

Research on a Simple, Cheap but Globally Effective Condition Monitoring Technique for Wind Turbines

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Abstract- Vibration measurement and lubrication oil analysis are used in wind turbines (WT) as condition monitoring systems (CMS). However, they do not provide a complete solution to the WT CMS problem. The former measurement is sophisticated with high hardware costs, suffering from spurious alarms; the latter monitors the wear and fatigue of gears and bearings, but cannot detect electrical abnormalities occurring in the WT generator and electrical system. So, a simpler, cheaper but moreover globally comprehensive WT CMS is still needed, especially if the WTs are to go offshore, where they are confronted with higher risks and difficulties of access. To meet this requirement, a new WT condition monitoring technique has been researched in this paper. As the WT operates over a widely varying power range, dependant on the stochastic variations of the wind, the monitoring signals are usually non-stationary. In view of this, a wavelet-based adaptive filter is designed to extract the power energy at prescribed, fault-related frequencies which vary with time. The energy information obtained is then used as an indicator of WT condition. The central frequency of the filter is adaptive to the average rotational speed of the generator, and the filter bandwidth depends upon the fluctuation of wind speed. By using this filter, fault features can be extracted whether the WT runs at fixed or variable speed. The proposed technique has been experimentally validated on a WT Test Rig using both synchronous and induction generators as exemplars. Experiments prove that the proposed technique is efficient in assessing the WT condition for both mechanical and electrical abnormalities.

I. INTRODUCTION

Nowadays, with the extensive use of WTs all over the world, the condition monitoring of these machines is attracting attention from both industry and academia. Currently, almost all condition monitoring techniques being used in the wind industry, e.g. vibration measurement and lubrication oil analysis, are borrowed from other industries [1] where they have achieved success. However, they have not yet proved their success in the wind industry due to the peculiarities of the WT, which has a slow and variable speed. The present vibration-based condition monitoring systems (CMSs) are sophisticated, costly and not necessarily adapted to all types of WTs. The oil particle counter designed for detecting the wear/fatigue of mechanical components is unable to detect electrical failures occurring elsewhere in the WT. However, reliability surveys show that WT electrical system has similar or even higher failure rate than its mechanical system [2, 3]. For these reasons, a simpler, cheaper but moreover globally

comprehensive WT CMS is still needed and this paper will report such a technique.

From a global view, the mechanical torque and speed of driving shaft and the generator electric power output can respectively be regarded as the input and output of a WT. As a result of the electro-mechanical coupling of the generator, both energy flows will be disturbed by mechanical and electrical abnormalities occurring in WT. Therefore, in a theoretical sense WT condition monitoring and fault diagnosis should be applicable to either of them. However, the torque signal is costly and difficult to extract in practice, so this research will be based entirely on power signal analysis.

II. DESIGN OF A WAVELET-BASED ADAPTIVE FILTER

The Continuous Wavelet Transform (CWT) has demonstrable merits in processing non-stationary WT signals [5], therefore a wavelet-based adaptive filter, based on the CWT, is designed in this work to extract the power energy at various fault-related frequencies. The CWT of a real-time signal $x(t)$ is defined as [6]

$$CWT(b, a) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \psi^* \left(\frac{t-b}{a} \right) dt \quad (1)$$

where $\psi(t)$ is the mother wavelet, which is Morlet wavelet in this work. a and b respectively represent the parameters of wavelet scale and time-shift. The asterisk '*' stands for the complex conjugate.

Traditionally, the wavelet function $\psi(t)$ is dilated or compressed continuously by changing the parameter a , so that the signal components within frequency range $\omega \in [0, \text{half sampling frequency}]$ are projected onto appropriate frequencies in the entire time-frequency space. An illustrative example of the CWT is given in Fig.1.

It can be easily imagined that this conventional use of the CWT will be computationally intensive. Moreover, most of the calculations are unnecessary for machine condition monitoring, because the fault-related frequencies are few, and the other frequency band does not require analysis. In addition, a computationally inefficient algorithm is less suitable for on-line condition monitoring, than for off-line signal processing. A more efficient algorithm for use on-line would extract only the fault-related frequency components.

Two more difficulties limit the application of the CWT in WT condition monitoring. The first is that the conventional CWT manifests the signal in time-scale, rather than in time-

frequency domains, it is inconvenient to relate a fault-related characteristic frequency to a wavelet scale. The second is that the frequencies of those fault-related components in WT signals are constantly varying with time and tracking these varying characteristic frequencies to extract its energy accurately is a tough task. The conventional CWT does not give a satisfactory answer to these difficulties.

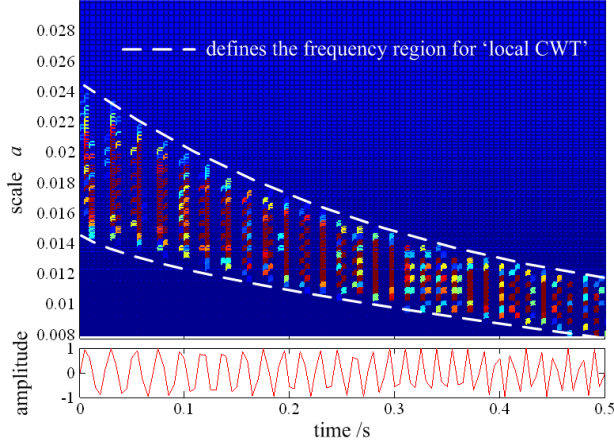


Fig.1 An illustrative example of the CWT.

To remove the difficulties an adaptive filter has been designed to extract a prescribed time-varying frequency component from the WT power signal. An adaptive, two-dimensional, time-frequency sliding window is specially designed to accomplish this task. It is shown in Fig.2. Its time duration is T , its central frequency ω_c is the mean value of the characteristic frequency during T and adaptive to the rotational speed of the WT driving shaft. The cut-off frequencies ω_{upper} and ω_{lower} of the sliding window depend upon the fluctuation ω_f of the characteristic frequency during the time duration T .

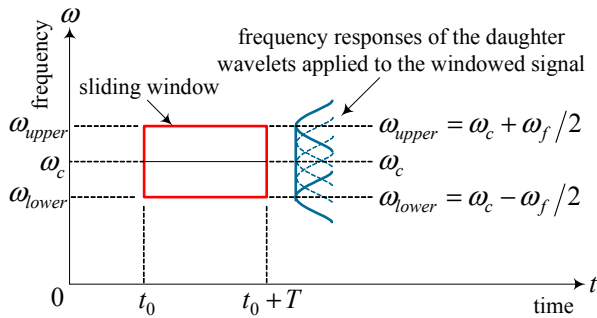


Fig.2 The two-dimensional sliding window.

From Fig.1, it is seen that ω_f is probably also varying. For WT, ω_f is intrinsically dependant on the fluctuation of wind speed/direction and air density at the time. Practice shows that the fluctuation rate of onshore wind speed is 12~20% approximately, while offshore is about 6%. According to [7], the following relation exists between a frequency ω and a wavelet scale a :

$$a = \frac{\omega_0}{\omega} \quad (2)$$

where ω indicates the frequency of interest and ω_0 is the reference frequency, in this work the central frequency of the mother wavelet.

With the aid of (2), the scale range for implementing the filter related 'local CWT' is defined as:

$$a \in [a_c - a_f/2, a_c + a_f/2] \quad (3)$$

which corresponds to frequency range:

$$\omega \in [\omega_c - \omega_f/2, \omega_c + \omega_f/2] \quad (4)$$

where $a_c = \omega_0/\omega_c$ and $a_f = \omega_0/\omega_f$.

Subsequently, by implementing the CWT locally in the scale range defined by (3), a matrix of wavelet coefficients is obtained, i.e.:

$$CWT_{local}(b, a) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \psi^* \left(\frac{t-b}{a} \right) dt \quad a \in [a_c - a_f/2, a_c + a_f/2] \quad (5)$$

The energy, A , of the frequency of interest during the period, T , is characterized by:

$$A(t_0 + T/2) = \max(CWT_{local}(a, b)) \begin{cases} a \in [a_c - a_f/2, a_c + a_f/2] \\ b \in [t_0, t_0 + T] \end{cases} \quad (6)$$

Then, move the sliding window forward along the time axis of the signal, define the scale range again, according to the shaft speed in the new time duration and conduct the 'local CWT' of the new windowed signal. In the end, get the energy, A , of the frequency of interest during the new period, T .

These calculations are then repeated until the whole data series of the inspected signal has been analyzed. Finally, the variational tendencies of the energy in the frequency band of interest are obtained, from which the running condition of the WT can be assessed.

This task could of course, be accomplished by a series of conventional band-pass filters, but a conventional filter would not have the feature extraction advantages of the CWT from non-stationary signals. This point has been demonstrated in previous literature, so the comparison of these two approaches will not be repeated here to keep the present paper concise.

III. ADVANTAGES OF APPLYING GENERATOR TOTAL POWER SIGNAL TO WIND TURBINE CONDITION MONITORING

Wind turbine converts the kinetic energy of the wind into electric power. It consists of both mechanical and electrical conversion, control and transmission systems. The structure of a real large scale wind turbine is shown in Fig.3.



Fig.3 Structure of a real large wind turbine.

Currently, the WT condition monitoring is accomplished mainly by analyzing vibration signals from critical components, such as the main bearing, the blades, the gearbox and generator bearings. The wear of the gearbox can also be monitored by temperature measurement or lubrication oil analysis. In recent years, with the further development of non-destructive testing techniques, some more advanced techniques like optical strain measurements have also been adopted to monitor the WT blade [8]. The application of these techniques does improve machine reliability, but to date these methods have not been widely adopted in the onshore wind industry because of the capital cost involved, the risk of false/missed alarms and the fact that the methods are not globally applicable to all types of WT. Furthermore the necessity of condition monitoring is not so great onshore, where access is simple and turbine condition can be ascertained during maintenance engineer visits. However, offshore the same will not be true and the need for a CMS is more pressing.

So, a simpler, cheaper, globally comprehensive WT CMS is still needed.

From a global view, the mechanical torque and speed measured on the WT driving shaft and the total 3-phase electric power measured from the terminals of the generator are the input and output of a WT system and both energy flows are disturbed by WT abnormalities caused by mechanical or electrical faults[9]. In view of this it is considered that these two power flows will definitely benefit the condition monitoring of a WT. At present, some commercially available WT SCADA systems do collect generator electric signals (e.g. current and voltage signals), but few them apply these signals to condition monitoring. Considering the difficulties of measuring shaft torque signal from real wind turbines (e.g. the WT shown in Fig.3), this research is conducted based on analyzing the 3-phase total power signals measured from the terminals of WT generator.

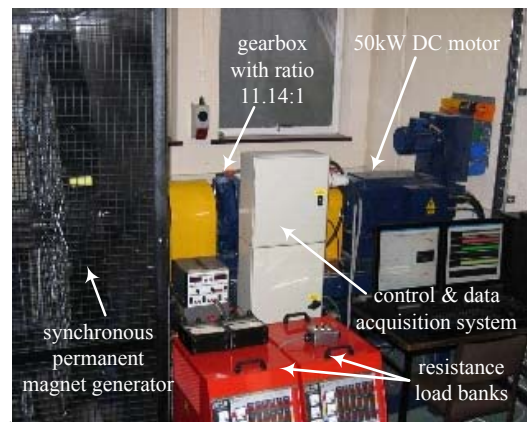
In comparison to classical vibration/temperature/ lubrication oil measurement, the generator total power signal possesses the following advantages in WT condition monitoring:

- It reduces the number of transducers. Moreover, the transducers used to measure power signal are relatively cheaper than accelerometers and the oil particle counter. So, using total power measurement should be a simple and cost-effective approach;
- The power signal is already available in all WTs whether geared or direct drive. Moreover, it can be accessed conveniently. So, the power signal analysis has global application.
- Both mechanical and electrical failures occurring in WT will disturb its power output signal. In turn, the power signal carries the information from both mechanical and electrical abnormalities in WTs. So, the power analysis is a globally effective approach.
- The total three phase power signal benefits over the single phase power signal by the absence of the line frequency component and its higher harmonics. This makes faults easier

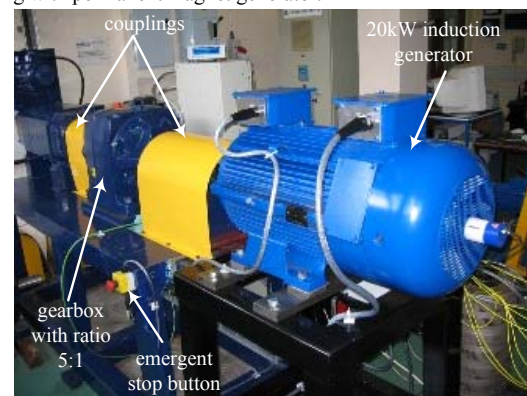
to observe and extract from the total power signal making it more sensitive to WT faults.

IV. CONDITION MONITORING BY POWER SIGNAL ANALYSIS

In view of above, the WT generator total power signal will be employed to develop a new condition monitoring technique accomplished by tracking the energy variation of fault-related frequency components, using the wavelet-based adaptive filter designed in Section II. This approach has been experimentally validated on a wind turbine condition monitoring test rig, which is equipped with either a permanent magnet synchronous generator or an induction generator. The test rig is shown in Fig.4. The rig comprises a 50kW DC variable speed-driven controlled motor and a two-stage gearbox. The synchronous generator is a 10 kW, 3-phase permanent-magnet machine with 84 stator coils, 108 rotor magnets with a rectified output fed to a resistance load bank. The induction generator is a 32kW, 3-phase, wound rotor machine, the rotor circuit contains 3-phase resistances, so that a rotor circuit imbalance can be simulated and the stator is connected to the 3-phase mains. The system has been 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.



(a) test rig with permanent magnet generator.



(b) test rig with induction generator.

Fig.4 Wind turbine drive train test rig.

Both electrical and mechanical drive train faults could be simulated on the test rig. In this paper only a rotor mass imbalance fault has been simulated on the synchronous generator, as shown in Fig.4a, and a rotor electrical imbalance fault simulated on the induction generator, as shown in Fig.4b. These two faults were considered as illustrative examples for demonstrating the effectiveness of the proposed approach in WT condition monitoring in the following two paragraphs:

A. Rotor imbalance as shown in shown in Fig.4a

In the experiment, the rotor imbalance fault was simulated by directly attaching a 1.027kg weight mass to the outer surface of the generator rotor.

When the synchronous generator ran at varying speed, the speed and torque were measured from the driving shaft, and the total power signal was measured at the generator terminals using a sampling frequency of 1kHz. The time-waveforms of the signals before and after the unbalance mass was attached to the rotor are shown in Fig.5.

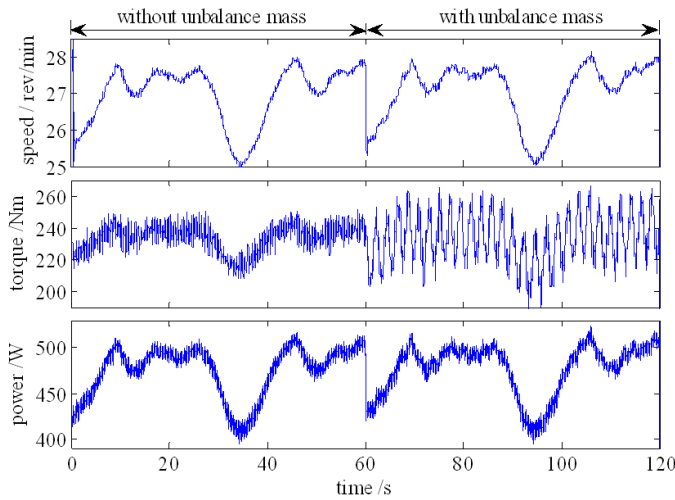


Fig.5 Signals when a rotor imbalance fault was simulated

From Fig.5, it can be seen that when unbalance was present, the torque signal measured from the driving shaft gave an apparent response. It fluctuated with a large dynamic range at the rotational frequency of the generator. By contrast, no obvious symptom could be observed from the generator power signal. This is because the rotor and stator of the generator are both supported by steel spokes [10] and the unbalance mass did not cause a significant change between them affecting the machine air gap. As the air gap was undisturbed the generator power was not significantly affected by the fault. However, even in such a situation, the power signal should be affected by unbalance and the proposed technique will seek to identify this effect. What Fig.6 shows are the variations of the generator rotational frequency and its power energy extracted by using the adaptive wavelet-based filter designed in Section II.

From Fig.6, it can be seen that the mechanical unbalance caused the power 'A' at generator rotational frequency to increase, though the increment was small. This experiment

provides a proof of the powerful capability of the proposed approach in detecting incipient WT faults.

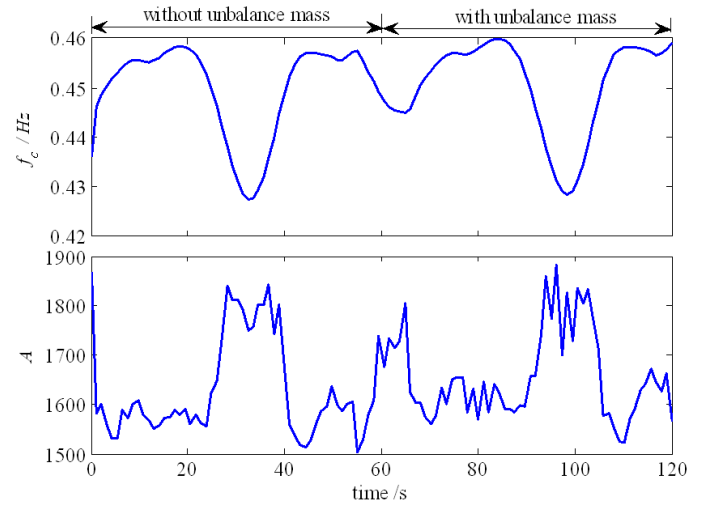


Fig.6 Characteristic frequency and its energy before and after a mechanical imbalance fault occurs.

From Fig.6, it can be seen that the mechanical unbalance caused the power 'A' at generator rotational frequency to increase, though the increment was small. This experiment provides a proof of the powerful capability of the proposed approach in detecting incipient WT faults.

B. Phase circuit imbalance as shown in Fig.4b

The phase circuit imbalance fault was simulated by adjusting the phase resistance of the generator rotor using an externally connected resistance load bank. Likewise, the rotational speed and mechanical torque of the driving shaft and the generator total power signals were collected in the experiment when the phase circuit imbalance fault was periodically applied to the generator rotor. The signals obtained in this experiment are shown in Fig.7.

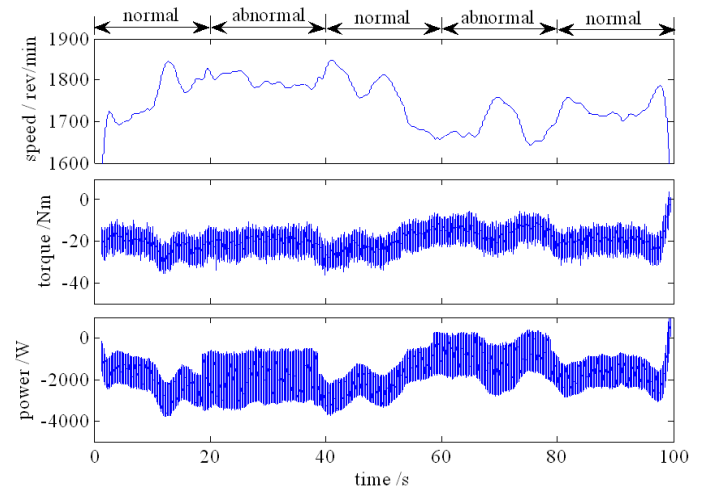


Fig.7 Signals when a phase circuit imbalance fault was simulated in the generator rotor.

From Fig.7, it is seen that as the shaft speed was varying, the fault symptoms cannot be observed clearly from either shaft

torque or total power signals. Considering that an opposing magnetic field will be created in the air gap of the machine when the rotor phase resistances are imbalanced, which will be modulated at $2f_s$, the wavelet-based adaptive filter designed in Section II is applied to track the power variation at twice slip frequency $2f_s$. The computational results are shown in Fig.8.

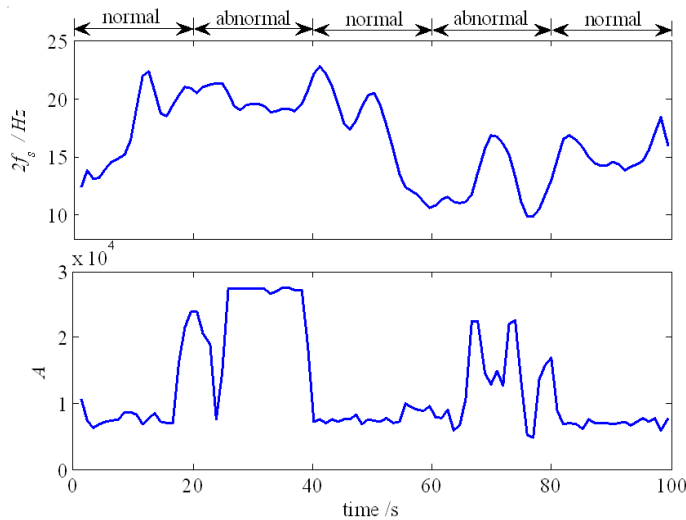


Fig.8 Condition monitoring of the WT with an induction generator.

From Fig.8, it is found that, although the twice slip frequency varies under fault conditions, it does not provide a significant indication in the power time waveform, however, the power change is clearly identified by the adaptive filter. In other words, in the experiment the occurrence of the faults has been correctly predicted by the energy 'A' extracted using the filter.

V. CONCLUDING REMARKS

In view of the need to improve the availability of WTs, the use of cost-effective, commercial, condition monitoring techniques, a simple, cheap but globally effective WT condition monitoring technique has been researched using a wavelet-based adaptive filter. Experiments show that the proposed technique is not only valid for detecting electrical faults in WT generator, but also effective in monitoring mechanical faults in the drive train even though the rotational speed of the WT is constantly varying. The technique may be applied to all types of WTs because power signals are available from all of them.

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