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A novel order tracking method for wind turbine planetary gearbox vibration analysis based on discrete spectrum correction technique

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A B S T R A C T

Wind turbine gearboxes generally exhibit complex vibration characteristics due to wide variations in the operating conditions, and dynamics of the structure coupled with flexible supports. Conventional spectral analysis method may not provide reliable health monitoring and fault diagnosis of the gearbox. In this study, a novel order tracking method based on discrete spectrum correction technique is proposed to analyze wind turbine gearbox vibration for the purposes of health monitoring and fault diagnosis. The effectiveness and robustness of the proposed method are demonstrated through simulations and engineering tests. The results show that the shaft rotating speed could be accurately identified from the vibration signal together with amplitudes of significant gear meshing components. Modulation sidebands of both the planetary and fixed-shaft gears in a healthy wind turbine gearbox were further analyzed, which revealed inherent shaft misalignment in the fixed-shaft gear. Meshing frequency of the planetary gear was modulated by both the rotating frequencies of sun gear and planetary carrier, while fundamental modulation frequency of the planetary carrier was found to be related to rotating frequency of the carrier multiplied by the number of planet gears. The monitoring of such particular vibration features would be helpful in enhancing the operational performance of wind turbines through reliable health monitoring of gearboxes and reducing the misdiagnosis of faults.

1. Introduction

Energy harvesting via wind turbines has been growing steadily in recent years. Owing to their widely varying operation conditions, such turbines exhibit complex dynamic properties and vibration responses. Vibration signals based methods have been explored for monitoring of their operational health so as to reduce the maintenance costs and unscheduled interruptions in their operation [1]. For a 750 kW wind turbine of 20-year life cycle, the operational and maintenance costs account for about 25%–30% of the overall energy generation cost or 75%–90% of the total investment costs [2,3]. Large size turbines generally incur more frequent failures and thus pose greater maintenance demands [4]. Reducing the operational and maintenance costs of the wind turbines has thus become an increasingly important challenge. Health monitoring of such turbines is thus vital for detecting the potential failures in a timely manner so as to minimize downtime and maximize productivity.

Vibration analysis continues to be the most popular technology employed in wind turbine for monitoring and diagnosing the gearbox, the bearings and other components. Wind turbines generally employ planetary gearboxes to achieve higher transmission ratio and output power within compact space. The wind turbines, however, exhibit complex dynamic responses due to extreme loading and widely varying operating conditions arising from wind gusts and speed fluctuation. The gearboxes are thus prone to widely different types of mechanical failures such as shaft imbalance, shaft misalignment, and fatigue damages of the shaft, bearings and gears [1]. Time-frequency analysis methods are commonly used for analysis of signals under non-stationary conditions. Tang [5–7] presented different methods for extracting transient response features for diagnosing wind turbine gearbox faults, such as Morlet wavelet combined with Wigner-Ville distribution (WVD), adaptive Morlet wavelet combined with SVD, and manifold learning combined with Shannon wavelet and singular value decomposition (SVD). Li [8] proposed a noise-controlled second-order enhanced stochastic resonance method based on Morlet wavelet to extract fault features of a wind turbine gearbox. It

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has been reported that the above mentioned methods yield limited reliability and accuracy of planetary gearbox faults predictions due to complexity of the planetary gearbox vibration response signals under widely varying and non-stationary operating conditions together with amplitude and frequency modulations [9].

Feng [10,11] introduced adaptive optimal kernel time-frequency analysis methods to identify constituents' frequency components and time-varying features for the planetary gearbox vibration monitoring. Aimed at early failure detections of planetary gearboxes, Hong [12] introduced Fourier series analysis and robust feature extraction algorithms. These methods have shown improved fault detection performance to some extent, but uncertainties associated with complex dynamic behavior of the gearbox limited the prediction accuracy. Most wind turbine gearboxes consist of multistage planetary gears and fixed-shaft gears supported by flexible elements such as rubber or plate springs, which leads to natural shaft misalignment and more complex vibration responses compared to a single planetary gearbox or fixed-shaft gearbox [13]. The vibration spectra of wind turbines exhibit substantial and complex modulation sidebands attributed to both the planetary and fixed-shaft gears, even when the wind turbine gearbox is healthy, which make the faults diagnosis of gearbox much more difficult and may even lead to misdiagnosis. The analysis of signals with complex modulation sidebands has not yet been adequately addressed in reported studies even for healthy wind turbine gearboxes. This study is in-part motivated by the need to build a better understanding of these modulation sidebands and the associated causal factors.

Order tracking analysis is an effective method for transient signal analysis owing to its merit in separating and identifying speed-related vibration such as rotor imbalances, shaft wear, gear damage and bearing defects [14]. Signal sampling with constant angular increments is critical for the order tracking analysis, which can be typically accomplished via analog instruments. Digital methods based on interpolations [15] have also been introduced for angular re-sampling, which strongly relate accurate knowledge of the rotating speed. Measurement of rotating speed via a tachometer is vulnerable to possible sampling loss and unacceptable errors when the rotating speed changes rapidly. Moreover, the installation of a tachometer in some machines poses difficult challenges. A number of studies have thus explored indirect estimations of rotating speeds based on vibration analysis, especially the estimation of instantaneous frequency (IF) [16,17]. The reported methods may be categorized into four different classes based on the algorithm, namely phase demodulation methods [18–20], parametric eigenvalue methods [21], signal modeling methods [22] and time-frequency distribution (TFD) methods [23–27]. The TFD-based methods have attracted relatively more attention considering the greater prediction reliability and robustness to signal noise. The estimations of instantaneous frequency based on TFD have employed two different techniques involving moments and peaks of TFD [17]. The IF estimation based on moments of TFD, however, is limited in analyses of practical multi-components signals, because it has physical meaning only for mono-component signals. The IF estimation on the basis of peaks of TFD is also restricted to the time and frequency resolution. Villa [28] proposed an angular re-sampling algorithm suitable for use in wind turbines, but it requires a tachometer that may contribute to estimation errors. Urbanek [20] compared the amplitude- and phase-based methods for speed tracking in wind turbine applications. A few studies have introduced TFD peaks based methods for extracting instantaneous rotating speed or a desired cyclo-stationary component from the wind turbine gearbox vibration signals [29–31]. These methods, however, required higher time-frequency resolution to ensure precision of extractions.

Although there are many studies have been performed on wind turbine gearbox fault diagnosis, most existing methods were limited by the complex vibration under widely varying conditions, or time-frequency resolution requirements. And, there is little study from the literature that focuses on the cause of the modulation sidebands in the vibration spectrum of a healthy wind turbine gearbox. Since the vibration characteristics of a healthy gearbox are always taken as reference to detect and diagnose the fault, it is necessary to build a better understanding of the dynamic vibration behavior of a healthy wind turbine gearbox. In this study, the vibration characteristics of a healthy wind turbine gearbox operating under stationary conditions are discussed. The spectral components associated with gear meshing components of the wind turbine gearbox's TFD are extracted for estimating the instantaneous rotating speed of the shaft. A novel order tracking method is subsequently proposed to analyze non-stationary vibration responses of the wind turbine gearbox. The corrected frequency, amplitude and phase responses are obtained using the energy centrobaric correction method, a class of discrete spectrum correction techniques, which permits accurate predictions even under poor frequency resolution. Since the corrected frequency based on energy centrobaric relates to the first moment of TFD, the proposed IF estimation method thus combines both the moments and peaks of TFD, while it overcomes the limitation attributed to signal resolution. The effectiveness and robustness of the method are demonstrated through simulations and engineering applications, and the instantaneous rotating speeds of wind turbine gearbox shafts could be precisely extracted without tachometers. The modulation sidebands of planetary gears and fixed-shaft gears in wind turbine vibration are further analyzed using the proposed method, which provided significant results for health monitoring and fault diagnosis of wind turbine gearboxes.

2. Wind turbine gearbox structure and vibration signal

2.1. Structure

This study considered the gearbox of a typical 1.5 MW wind turbine, which includes two stages of planetary gears and one stage of fixed-shaft gear, as shown in Fig. 1. Table 1 lists the basic parameters of the gearbox, where Z_1, Z_2 and Z_3 denote the number of teeth of different gears within the three stages of the gearbox. Taking the rotating frequency of the input shaft as a reference 1 Hz (the planetary carrier in Stage I gear), the rotating frequency of the gears within each stage can thus be calculated as those in Table 1.

Taking the input or output shaft as the reference shaft, and normalizing its rotating frequency (f_n) as 1 order, the orders corresponding to meshing frequencies of Stages I, II and III gears (f_{zI},f_{zII} andf_{zIII}) are computed and listed in Table 2. It should be noted that

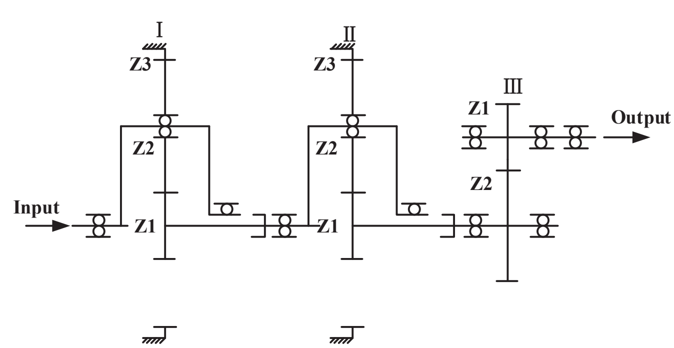

Fig. 1. The structure of the wind turbine gearbox.