Simulation Investigation of Wind Turbine Imbalance Faults

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Abstract--This paper investigates the use of simulations to study wind turbine imbalance faults. The dynamics of a model wind turbine generator (WTG) are simulated in a combined environment of TurbSim, FAST (Fatigue, Aerodynamics, Structures, Turbulence), and Simulink in three different scenarios, i.e., normal operating conditions, blade imbalance, and aerodynamic asymmetry. The blade imbalance is simulated by scaling the mass density of one blade, which creates an uneven distribution of mass with respect to the rotor. The aerodynamic asymmetry is simulated by adjusting the pitch of one blade, which creates an uneven torque across the rotor. The time-domain simulation results of the WTG output electric power are transformed into the frequency domain using the Fast Fourier Transform (FFT). A power spectrum density (PSD)-based method is then developed to compare two imbalance fault scenarios with the normal operating conditions in the frequency domain. Results clearly show that both the blade imbalance and the aerodynamic asymmetry generate an excitation in the output electric power with the characteristic frequencies the same as the rotating frequencies of the wind turbine. This work provides preliminary results that are useful for online detection of imbalance faults for wind turbines.

Index Terms—aerodynamic asymmetry, blade imbalance, fault detection, imbalance fault, power spectrum density (PSD), wind turbine

I. INTRODUCTION

THE penetration of wind power has increased greatly over the last decade in the United States and across the world. In 2009, wind power provided 39% of all new generating capacity installed in the United States [1]. As the number of wind turbines continues to grow, it becomes more and more challenging for engineers to do inspection and maintenance for the wind turbines.

On average, each wind turbine is not operational for 52-237 hours per year [2]. These downtimes are caused by manufacturing or installation errors, aging effects, harsh environment, and variable loading conditions experienced by wind turbine components. For example, wind turbines usually operate in varying conditions with turbulent wind gusts that change in magnitude and direction frequently. This causes wind turbine components to be exposed to dynamic loads, causing fatigue, shaft imbalance, aerodynamic asymmetry, and other undesirable loading conditions. Over time, these conditions cause failures in the components of wind turbines well before the expected design life of the components. These faults and component defects need to be detected and diagnosed before they cause problems.

As many wind turbines are situated on high towers, installed in remote rural areas, and distributed over large geographic regions, inspection and maintenance for the wind turbines requires significant effort and cost. It is reported that the operation and maintenance cost can account for 10–20% of the total cost of energy for a wind project [3]. Moreover, wind turbines are inevitably subject to failure even with frequent and careful inspection and maintenance [4]. Repairing the failed components requires additional cost and can cause significant downtime. According to General Electric (GE) Energy, a $5,000 bearing replacement can easily turn into a $250,000 project involving cranes, service crew, gearbox replacements, and generator rewinds, not to mention the downtime loss of power generation [5]. In particular, for offshore wind turbines, bad weather conditions, e.g., storms, high tides, etc., can prevent any repair actions for several weeks. The downtime of wind turbines in turn results in significant losses of the electric energy production. To make wind energy competitive with traditional forms of energy resources for electricity generation, it is necessary to minimize the maintenance costs and improve the reliability of wind turbines. Online condition monitoring and fault detection is an effective means of not only increasing the reliability, but also reducing the costs associated with operation and maintenance of wind turbines.

This paper investigates the use of simulations to study imbalance faults of wind turbines. The dynamical model of a WTG is developed in a combined environment of TurbSim, FAST, and Simulink, where TurbSim generates the wind data; FAST simulates the dynamics of the wind turbine; and Simulink simulates the dynamics of the generator and other electrical components of the WTG system. Simulation studies are then carried out in three different scenarios, i.e., normal operating conditions, blade imbalance, and aerodynamic asymmetry, for the model WTG. The blade imbalance is simulated by scaling the mass density of one blade, which creates an uneven distribution of mass with respect to the rotor. The aerodynamic asymmetry is simulated by adjusting the pitch of one blade, which creates an uneven torque across

the rotor. The time-domain simulation results of the WTG output electric power are transformed into the frequency domain using a PSD-based technique. Results show that an excitation appears at the rotating frequency of the wind turbine in the PSD of the electric power in the imbalance fault scenarios. This work provides preliminary results that are useful for online detection of wind turbine imbalance faults.

II. WTG MODEL AND SIMULATION PLATFORM

A. WTG Model

The dynamical model of a 10-kW WTG system is built in a FAST and Simulink combined environment, as shown in Fig. 1. FAST is used to simulate the dynamics of the wind turbine; while Simulink is used to simulate the generator and other electrical components of the WTG system.

FAST version 7.0 is chosen for the simulation of the model wind turbine. FAST, an aeroelastic code developed initially by Oregon State University, is one of the most advanced design codes for horizontal axis wind turbines [6]. In this simulation study, FAST works as a subroutine in Simulink. The signals of the electric power, electric torque, and rotating speed are used to connect the FAST and Simulink models of the WTG system.

The model wind turbine in FAST mainly includes tower, blades, shaft, furl, and support platform. The hub height of the wind turbine is 34 meters. The wind turbine has 3 blades with a rotor diameter of 2.9 meters. The wind turbine has an upwind configuration, which means the blades are upwind of the tower. A 48-pole permanent magnet synchronous machine is simulated in Simulink to convert mechanical energy from the turbine into the electric energy. The output current and voltage signals are recorded for calculation of the WTG output electric power.

B. Wind Speed Data

TurbSim, a program developed by the National Renewable Energy Laboratory (NREL), is a stochastic, full-field, turbulent wind simulator [7]. An average wind speed of 15.7 m/s is used in the simulation. TurbSim is used to produce
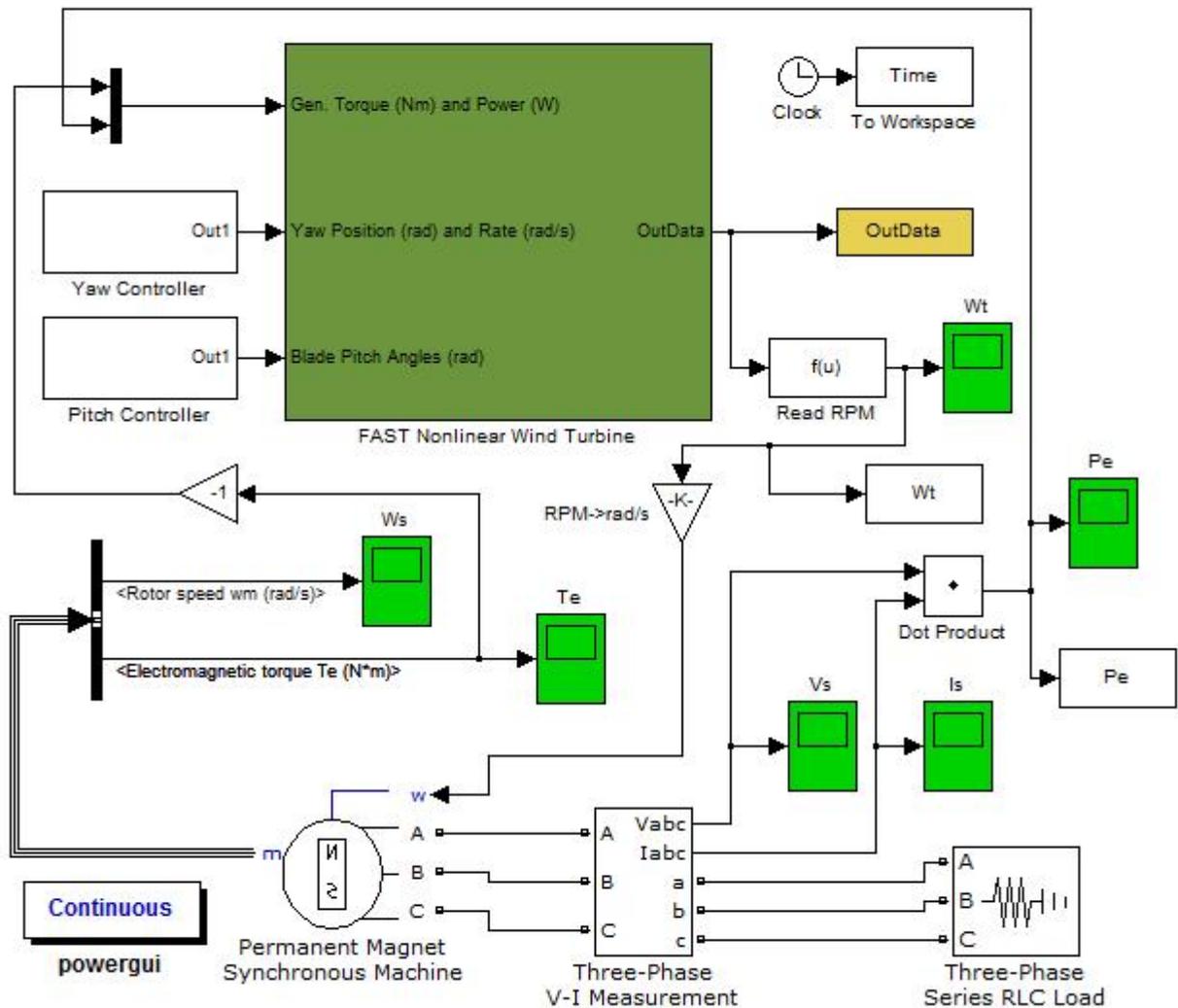
Fig. 1. The model WTG in FAST/Simulink

wind velocity vectors in a time series across the entire swept area of the rotor. The IEC Kaimal turbulence model is used to generate the wind turbulence in all simulations [7]. The cross-section area (8m×8m) of the wind flow is divided into a 6×6 grid where the wind velocity and direction is calculated by TurbSim for each grid cell.

The output files of TurbSim are used for the aeroelastic simulation in FAST to produce variable wind speed in a time series. The overall structure of the model WTG system with the wind speed data is show in Fig. 2.
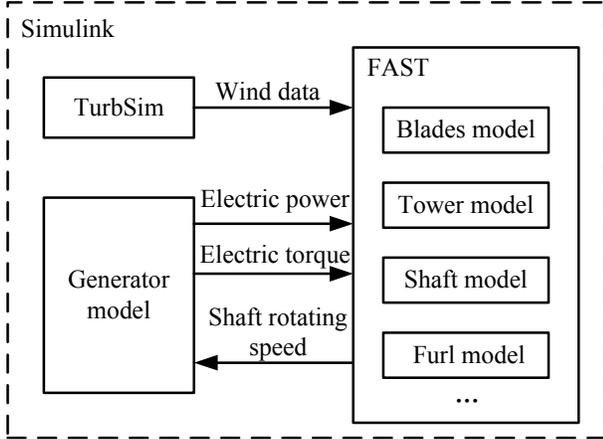
Fig. 2. The structure of the WTG model with wind data.

C. Imbalance Fault Simulation

FAST is used to simulate the dynamics of the model wind turbine in normal operating conditions as well as in two imbalance fault scenarios. One of the most common imbalance faults in WTG systems is shaft/blade imbalance, which occurs when the mass of the wind turbine components are not evenly distributed with respect to the rotor. The blade imbalance can be caused by errors in manufacturing, construction, wear and fatigue during the operation of the wind turbine, or the unbalanced icing on the blades. Another common imbalance fault in wind turbines is aerodynamic asymmetry, which means the torque is unevenly distributed among the three blades. This fault can be caused by several factors, including high wind shear and errors in control mechanisms. For instance, if the pitch of one blade is slightly different from the other two blades, the torque on the rotating shaft is not balanced, which generates an aerodynamic asymmetry fault.

The two imbalance faults are simulated and compared with the normal operating conditions. The blade imbalance is simulated by scaling the mass density of one blade, which creates an uneven distribution of mass with respect to the rotor. Aerodynamic asymmetry is simulated by adjusting the pitch of one blade, which creates an uneven torque across the rotor. The output electric power of the WTG is recorded in each simulation. The data is then converted to the frequency domain by using a PSD-based method to extract the signature and the characteristic frequency of each fault.

D. Characteristic Frequencies of Imbalance Faults

When an imbalance fault occurs on a shaft, an additional force, F_{im}, will be induced in the turbine shaft, which rotates at the rotating speed of the turbine. In the blade imbalance, this additional force is centrifugal [8] and can be expressed by:

$$F_{im} = m_R \cdot r_R \cdot \omega^2 \qquad (1)$$

where m_R is the equivalent imbalance mass; r_R is the distance between the equivalent imbalance mass and the center of the shaft; and ω is the shaft rotating speed. Fig. 3 illustrates the effect of blade imbalance of a wind turbine.
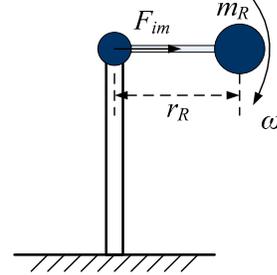
Fig. 3. The effect of blade imbalance of a wind turbine.

In aerodynamic asymmetry, the equivalent force F_{im} on the shaft is:

$$F_{im} = T_a / r_a \qquad (2)$$

where T_a is the torque created by the aerodynamic asymmetry and r_a is the equivalent length of the arm of force. The effect of aerodynamic asymmetry is illustrated in Fig. 4. The asymmetry force F_{im} can be interpreted as an equivalent of three forces F_{im}, F_{im1}, and F_{im2} applied to the rotor, where the magnitudes of F_{im}, F_{im1}, and F_{im2} are identical and F_{im1} is in the opposite direction of F_{im2}. Among the three forces, F_{im} and F_{im2} generate the torque to rotate the rotor of the wind turbine and F_{im1} causes the vibrations of the shaft.
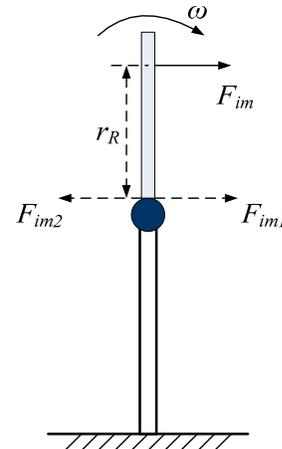
Fig. 4. The effect of aerodynamic asymmetic of a wind turbine.

During the rotation of an imbalanced-shaft wind turbine,

the vibration of the system due to the imbalance fault is mainly in the horizontal direction, due to a larger stiffness in the vertical direction and a smaller stiffness in the horizontal direction [8]. The horizontal component of the force F_c is shown as follows [8]:

$$F_c = F_{im} \cdot \sin(\omega t + \varphi) \tag{3}$$

where φ is the initial phase angle of F_c. Consequently, the vibration at the frequency of the wind turbine rotating speed, which is known as the 1P frequency, appears in the torque of the shaft. The same result is provided in [9] based on the force analysis of the rotor in an icing blade condition.

At the steady state, the mechanical force equals to the electric force, which is proportional to the output electric power. Therefore, the 1P component also appears in the output electric power signal of the WTG system.

III. FAULT SIGNATURE EXTRACTION

Since the characteristic frequency of imbalance faults is at 1P, i.e., the variable rotating frequency of the wind turbine shaft, an appropriate signal processing method needs to be developed for fault signature extraction. Continuous Wavelet transform has been applied in [10] for induction generator rotor circuit imbalance fault detection where the induction generator was operated in variable speed conditions. However, in the research of wind turbine imbalance faults, the blade imbalance or aerodynamic asymmetry does not generate significant unbalance as the rotor circuit imbalance does. Therefore, continuous Wavelet transform may not be sensitive enough for detection of the wind turbine imbalance faults. In this paper, a PSD-based method is developed for wind turbine imbalance fault signature extraction.

In the standard PSD, the time-domain signals are required to be stationary. However, in this application the characteristic frequency of the imbalance faults, i.e., the 1P frequency, is variable during the wind turbine operation. Therefore, the standard PSD does not work well for this application. In order to extract the signature of the faults, a modified PSD method, called the indirect PSD method, is developed, in which the variable 1P frequency is converted to a constant base frequency. The flow chart of this method is shown in Fig. 5. First, the electric power signal is sampled at a certain frequency, e.g., 2 kHz. Second, only a part of these sampled data are chosen for further analysis. In other words, M samples are neglected between two continuously selected samples, where M depends on the 1P frequency of the last selected sample. Using the notations in Fig. 5, M equals to $[L \cdot f_b / f_r(N)] - 1$. This sample selection process results in a reduced and variable sampling frequency for the electric power signal. By using this method, the fault characteristic frequency of 1P is converted to be a constant value, which is called the base frequency. Consequently, the interference of variable shaft rotating speed to the PSD is eliminated. In the proposed method, the base length L should be chosen based on two criteria. First, L should be large enough to eliminate the quantization error of M. Second, L should be small enough to guarantee that the reduced sampling frequency is greater

than the twice of 1P. Finally, the standard PSD method is applied to analyze the selected samples of the electric power signal. The proposed method integrates the vibrations during the whole sampling period. However, the continuous Wavelet transform-based method can only integrate the vibrations of the support length of the wavelet functions, which is only a part of the sampling period. Therefore, the proposed method is more sensitive than the continuous Wavelet transform-based method.
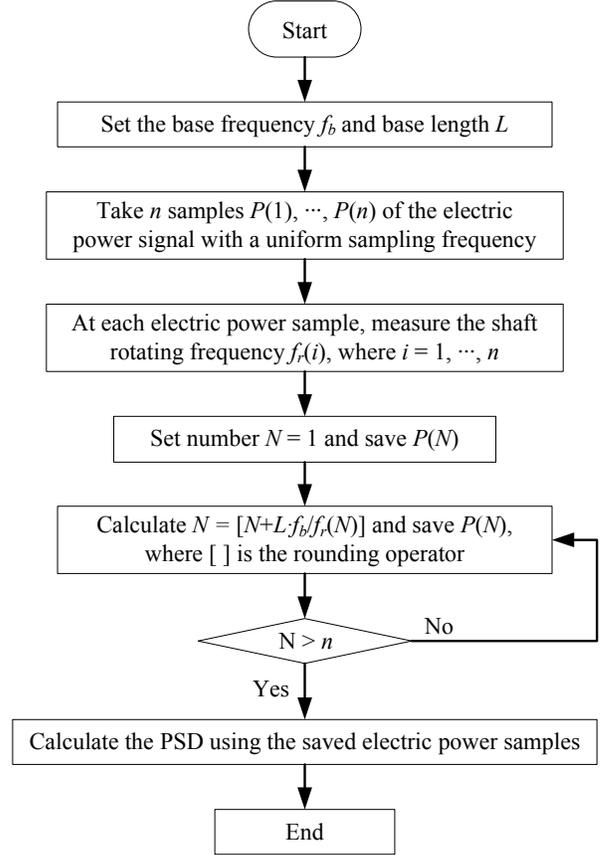
Fig. 5. Flow chart of the indirect PSD method for fault signature extraction.

IV. SIMULATION RESULTS

A. Normal Operating Conditions

First, a normal operation case is simulated using the turbulence wind file generated by TurbSim and the balanced model wind turbine in FAST. The turbulence wind data is also used in the simulations of imbalance fault scenarios for the wind turbine.

Each simulation runs for 30 seconds with the sampling frequency of 2 kHz. The output electric power of the model WTG simulated in Simulink is recorded in the time domain. The PSD of the electric power signal is calculated by using a fast Fourier Transform (FFT), as shown in Fig. 6. The figure shows that no excitation is observed at the 1P frequency in the PSD curve. This case is referred to as the baseline case for the remainder of the paper, which is then used for comparison against the two imbalance faults in the frequency domain.
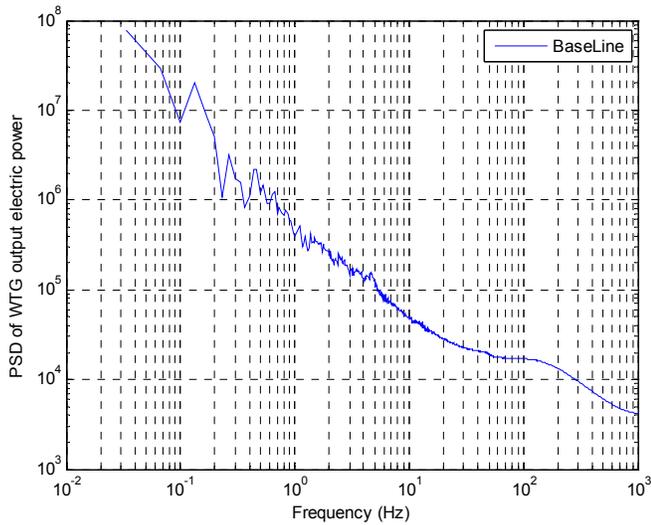
Fig. 6. The PSD of the baseline case.

Fig. 7. Comparison of the blade imbalance faults and baseline case using the standard PSD method.

Fig. 8. Comparison of the blade imbalance faults and baseline case around the 1P frequency using the standard PSD method.
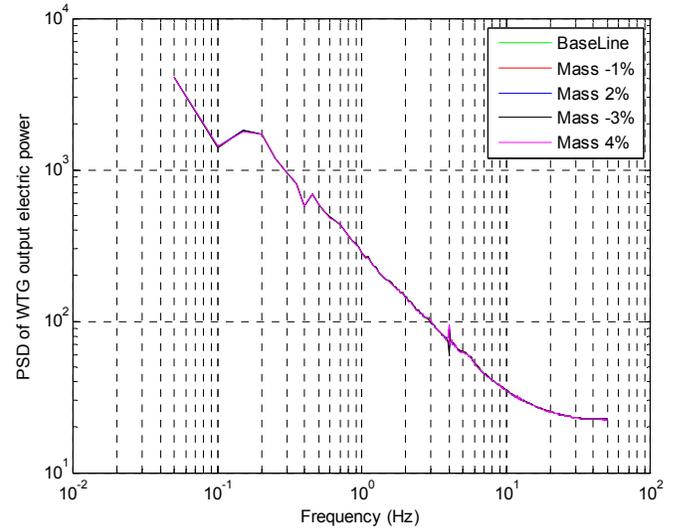
Fig. 9. Comparison of the blade imbalance faults and baseline case using the proposed indirect PSD method.
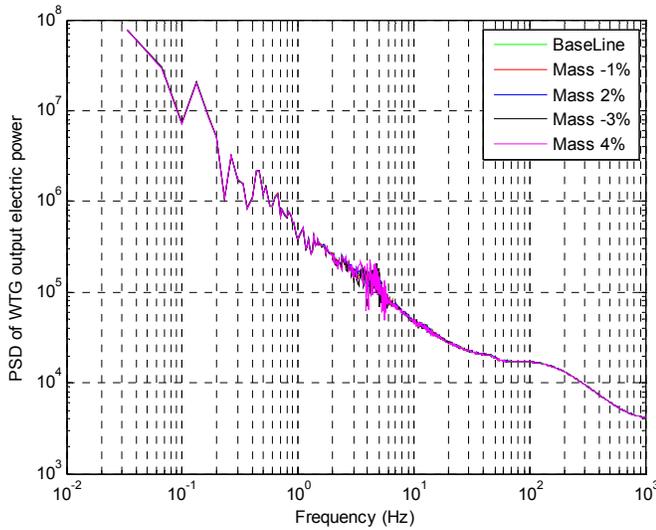
Fig. 10. Comparison of the blade imbalance faults and baseline case around the 1P frequency using the indirect PSD method.
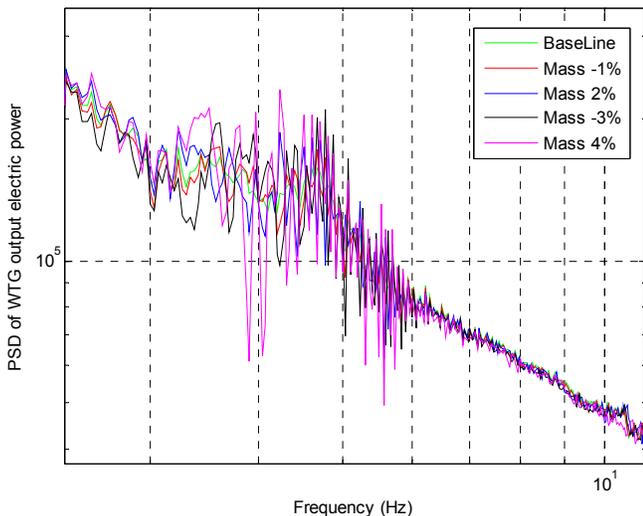
B. Blade Imbalance

The mass density of one blade is scaled up and down for the blade imbalance fault simulations. Four scenarios are simulated with the mass density of one blade adjusted by -1%, +2%, -3%, and +4%; while the mass densities of the other two blades are held constant. The four blade imbalance scenarios and the baseline case are compared with each other in the frequency domain. The standard PSD results are shown in Figs. 7 and 8. The indirect PSD results are shown in Figs. 9 and 10. From Figs. 7 and 8, the output electric power excitation becomes more significant at 1P when the degree of the blade imbalance becomes higher. In the simulations, the WTG is operated in variable speed conditions to adapt to the variations of the wind speed. Consequently, the 1P frequency varies in the range of 3 Hz to 5 Hz. However, it is difficult to quantify and evaluate the blade imbalance faults by using the standard PSD method, as shown in Figs. 7 and 8. In the

indirect PSD method, the base frequency is chosen to be 240 rpm or 4 Hz and the base length is 20. It is clearly shown in Figs. 9 and 10 that the characteristic frequency of the blade imbalance is the same as the base frequency. Furthermore, Fig. 10 shows that the magnitude of the excitation of the electric power signal at 1P depends on the degree of the blade imbalance. The greater the blade imbalance, the higher magnitude of the excitations appears at 1P in the PSD plot.

C. Aerodynamic Asymmetry

In order to simulate aerodynamic asymmetry faults of the wind turbine, the pitch angle of one blade is adjusted by -2 degree, +4 degree, -6 degree, and +8 degree; while the pitch angle of the other two blades are held constant at 11.44 degree. All the simulation results are processed and analyzed in the same way as in Section IV-B. The standard PSD results are shown in Figs. 11 and 12. The indirect PSD results are shown in Figs. 13 and 14. From Figs. 11 and 12, the magnitude of the excitation of the electric power signal increases when the degree of the aerodynamic asymmetry increases. The excitation frequency again is 1P in the range of 3 Hz to 5 Hz. Similar to the analysis for the blade imbalance faults, the aerodynamic asymmetry is difficult to quantify and evaluate by using the results obtained from the standard PSD method. However, Figs. 13 and 14 clearly show that the characteristic frequency of the aerodynamic asymmetry is around the base frequency of 4 Hz or 1P by using the indirect PSD method. Moreover, the greater the imbalanced pitch angle, the higher magnitude of excitations appears at the characteristic frequency in the PSD plot. Moreover, the decrease of the blade pitch angle leads to more electric power generation, and consequently, the increase of the magnitude of the PSD curve.
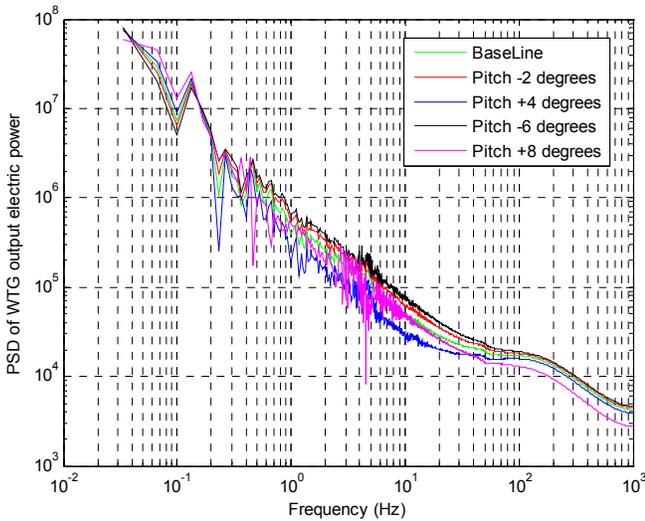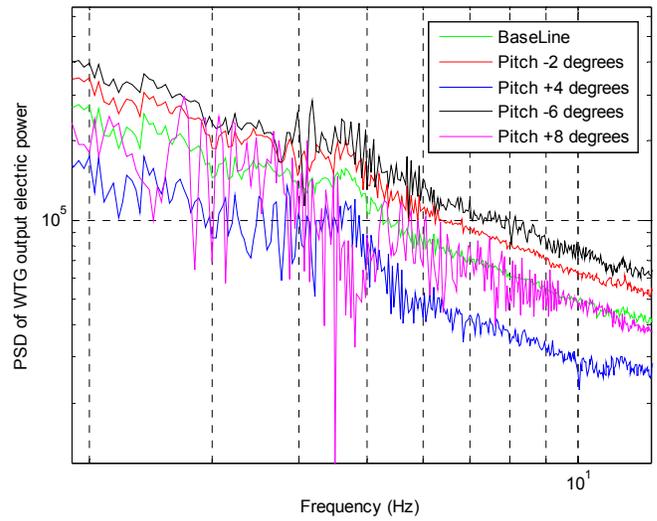
Fig. 12. Comparison of the aerodynamic asymmetric faults and baseline case around the 1P frequency using the standard PSD method.
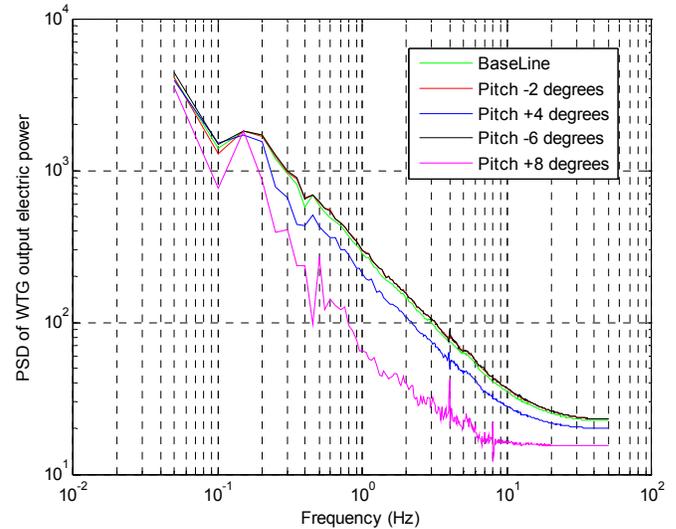
Fig. 13. Comparison for the blade imbalance faults and baseline case using the indirect PSD method.

Fig. 11. Comparison of the aerodynamic asymmetric faults and baseline case using the standard PSD method.
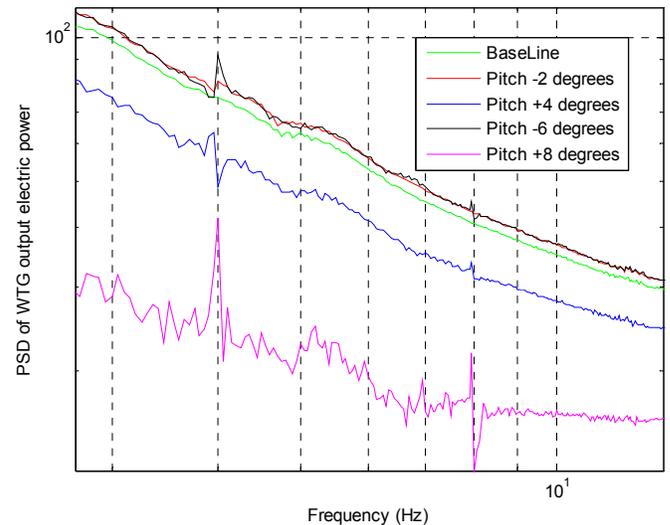
Fig. 14. Comparison of the aerodynamic asymmetric faults and baseline case around the 1P frequency using the indirect PSD method.

V. Conclusion

This paper has presented the use of simulations to study imbalance faults of wind turbines based on the electric power signals. A PSD-based method has been developed to extract the signature and identify the characteristic frequency of the imbalance faults for the wind turbines operated in variable-speed conditions. Simulation results have shown that the excitations appear at 1P in the PSD of the electric power signals of a 10-kW model WTG for two imbalance faults: blades imbalance and aerodynamic asymmetry. By using the proposed indirect PSD method, the imbalance faults of the wind turbine can not only be discovered but also be quantified and evaluated by the location and degree of the 1P excitation in the PSD plots. In future work, the simulation studies will be validated with experimental studies on practical wind turbines.

VI. References

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VII. Biographies

Xiang Gong (S'09) received the B.Eng. degree in electrical engineering from Huazhong University of Science and Technology, Wuhan, China, in 2006, and the M.Eng. degree in electrical engineering from Zhejiang University, Hangzhou, China, in 2008. Currently, he is working towards the Ph.D. degree in the Department of Electrical Engineering at the University of Nebraska−Lincoln.

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From 1997 to 1999, he was an Electrical Engineer in China Petroleum & Chemical Corporation (Sinopec). Since 2008, he has been an Assistant Professor of Electrical Engineering with the University of Nebraska–Lincoln. His research interests include renewable energy systems, smart grids, power system control and optimization, energy storage, power electronics, and condition monitoring and high-performance computation for electric power and energy systems. He is the author or coauthor of 3 book chapters and more than 50 papers in refereed journals and international conference proceedings.

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