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Wind turbine high-speed shaft bearings health prognosis through a spectral Kurtosis-derived indices and SVR

Lotfi Saidi [a,*], Jaouher Ben Ali [a], Eric Bechhoefer [b], Mohamed Benbouzid [c,d]

[a] University of Tunis, ENSIT – Laboratory of Signal Image and Energy Mastery (SIME), LR 13ES03, 1008, Tunisia
[b] Green Power Monitoring Systems, LLC, VT 05753, USA
[c] University of Brest, FRE CNRS 3744 IRDL, 29238 Brest, France
[d] Shanghai Maritime University, Shanghai, China

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ABSTRACT

A significant number of failures of wind turbine drivetrains occur in the high-speed shaft bearings. In this paper, a vibration-based prognostic and health monitoring methodology for wind turbine high-speed shaft bearing (HSSB) is proposed using a spectral kurtosis (SK) data-driven approach. Indeed, time domain indices derived from SK are used and a comparative study is performed with frequently used time-domain features in the bearing degradation health assessment. The effectiveness is quantified by two measures, i.e., monotonicity and trendability. Among those features, the area under SK is utilized for the first time as a condition indicator of rolling bearing fault. A support vector regression (SVR) model was trained and tested for the prediction of the HSSB lifetime prognostics, showing the superiority of SK-derived indices of degradation assessment. We verified the potential of the prognostics method using real measured data from a drivetrain wind turbine. The experimental results show that the proposed approach can successfully detect an early failure and can better estimate the degradation trend of HSSB than traditional time-domain vibration features.

1. Introduction

Bearings used in wind turbine generators (WTGs) are subjected to harsh environments during operation, including vibrations and shocks under varying wind speed. These loads push the bearings beyond their limits, which can explain the higher than expected failure rate [1–5].

Ambitious worldwide renewable energy targets are pushing wind energy to become a mainstream power source. Despite high wind turbine availability (>96%, depending on turbine), and a relatively low failure rate of mechanical components compared to electrical components, failures of mechanical components in drivetrains often create high repair costs and revenue loss due to long down times [1,6].

In most WTGs concepts, a gearbox is commonly used to adjust the rotor speed to the generator speed. Today, the actual service life of wind turbine gearboxes is less than the lifecycle designed of 20 years [6]. Failures can be found at several bearing locations, predominantly planet bearings, intermediate shaft and high-speed shaft bearings (HSSBs) [2] (Fig. 1).

WTG rolling element bearings (REBs) are incorporated in the support of the rotor and rotor shaft, the gearbox shafts, and the generator input shaft. The bearing arrangement depending heavily on the layout of a drivetrain. Rotor shaft bearings support the main shaft as well as the rotor blades, operating under dynamic axial and radial load conditions as well as slow speeds, approximately 20–30 rpm. The rotor blades impose cyclic loads onto the main shaft, thus causing the shaft itself to bend, resulting in misalignment within the bearings. Intermediate speed and high-speed bearings in the gearbox can also be subject to damage from these loads [2–6].

Vibration analysis is the most common condition monitoring technology used in the industry for any kind of rotating equipment and is an effective tool for the bearing fault diagnosis [1–5]. Vibration based techniques are commonly used to detect bearing faults in WTGs. In order to detect bearing faults effectively and to develop more sophisticated vibration based algorithms for fault detection, a thorough understanding of vibration signatures of bearings with faults is required. Various methods are described in the literature [1,7,14,19].

The vibration analysis methods dedicated to bearing fault diagnosis can be classified into time- domain, frequency-domain, and time-frequency based approaches [8,9]. A number of scholars have

* Corresponding author.
E-mail address: lotfi.saidi@esstt.rnu.tn (L. Saidi).

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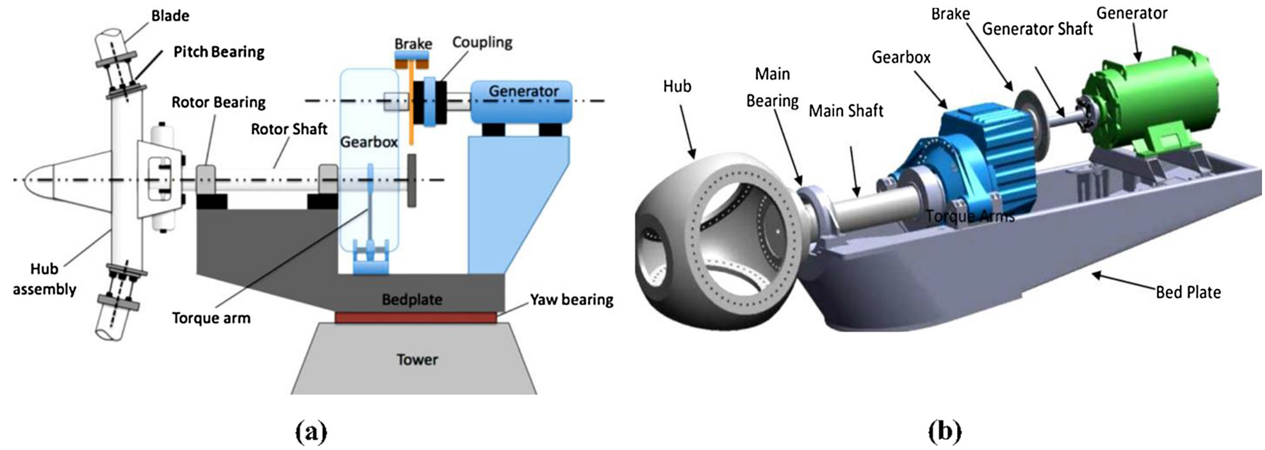

Fig. 1. (a) Components of the WTG including; tower; yaw system; generator; gearbox; low-speed shaft (main shaft); HSS; blades; nacelle; hub; meteorological unit (anemometry and wind vane); brake system; main bearing [2]. (b) A simplified representation of the three bladed WTG nacelle with a zoom on its drivetrain [2].

studied the vibration signals behavior generated by REB to estimate their remaining useful life (RUL).

In [10], Soualhi et al. an approach is presented that combined the Hilbert-Huang transform, support vector machine (SVM), and support vector regression (SVR) for the monitoring of REBs. This approach indicates health, classifies the degradation severity and predicts the RUL. Experimental results show a reliable method for bearing condition monitoring.

Boškoski et al. [11], proposed an approach to estimate the RUL for REBs fault prognostics that uses Rényi entropy, Bayes' rule, and non-parametric Gaussian process models. The proposed approach was evaluated on the dataset provided for the IEEE Prognostics and Health Management (PHM) 2012 Prognostic Data Challenge.

In [12], Ben Ali et al. proposed a method based on a data-driven prognostic approach, exploring the combination of Simplified Fuzzy Adaptive Resonance Theory Map neural network and Weibull distribution. They were able to judge the health state of REBs and to estimate the RUL using these PHM tools. Experimental results showed that their proposed method could effectively predict the RUL of REBs based on vibration signals.

Detection of localized faults in planet bearings is more difficult than fixed-axis bearings because of the complicated and time-varying vibration transmission path between the fault and a measurement point on a ring gear. No published work has been found which simulates this time-varying transmission path and determines the vibration signature of a planetary drive containing a localized planet-bearing fault.

The envelope analysis, also called the high-frequency resonance technique (HFRT), is a powerful tool in these conditions [16]. It is widely used for demodulating resonances detected using the classical spectrum. But in practice, choosing a suitable resonance frequency is a challenging task.

The localization of main resonances to be a difficult task and will increase the computational time if we must analyse all resonances which can arise using the classical spectrum. Kurtosis can make this procedure less difficult; it is a scalar measurement which makes it possible to locate transients in the signal. Spectral Kurtosis (SK) is one of the new methods, that is used to locate the optimal band frequency [17,20–22].

The main objective of this paper is to investigate wind turbine HSSB degradation in run-to-failure testing using time indicators derived from SK, then estimate the RUL using SVR.

The decision whether a particular experimental run is likely to contain degradation data was based on the maximum value of the SK for the particular measurement. The idea behind this approach is the property of the SK which states (Antoni et al., [20]) that the value of $SK(f)$, defined by Eq. (2), increases with the intensity of the fluctuations in the impulse amplitudes [20]. Consequently, the value of the SK can be used as an indication of the severity of the damage.

This paper is organized as follows. Section 2 introduces the WTG and its drivetrain and the bearings operation conditions and challenges. Section 3 presents a brief description of SK technique. Section 4 shows the resulting benefits by means of experimental tests using SK-derived features and RUL estimation. Finally, Section 5 concludes this paper.

2. Inspections of wind turbine drivetrain

2.1. Structure of wind turbines and bearings

Wind power generation is rapidly growing as a source of clean and green energy. Wind is available free of charge: the main costs for WTGs are construction and maintenance. The design life of wind turbines is 20-year [2–6], therefore, WTGs require periodic inspections and repairs in order to achieve this estimated 20-year lifespan. Throughout this operating period, the gearbox, bearings, blades and all other parts of each wind turbine are thoroughly inspected [23,28].

A typical three-blade horizontal axis WTG is shown in Fig. 1(a) [7]. Its internal structure and major components are illustrated in Fig. 1(b). The WTG has these major components; the nacelle is a box-shaped housing unit installed next to the turbine's blade whose rotation is powered by the wind. Inside the nacelle is a main shaft that enables the rotation of the rotor blade; a gearbox which increases the rotation speed in order to generate electric power; a generator which converts the wind power to electrical power; and a yaw system drive that changes the direction of the turbine in accordance with the direction of the wind. The wind turbine rotor is composed of the wind turbine blades, where the aerodynamic power conversion takes place, and the hub, where the blades and the low-speed shaft are attached. Furthermore, most modern wind turbine rotors are equipped with pitch servos inside the hub, that rotate the blades along their longitudinal axes to control the aerodynamic behavior of the blades [2–8].

As shown in Fig. 1(b), the nacelle of a WTG contains the power transmission system/drivetrain, the electric generator, control subsystems and some auxiliary elements such as cooling and mechanical braking systems. The drivetrain transmits the mechanical power captured by the rotor to the electric generator. It consists