condition monitoring and fault diagnosis techniques for them would be highly desirable and this will be especially important if they are deployed offshore. SCADA techniques are being applied widely to wind turbines but the data rate, once every 5-10mins, is too slow for most rotating machine fault diagnosis. There are many techniques developed in electric power production, aerospace, marine propulsion, and other process industries that could be applied to wind turbines [3]. However, the results to date have not proved satisfactory, 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 [4]. However, the majority of wind turbine condition monitoring and fault diagnosis techniques proposed have used the Fourier Transform (FT), which is less capable of solving the problem due to its shortcomings in dealing with non-stationary signals. In view of this, the potential application of the wavelet transform to the condition monitoring and fault diagnosis of wind turbines is investigated in this paper as an extension of the 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. A new technique, inspired by the torque-speed data obtained from a series of full and half-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 power signal analysis is also investigated with the aid of the CWT.

2 Test Rig

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.

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 a three phase rectified output fed to a resistance load bank. The system is instrumented using 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. 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. Both generator electrical and wind turbine mechanical faults were simulated on the test rig as follows:

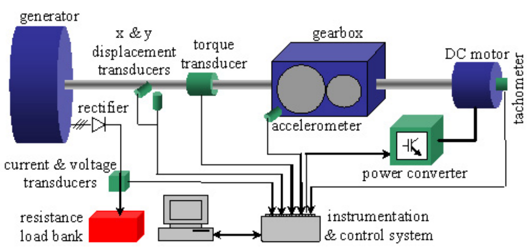

Fig.1: Wind turbine test rig.

- A generator stator winding fault was simulated by simultaneously shorting 3 coils on the stator;
- A full short circuit fault was simulated by connecting the phase terminals of the generator to ground;
- A rotor imbalance fault was simulated by attaching a mass to the outer surface of the generator rotor.

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.2. The polynomial equations fitting to these data are also derived with the aid of the polynomial curve fitting technique [7]. In Fig.2, the fitting curves and the corresponding polynomial equations are given for facilitating analysis.

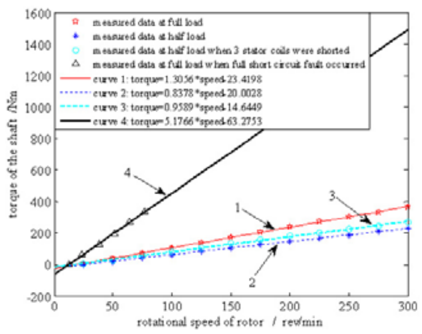

Fig.2: The shaft torque and speed data measured in the full and half-load tests.

From Fig.2, 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 [8], the following relations exist between the torque and speed of a synchronous generator wind turbine:

$$\begin{cases} \omega_s = \omega_r / r_g \\ T \propto \omega_s / X_a \\ T_{pm} \approx T \end{cases} \quad (1)$$

where ω_r represents the rotational speed of the DC motor, ω_s the rotational speed of the synchronous generator and r_g the gear ratio, X_a the synchronous reactance of the generator, T_{pm} the mechanical torque created by wind force, and T the torque created by generator.

With the aid of Eq.(1) the proposed technique will use a criterion C as a versatile function for monitoring the running condition of the wind turbine, i.e.

$$C = T/\omega_s \quad (2)$$

where both torque T and speed ω_s are measured on the generator shaft. Criterion C can be used not only to monitor the presence of a drive train mechanical fault, but also 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 T_{pm} and ω_r.

4 Condition monitoring of the wind turbine

In order to verify the effectiveness of C in wind turbine condition monitoring, two illustrative examples are given in the following Sections.

4.1 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. When the connection state of the coils was changed periodically, the torque and rotational speed signals were collected from the generator shaft. The time-waveforms of the signals are shown in Fig.3.

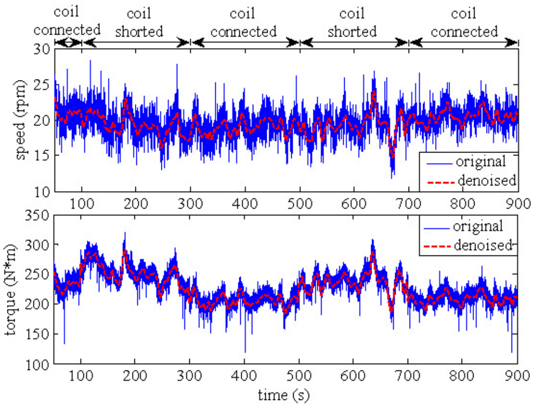

Fig.3: The torque and speed signals when the coils are well connected and shorted periodically.

From Fig.3, it can be seen that the shaft torque and rotational speed are indeed very noisy as. So a de-noising process is essential before using them to calculate criterion *C*. By using the DWT, the signals are de-noised and the results are also plotted in Fig.3. Obviously, the noise contained in the original signals has been successfully removed. Then, *C* is calculated and shown in Fig.4, in which the results obtained from the original signals are also shown for comparison.

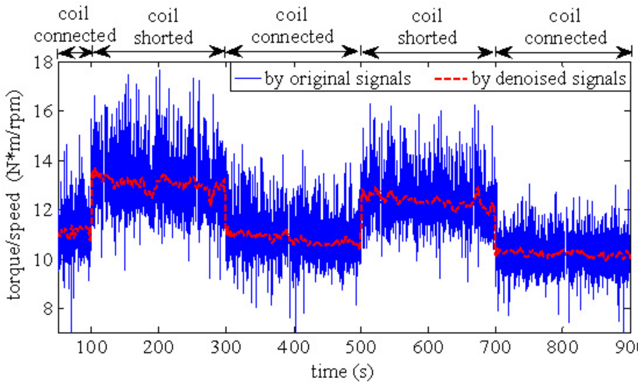

Fig.4: Criterion *C* derived in the case of generator winding fault.

Fig.4 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*.

4.2 Rotor Imbalance Fault

One more proof of the effectiveness of *C* is given by the detection of a rotor imbalance fault. It is known that wind turbine rotors are prone to imbalance due to damage to blades or unequal icing. Once the rotor is imbalanced a strong vibration at the shaft rotational frequency will be introduced into the system. It travels along the drive train, and finally arrives at the generator and a dynamic air-gap eccentricity is introduced. The characteristic frequency of this type of fault will be the rotational frequency of the shaft where the imbalance happens. A rotor imbalance fault was simulated by directly attaching a 1.027kg weight mass to the outer surface of the generator rotor. The shaft torque and rotational speed signals collected before and after the attachment of the unbalance mass are shown in Fig.5.

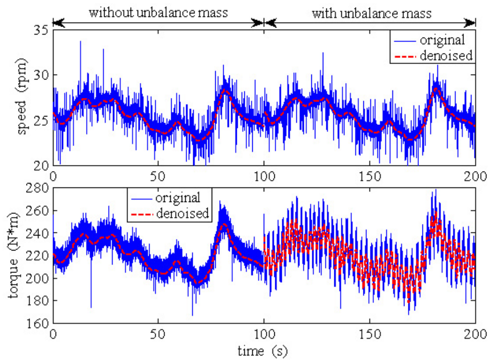

Fig.5: The torque and speed signals in the case of rotor imbalance fault.

The DWT was applied to remove the noise before performing the calculation of *C*. The de-noised signals are also plotted in Fig.5, from which a significant fluctuation of shaft torque due to the unbalance mass is clearly observed. By using the de-noised signals, *C* is calculated and the results are shown in Fig.6.

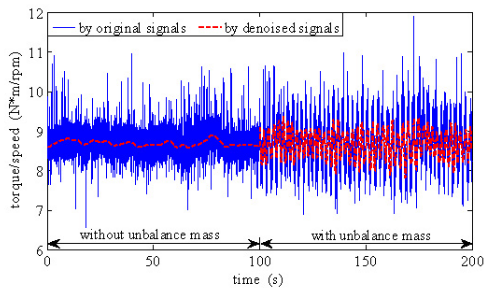

Fig.6: *C* in the case of rotor imbalance fault.

From Fig.6, 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.

5 Diagnosing mechanical faults

The vibro-acoustic method is traditionally popular for diagnosing the mechanical faults in rotating machines. However, this approach involves the use of a considerable number of transducers with a consequent cost. For example a system recently developed by Bently Nevada [9] includes 8 accelerometers (2 for nacelle, 1 for main bearing, 3 for drive train, and 2 for generator), 2 displacement transducers and one keyphasor transducer. These transducers are connected to a dedicated data acquisition and processing device known as a Dynamic Scanning Module (DSM). This sort of condition monitoring systems is sophisticated and costly and probably cannot be justified on a wind turbine except for the most high risk locations. Furthermore, the compact nature of the wind turbine nacelle means that transducer installation is difficult.

Reducing the number of transducers required for condition monitoring a wind turbine is strongly recommended. To meet this aim, the possibility of detecting wind turbine mechanical faults using the generator power signal analysis as proposed in [3] is investigated. If this works, the number of transducers fitted to a wind turbine could be significantly reduced. To prove the feasibility of this idea, a rotor imbalance fault is diagnosed using the terminal power signal of the generator. 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.7. In order to detect the faulty feature CWT is applied to the power signal, and the results are shown in Fig.8.

From Fig.8, 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.5). 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.

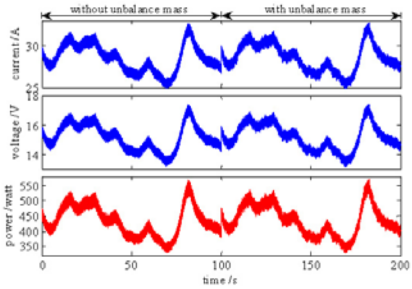

Fig.7: Electrical signals in the case of rotor imbalance fault.

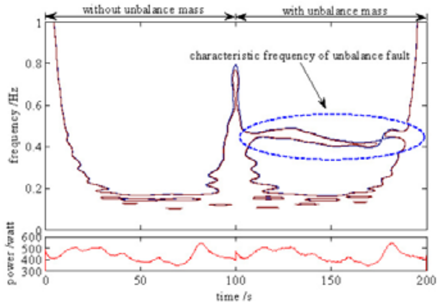

Fig.8: The CWT map of the power signal.

6 Conclusions

From these preliminary investigations, it has been concluded 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*, rather than by using traditional vibration signals.
- The DWT has a powerful de-noising 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 shaft torque, 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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