Current-Based Online Bearing Fault Diagnosis for Direct-Drive Wind Turbines via Spectrum Analysis and Impulse Detection

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Abstract--**Online fault diagnosis is an effective means to improve wind turbine reliability and performance and reduce wind turbine operating and maintenance costs. Current-based fault diagnosis techniques have received more and more attention in academia and industry due to their nonintrusive character and economic advantages. This paper presents an algorithm based on power spectral density (PSD) analysis for bearing fault signature extraction of direct-drive wind turbines by only using stator current measurements. An impulse detection method is then applied to screen out the excitations in the PSD spectrum, where the excitations at the characteristic frequencies of the bearing fault are extracted as the fault signature. A median filter-based method is then designed to evaluate the physical condition of the wind turbine based on the extracted fault signature to determine whether maintenance is required. Experimental results are provided to demonstrate the effectiveness of the proposed method for bearing faults diagnosis of a direct-drive wind turbine operating at variable-speed conditions.**

Index Terms--**Bearing fault, current measurement, power spectral density (PSD) analysis, impulse detection, median filter, direct-drive wind turbine, fault diagnosis.**

I. Introduction

THE penetration of wind power has increased greatly over the last decade in the United States and across the world. The American wind power industry installed 1,118 MW of new capacity in the first quarter of 2011 alone and entered the second quarter with another 5,600 MW under construction [1]. By 2030, wind energy is expected to provide 20% of the U.S. electricity needs [2]. As the number of wind turbines continues to grow, the need for effective condition monitoring and fault diagnosis systems becomes increasingly important [3]. Online condition monitoring and fault diagnosis is an effective means of not only increasing the reliability, but also reducing the costs associated with operation and maintenance of wind turbines.

Current-based (mechanical-sensorless) fault diagnosis techniques use generator current measurements that have been used by the control system of a wind turbine generator (WTG); no additional sensors or data acquisition devices are needed. Moreover, current signals are reliable and easily accessible from the ground without intruding the WTGs. Therefore, current-based fault diagnosis techniques have great economic benefits and potential to be adopted by the wind power industry. Many studies have shown that the signatures of WTG bearing faults are able to be successfully extracted by using stator current measurements [4], [5]. Furthermore, the signatures of other wind turbine faults can also be extracted, as long as they have one or more characteristic frequencies in the measured current signals [6].

In practical applications, it is desired to evaluate the wind turbine condition solely based on the fault signature in real time. When a bearing fault signature is detected, it indicates that the bearing corresponding to the fault signature is in a deteriorated condition and maintenance is required. For a bearing fault which generates excitations in the PSD of the processed current signal, an impulse detection method can be applied to screen out the signature of the bearing fault. There are many impulse detection methods based on signal statistics [7], fuzzy algorithm [8], and median filter [9]. Since the design of the algorithm for impulse detection is determined by the patterns of the processed signals, an effective method for detecting impulses in frequency spectra is required in this research.

This paper proposes a current-based online bearing fault diagnosis method for direct-drive wind turbines via spectrum analysis and impulse detection. The proposed method firstly estimates the shaft rotating frequency from generator stator current measurements. The variable characteristic frequencies of wind turbine bearing faults in the PSD of the estimated shaft rotating frequency signal are then converted to constant values by using the 1P-invariant PSD method proposed in [6]. An impulse detection method is then developed to detect and quantize the excitations (i.e., impulses) generated by bearing faults in the 1P-invariant PSD of the estimated shaft rotating frequency signal. The detected impulses are then used to evaluate the health condition of the wind turbine bearings. The proposed method is validated by experimental studies for bearing fault diagnosis of a direct-drive WTG operating in variable-speed conditions.

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II. Online Bearing Fault Diagnosis

A. Characteristic Frequencies of Bearing Faults

According to [10], the fault characteristic frequencies of a ball bearing in vibration measurements can be computed as functions of the geometry and rotating frequency of the bearing.

$$f_i = 0.5\cdot N_B\cdot f_r\cdot(1 + D_b\cdot\cos\theta/D_c) \quad (1)$$

$$f_o = 0.5\cdot N_B\cdot f_r\cdot(1 - D_b\cdot\cos\theta/D_c) \quad (2)$$

$$f_b = 0.5\cdot f_r\cdot (D_c/D_b)\cdot(1 - (D_b\cdot\cos\theta/D_c)^2) \quad (3)$$

$$f_c = 0.5\cdot f_r\cdot(1 - D_b\cdot\cos\theta/D_c) \quad (4)$$

where f_i is the characteristic frequency of bearing inner-race faults; f_o is the characteristic frequency of bearing outer-race faults; f_b is the characteristic frequency of bearing ball faults; f_c is the characteristic frequency of bearing cage faults; f_r is the rotating frequency of the bearing; N_B is the number of balls in the bearing; D_b is the ball diameter; D_c is the pitch diameter; and β is the ball contact angle, which is normally zero. The schematic diagram of a ball bearing with 8 balls is given in Fig. 1.

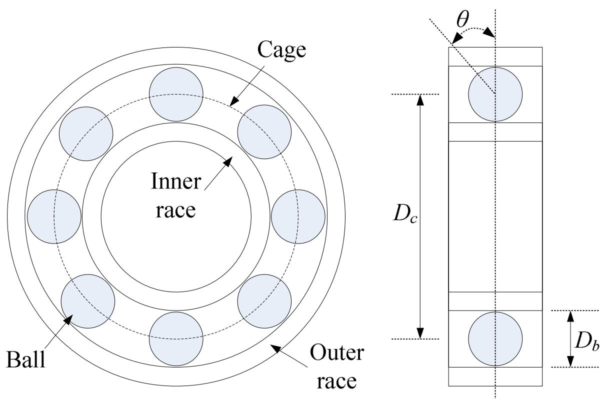

Fig. 1. Schematic diagram of a ball bearing.

The excitations of a bearing fault appear not only in the frequency spectrum of WTG vibration measurements, but also in the frequency spectrum of WTG shaft rotating frequency signals [11]. Therefore, the excitations at f_i, f_o, f_b, and f_c, in the frequency spectrum of shaft rotating frequency signals are signatures for bearing fault diagnosis. In this paper, the ball bearing 7C55MP4017 is used for the experiments.

B. Current Signal Processing

In the proposed method, only one phase stator current is measured form generator terminals for wind turbine bearing fault diagnosis. The shaft rotating frequency of the WTG is estimated from the stator current measurements. In a direct-drive wind turbine, the relationship between the shaft rotating frequency and the fundamental frequency f_1 of the stator current is given below:

$$f_1 = p\times f_r \quad (5)$$

where p is the number of pole pairs of the generator. A phase lock loop (PLL) model is designed to calculate f_1 from the stator current measurements of the WTG. Then the shaft rotating frequency f_r can be obtained from (5).

By using the method proposed in [5], [6], which is called the 1P-invariant PSD method, the estimated shaft rotating frequency is processed in a way such that the variable characteristic frequencies of the wind turbine bearing faults become constant values in the PSD of the processed shaft rotating frequency signal. The excitations at the characteristic frequencies corresponding to the bearing faults will be extracted as the fault signature.

C. Bearing Fault Signature Extraction and Evaluation

Fig. 2 illustrates the schematic of the overall online bearing fault diagnosis framework for direct-drive wind turbines. The 1P-invariant PSD method is used to convert the variable characteristic frequencies of WTG bearing faults to constant values in the frequency domain. To facilitate the implementation of WTG bearing fault diagnosis in real automatically controlled and operated wind turbine systems, an impulse detection method is developed for automatic extraction of fault signatures in the 1P-invariant PSDs. The extracted fault signatures will be used by a fault signature evaluator to evaluate the health condition of the bearing and to determine whether maintenance is required.

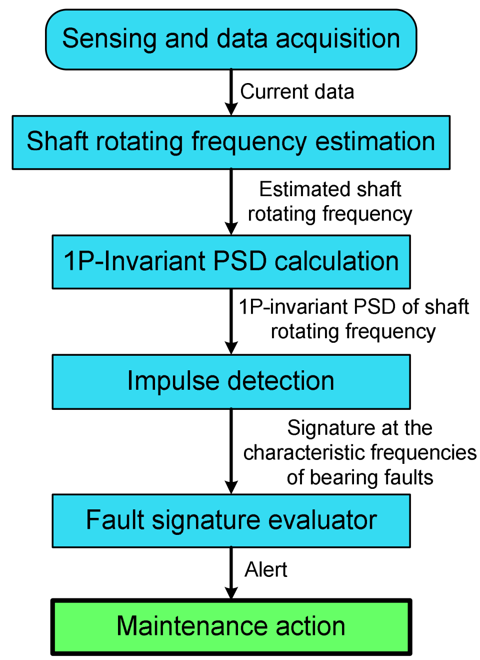

Fig. 2. The flowchart of the overall online bearing fault diagnosis framework for direct-drive wind turbines.

In a PSD spectrum, the magnitude at one frequency represents the energy of the time-domain signal at that frequency. If the signal has high energy around a certain frequency, it will generate an impulse at that frequency in the PSD of the signal. An impulse detection method is proposed to find the impulses in the 1P-invariant PSD signals. It has been reported that the spectra of the vibration of a WTG with three blades are determined by certain events. For instance, the vibration at the 3P frequency, which is three times the shaft rotating frequency f_r of a WTG, is generated by the effect of yaw error, wind shear, or tower shadow [12]. The excitations of the 1P-invariant PSD signals at the 3P frequency are noise for wind turbine bearing fault diagnosis. Therefore, the PSD signals are firstly pretreated by removing the excitations at the 3P frequency. The 1P-invariant PSD of the estimated shaft rotating frequency signals usually has nonstationary amplitudes in the frequency domain. Therefore, a localized method is required for impulse detection of the 1P-invariant PSD.

Assume that $x(f)$ is the sampled 1P-invariant PSD of an estimated shaft rotating frequency signal, where $f = 1, 2, 3, \ldots F$; and F is the length of $x(f)$. Define the energy of the estimated shaft rotating frequency signal at frequency f is:

$$P_x(f) = x(f) \tag{6}$$

If a moving window of length $2W+1$ is applied to $x(f)$, the total energy of the signal in the window is defined as:

$$P_W(f) = x(f-W) + x(f-W+1) + \ldots + x(f+W) \tag{7}$$

The ratio $R(f)$ is defined to be the percentage of the energy of the estimated shaft rotating frequency signal at the frequency f with respect to the total energy of the signal at all the frequencies contained in the moving window:

$$R(f) = P_x(f) \,/\, P_W(f) \tag{8}$$

The resulting $R(f)$ represents the locally normalized 1P-invariant PSD of the estimated shaft rotating frequency signal . If $R(f)$ at a certain frequency point is greater than a threshold T, it indicates that there is an impulse at that frequency. In practice, it is important to automatically generate the threshold T from the PSD signal. The median filter, which is a nonlinear filter, is well known for impulse removal [9]. Define $R_f(f)$ the result of $R(f)$ processed by a median filter. The threshold T is then set to be the maximum value of $R_f(f)$. Since the impulses that are not generated by bearing faults have been removed from the 1P-invariant PSD of the estimated shaft rotating frequency signal during a pretreatment process, the impulses generated by bearing faults have the highest amplitudes in the 1P-invariant PSD of the estimated shaft rotating frequency signals. In this paper, a three-order median filter is chosen to calculate $R_f(f)$ and the threshold T. The $R_f(f)$ is calculated by:

$$R_f(f) = Median[R(f-1), R(f), R(f+1)] \tag{9}$$

where $Median[X]$ stands for selecting the median of the data set X. The threshold T is then obtained as:

$$T = Maximum[R_f(f)] \tag{10}$$

where $Maximum[\ ]$ stands for the maximum value of $R_f(f)$.

In the 1P-invariant PSDs, the amplitudes of the impulses at the characteristic frequencies of bearing faults are the signature for wind turbine bearing fault diagnosis. Since there are no impulses at the characteristic frequencies of bearing faults when the bearings are healthy, a bearing fault signature evaluator is designed to generate an alert, if an impulse is detected at the characteristic frequencies of bearing faults.

III. Experimental Results

Experimental studies using a 160-W Southwest Windpower Air Breeze WTG, as shown in Fig. 3, was performed to validate the proposed method for bearing fault diagnosis. The generator has six pole pairs. The testing bearing is located between the rotors of the turbine and the generator. The WTG was operated in a wind tunnel, as shown in Fig. 4, which can provide controllable wind with the speed from 0 to 10 m/s. In the experiments, the wind speed in the wind tunnel was varied. One phase stator current of the WTG was recorded via a Fluke current clamp and National Instrument data acquisition system at a sampling rate of 10 kHz. The current samples were sent to a lab computer and acquired by the LabView software.

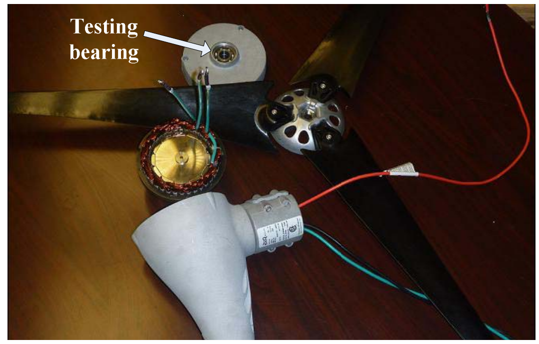

Fig. 3. The testing WTG.

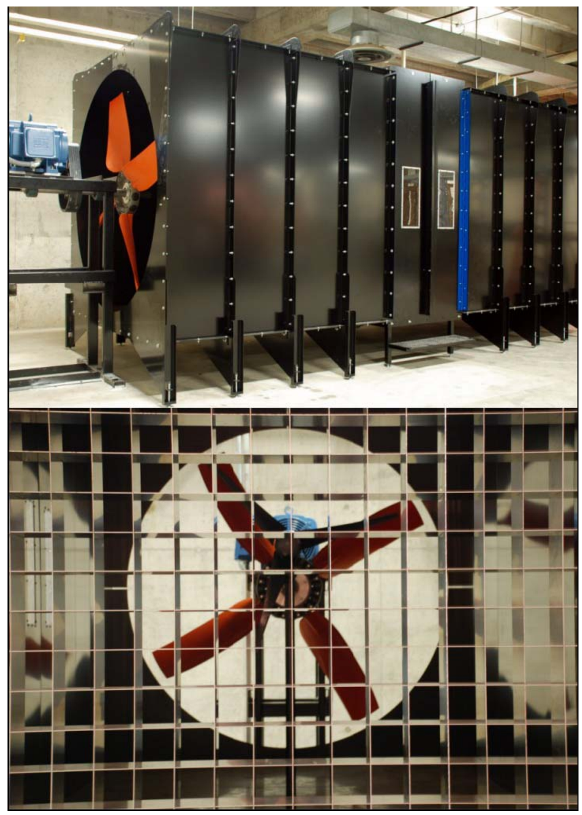

Fig. 4. The wind tunnel with the testing WTG.

A. WTG with Healthy Bearings

The WTG with healthy bearings was initially tested. The testing direct-drive wind turbine was operated with the rotating frequency in the range of 6 to 13 Hz, which leads to 36 to 78 Hz fundamental frequency in the stator current signals, which was then processed using the proposed method. The length of the stator current measurement is 50 second. The 1P-invariant PSD of the estimated shaft rotating frequency signal is plotted in Fig. 5, where the variable shaft rotating frequency from 6 to 13 Hz was converted to a constant value of 10 Hz by using the 1P-invariant PSD method. In Fig. 5, there are excitations at the frequencies of 10 Hz, 20 Hz, and 30 Hz besides the DC component in the 1P-invariant PSD of the estimated shaft rotating frequency signal. The first and second excitations are the 1P frequency and its harmonic, which were created by imbalance of the WTG, including shaft imbalance and rotor eccentricity [6]. WTGs are inevitably subjected to a certain degree of imbalance due to manufacturing and construction errors, icing, deformation, etc. The third excitation at the 3P frequency has been discussed in Section II of the paper. These excitations were treated as noise for wind turbine bearing fault diagnosis and were removed before using the impulse detection method for bearing fault diagnosis.

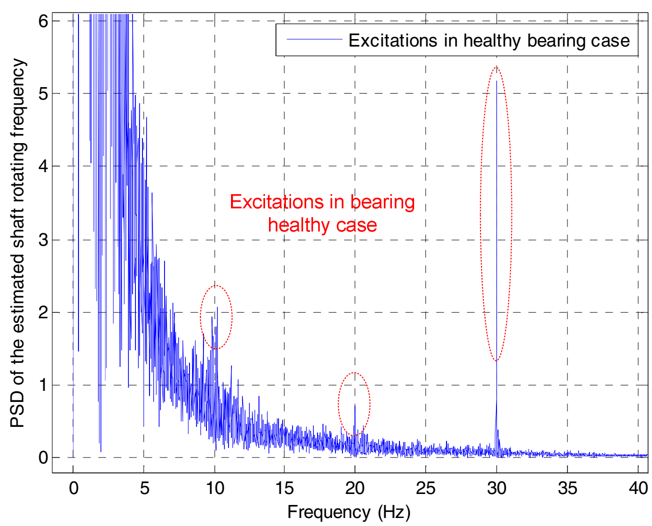

Fig. 5. The 1P-invariant PSD of the estimated shaft rotating frequency signal in the healthy bearing case.

B. Bearing with a Cage Fault

To accelerate the degradation of the testing bearing, it was pretreated by removing the lubrication oil. The WTG was operated in the wind tunnel continuously for approximately 25 hours. The WTG stator current signal was recorded every 20 minutes. The length of each record is 50 seconds. The wind turbine stopped rotating at the end of the experiment due to the damage of the cage of the testing bearing. Fig. 6 illustrates the bearing before and after the experiment.

Fig. 6. The testing bearing before and after the experiment.

The 1P-invariant PSDs of the shaft rotating frequency signals estimated from the first (healthy bearing) and the last stator current records (bearing with cage fault) are compared in Fig. 7, where the variable 1P frequency in the range of 6 to 13 Hz was converted to a constant value of 10 Hz. As shown in Fig. 7, an excitation appears in the PSD of the estimated shaft rotating frequency signal at a fixed frequency of 4 Hz in the bearing cage fault case. This fault characteristic frequency is the same as the one calculated from (4) for the WTG operating with a constant shaft rotating frequency of 10 Hz. Thus, the excitation at 4 Hz in the 1P-invariant PSD of the estimated shaft rotating frequency signal is an effective signature for bearing cage fault diagnosis. Moreover, the second-order harmonic of the excitation generated by the bearing cage fault can be found at the 8 Hz in Fig. 7.

The proposed impulse detection method was applied to extract the excitations in the 1P-invariant PSD for bearing cage fault diagnosis. The length of the window, W, was chosen to be 101. A third-order median filter was designed for threshold calculation. The locally normalized PSD [i.e., $R(f)$] of the last record (bearing with cage fault) is plotted in Fig. 8. The threshold was calculated to be 0.11. The impulses appear at 4 Hz and 8 Hz, where the impulse at 4 Hz indicates the signature of a bearing cage fault; the impulse at 8 Hz is the second-order harmonic of the excitation generated by bearing cage fault.

The proposed impulse detection method was also applied to determine whether there is a signature of the bearing cage fault in the PSD of the estimated shaft rotating frequency signal during the entire 25-hour experiment. The result is given in Fig. 9. It shows that the signature of the bearing cage fault appeared from the 6th hour of the experiment. The fault signature indicates a degradation of the bearing cage and maintenance should be taken immediately. Since there was no maintenance taken after the 6th hour of the experiment, the bearing was damaged and the wind turbine was stopped at the 25th hour of the experiment by the protection system.

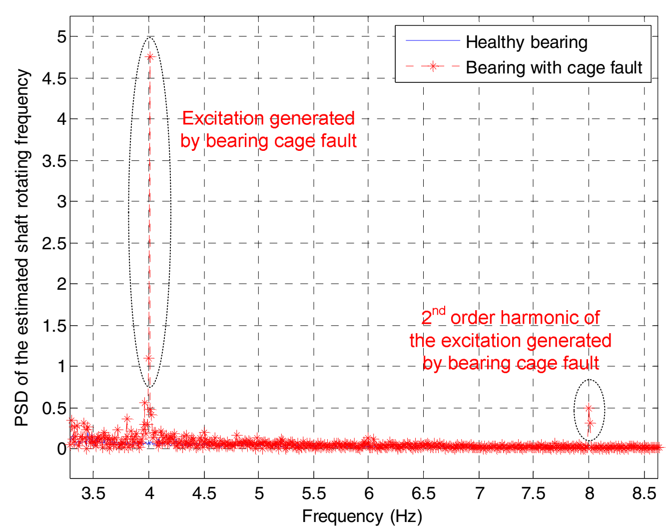

Fig. 7. Comparison of the 1P-invariant PSDs of the processed shaft rotating frequency signals estimated from the first and the last stator current records.

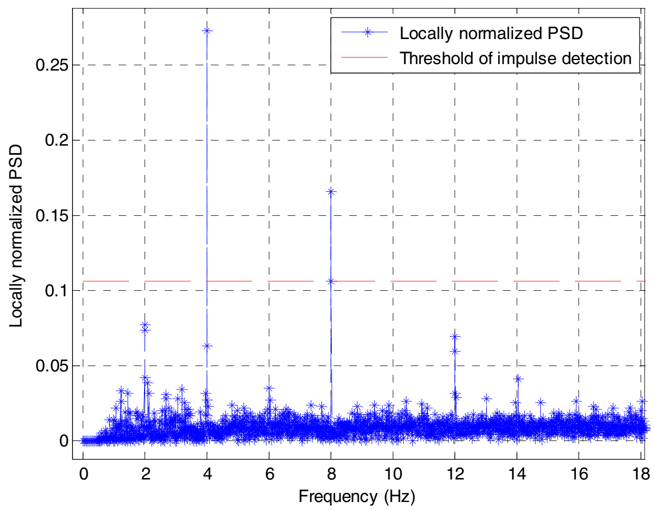

Fig. 8. Locally normalized PSD and threshold generated by the impulse detection method for the bearing with cage fault.

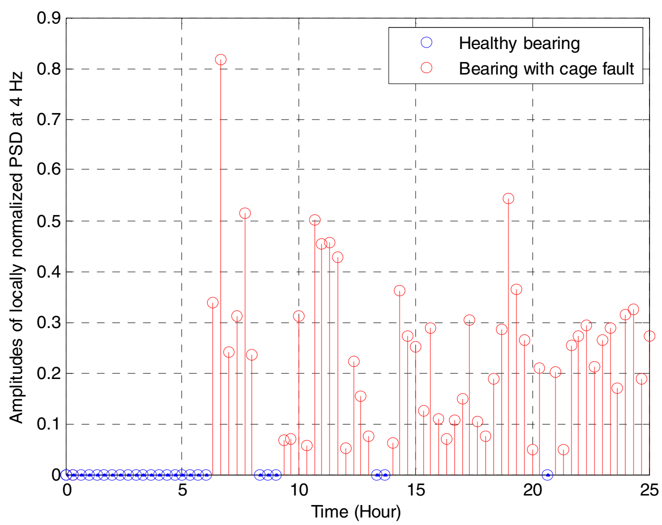

Fig. 9. Amplitudes of the locally normalized PSD at the bearing cage fault characteristic frequency of 4 Hz during the 25-hour experiment.

C. Bearing with an Outer-Race Fault

An outer-race fault was generated artificially for a testing bearing, as illustrated in Fig. 10. The healthy bearing and the bearing with an outer-race fault were installed in the WTG and tested, respectively. The length of the stator current record in each case was 50 seconds.

Fig. 10. The testing bearing with an outer-race fault.

Fig. 11 compares the 1P-invariant PSDs of the estimated shaft frequency signals for the WTG with a faulted bearing and against that with a healthy bearing, where in the 1P-invariant PSD the variable 1P frequency of 6~13 Hz was converted to a constant value of 10 Hz. As shown in Fig. 11, an excitation appears at a fixed frequency of 30.8 Hz in the PSD plot of the bearing outer-race fault case. This fault characteristic frequency is the same as the one calculated from (2) for the WTG operating with a fixed shaft rotating speed of 10 Hz. Therefore, the excitation at 30.8 Hz in the 1P-invariant PSD of the estimated shaft frequency is an effective signature for the bearing outer-race fault diagnosis.

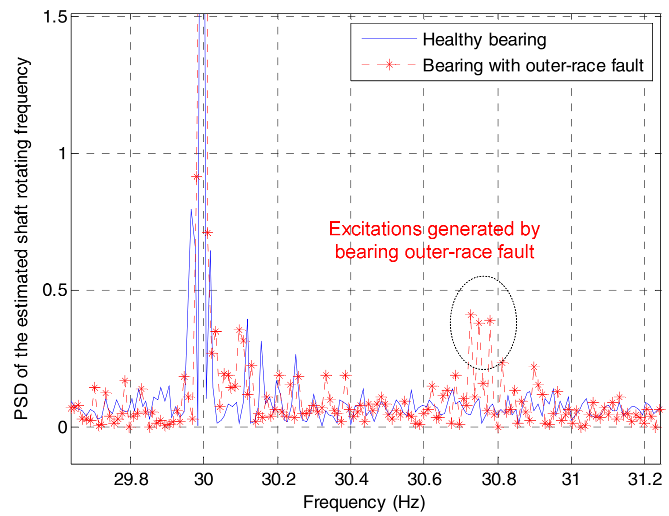

Fig. 11. Comparison of the 1P-invariant PSDs of the estimated shaft rotating frequency signals for the WTG with a bearing outer-race fault against that with a healthy bearing.

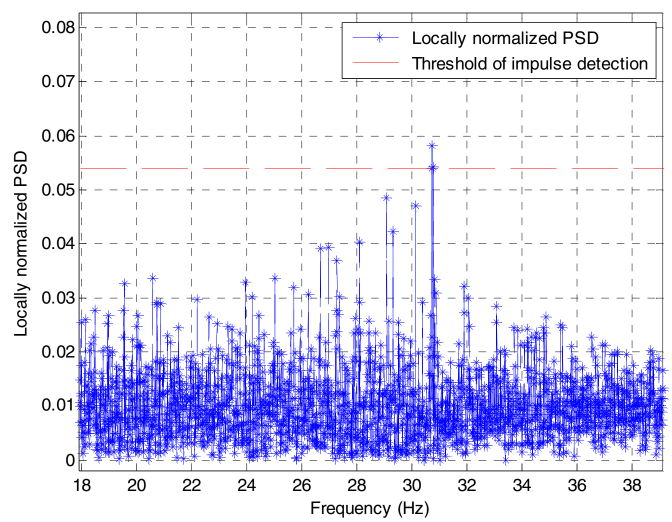

Fig. 12. Locally normalized PSD and threshold generated by the impulse detection method for the bearing with an outer-race fault.

As shown in Fig. 12, the proposed impulse detection method was successfully applied to extract the excitations in the 1P-invariant PSD for bearing outer-race fault diagnosis. The length of the window, W, was also chosen to be 101. The same third-order median filter as for Fig. 8 was used to calculate the threshold. The locally normalized PSD [i.e., $R(f)$] of the bearing outer-race fault case is plotted in Fig. 12, where the threshold was calculated to be 0.054. Fig. 12 clearly shows that the proposed method successfully detected the excitation at 30.8 Hz corresponding to the bearing out-race fault.

IV. Conclusion

A current-based online bearing fault diagnosis method using spectrum analysis and impulse detection has been developed for variable-speed direct-drive wind turbines. The proposed method converts the variable characteristic frequencies of bearing faults to constant values by using a 1P-invariant PSD method. The impulse detection method has then been designed to extract bearing fault signatures. If an impulse is detected at the characteristic frequency of a bearing fault, an alert will be generated and maintenance of the bearing will be required. Experimental studies for a WTG operating in a wind tunnel have shown that the proposed method can effectively diagnose various bearing faults for the WTG operating in variable-speed conditions.

V. References

[1] The American Wind Energy Association, "U.S. Wind Industry First Quarter 2011 Market Report," Apr. 2011, [Online]. Available: http://www.awea.org/learnabout/publications/reports

[2] United States Department of Energy, "20% wind energy by 2030: increasing wind energy's contribution to U.S. electricity supply," Rep. DOE/GO-102008-2567, Jul. 2008.

[3] B. Lu, Y. Li, X.Wu, and Z. Yang, "A review of recent advances in wind turbine condition monitoring and fault diagnosis," *in Proc. IEEE PEMWA 2009*, Lincoln, Nebraska, Jun. 24–26, 2009.

[4] Y. Amirat, V. Choqueuse, and M.E.H. Benbouzid, "Condition monitoring of wind turbines based on amplitude demodulation," *in Proc. IEEE Energy Conversion Congress & Exposition 2010*, pp. 2417–2421, Sept. 2010.

[5] X. Gong and W. Qiao, "Bearing fault detection for direct-drive wind turbines via stator current spectrum analysis," *in Proc. IEEE Energy Conversion Congress & Exposition 2011*, pp. 313–318, Sept. 2011.

[6] X. Gong and W. Qiao, "Imbalance fault detection of direct-drive wind turbines using generator current signals," *IEEE Trans. Energy Conversion*, vol. 27, no. 2, pp. 468–476, Jun. 2012.

[7] D. Umehara, M. Morikura, T. Hisada, S. Ishiko, and S. Horihata, "Statistical impulse detection of in-vehicle power line noise using hidden Markov model," *in Proc. IEEE ISPLC 2010*, Mar. 2010.

[8] S. Schulte, M. Nachtegael, V. D. Witte, D. V. der Weken, and E. E. Kerre, "A fuzzy impulse noise detection and reduction method," *IEEE Trans. Image Process.*, vol. 15, no. 5, pp. 1153–1162, May 2006.

[9] I. Pitas and A. N. Venetsanopoulos, Nonlinear Digital Filters: Principles and Applications, Kluwer Academic Publishers, 1990.

[10] F. Immovilli, M. Cocconcelli, A. Bellini, and R. Rubini, "Detection of generalized-roughness bearing fault by spectral-kurtosis energy of vibration or current signals," *IEEE Trans. Industrial Electron.*, vol. 56, no. 11, pp. 4710–4717, Nov. 2009.

[11] V. Choqueuse, M. E. H. Benbouzid, Y. Amirat, and S. Turri, "Diagnosis of three-phase electrical machines using multidimensional demodulation techniques," *IEEE Trans. Industrial Electronics*, vol.59, no.4, pp.2014-2023, Apr. 2012.

[12] R. Fadaeinedjad, G. Moschopoulos, and M. Moallem, "The impact of tower shadow, yaw error, and wind shears on power quality in a wind diesel system," *IEEE Trans. Energy Conversion*, vol. 24, no. 1, pp. 102–111, March 2009.