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Classification of imbalance levels in a scaled wind turbine through detrended fluctuation analysis of vibration signals

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ABSTRACT

This work proposes to identify different imbalance levels in a scaled wind turbine through vibration signals analysis. The experiment was designed in such a way that the acquired signals could be classified in different ways. A combination of detrended fluctuation analysis of acquired signals and different classifiers, supervised and unsupervised, was performed. The optimum number of groups suggested by k-means clustering, an automatic classifier with unsupervised learning algorithm, differs from the number of classes (or subsets) defined during the experimental planning, presenting another approach to the possible classification of vibration signals. Additionally, three supervised learning algorithms (namely neural networks, Gaussian classifier and Karhunen-Loève transform) were employed to this end, classifying the collected data in some predefined amounts of classes. The results obtained for the test data, just a little different regarding the training data, also confirmed their capability to identify new signals. The results presented are promising, giving important contributions to the development of an automatic system for imbalance diagnosis in wind turbines.

1. Introduction

A better understanding about the fields of global warming and climate change is the way for renewable energy sources to become a main concern for governments and international organizations and institutions. Therefore, the search for new alternative sources of energy has become the key to ensure a sustainable future. In this scenario, it is well stablished that renewable energy sources provide substantial benefits. Among various renewable energy sources such as solar, biomass, geothermal and hydraulic, wind stands out as a clean, efficient and promising alternative with little environmental impact.

Improvements on wind turbines reliability and performance are essential. Although potential problems can occur in any component of a wind turbine, the most common failures are presented on its rotor blades or tower. So, special attention must be paid to the mechanical effects of wind action on rotor blades to avoid excessive stresses, instability, fatigue and rupture. The harmful consequences from mechanical vibrations have been extensively studied by various researchers worldwide, e.g. Refs. [2,13]. Over the years, vibration analysis has been performed by using signal processing, e.g. Refs. [7,14,15,23,27,33,34,36,46].

One of the major concerns regarding a wind turbine is the negative effect of vibrations on its performance. Therefore, many researchers have paid much attention to mitigating and controlling vibrations on wind turbines [47]. investigated the performance of roller dampers for mitigation of edgewise vibrations on rotating wind turbine blades and his results indicated that the proposed damper could effectively improve the structural response of wind turbine blades [16]. showed a new active control strategy designed and implemented to control the in-plane vibration of large wind turbine blades which, in general, is not aerodynamically damped. It was concluded that the use of the proposed new active control scheme significantly reduces the in-plane vibration of large, flexible blades.

A nonlinear dynamic model was developed by Ref. [48] to study

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the torsional vibrations of wind turbine gearboxes having two planetary gear stages and one parallel gear stage. Many factors acting on the dynamic behavior of wind turbine gearbox components are considered by employing the numerical integration method. It was found that the external excitation is the most important influence on the torsional vibrations of wind turbine gearbox components.

In their work [40], proposed a model to control wind turbine vibrations by changing the rotational speed of the blades and a multi-modal mathematical model describing the dynamics of flexible rotor blades and their interaction with the turbine tower, all being formulated by using a Lagrangian approach. An active controller based on active tendons was proposed to mitigate wind-induced edgewise vibrations.

Feature extraction and fault diagnosis via vibration analysis is a common and effective mean for wind turbine condition monitoring, specially on rotation parts, as well as blade-cabin-tower coupling system [24]. calculated tower natural frequency based on the coordinate system. Wind-induced random vibration was analyzed and total wind force on blade-cabin-tower coupling system was determined.

[1] used a novel approach called Empirically Decomposed Feature Intensity Level (EDFIL) to identify the fault severity caused by intentionally produced cracks of different sizes in a wind turbine blade. He also showed that common vibration analysis techniques, such as Kurtosis, Root Mean Square, Crest Factor and Fast Fourier Transform (FFT) are not useful tools to diagnose wind turbine blade defects. As it was explained, more advanced monitoring techniques are required to deal with noise-contaminated and non-stationary signals of a wind turbine.

A combination of Detrended Fluctuation Analysis (DFA) and pattern recognition techniques was successfully applied to fault diagnosis in gearbox [12] and bearing [11] under various conditions of frequency, load and severity or kind of fault. Inspired by these previous works and taking into account the relevance of the above discussed subjects, this study performs a similar approach. The idea is to investigate whether this approach can be useful in the classification of vibration signals acquired from a scaled wind turbine and to evaluate the performance of different pattern recognition techniques.

2. Experimental setup

In this work, a set of blades with NREL S809 profile, specifically developed for use in horizontal-axis wind turbines (HAWTs), was designed by a in-house developed software [9], which uses a methodology of design from Ref. [3] to calculate the blades parameters, such as the chord and twist distribution, as shown by the images on Fig. 1. The blades were manufactured using a stereolithography technique, commonly called 3D printing, which guarantees the production of balanced blades, and after a polishing process the roughness can be negligible. Three blades were built, each with 0.20 m length, 15 g and tip speed ratio λ equal to seven.

The experiments were carried out on a bench composed of a wind turbine shaft and a three-bladed rotor, a torque transducer and an electric motor, as shown in Fig. 2. This bench was located in an open circuit subsonic wind tunnel approximately 6.5 m long with a test section of 0.50 × 0.50 m, powered by a 1.49 kW (2 hp) exhauster. To guarantee that the blades work in their tip speed ratio (λ) of project, the rotor remained at a constant rotation of 900 rpm and the mean wind velocity at the test section was 2.71 m/s with standard deviation of 0.035 and turbulence level below 2%. The blockage ratio found in the test section was 50.77% and the blockage factor required for correction of Cp (power coefficient) calculation was 0.84 [5].

The aim of the present work is to verify if the approach successfully applied in previous fault diagnosis works can be useful to distinguish unbalanced levels of scaled wind turbine. Given that, the following main work conditions were regarded:

1. Imbalance on a single blade by mass addition. This condition reproduces several situations, such as accumulated dirt over a blade or any object attached to it. This condition was simulated by mass addition (0.5, 1.0 and 1.5 g) at the tip of only one blade.
2. Imbalance on a single blade by lacking mass. This condition reproduces the possibility of a broken blade or excessive weight loss on a blade. This condition was simulated by mass addition (0.5, 1.0 and 1.5 g) at the tip of two blades.
3. Balanced system. This normal condition can be obtained in two different ways: when all blades are of same mass and their rotor is balanced, or by using only the shaft. These configurations also help us to certify the balance of the system.

In addition, a question can be formulated concerning the most adequate amount of classes to be used for this setup. Three groups as the main work conditions, as well as seven (and even eight) groups as subsets are possible answers. For all test conditions, rotor remained at a constant rotation of 900 rpm.

Signals were captured through a Bruel & Kjaer accelerometer, model 4381V, which is located in the shaft bearing closer to the blades, as shown in Fig. 2. The sensor is coupled to a Bruel & Kjaer amplifier, model 2692. For band filtering, 1.0 Hz (high) and 100.0 Hz (low) were chosen as limits. Afterwards, a Tektronix oscilloscope, model 1062 TBS, was used to record signals. Each signal was composed of 500 data points acquired with a sampling rate of 250 Hz (250 samples/s). For all tested conditions, rotor remained at a constant rotation of 900 rpm. For each balanced level, 50 vibration signals were captured, resulting in a dataset of 400 vibration signals. Fig. 3 shows a representative normalized vibration signal.

The Nyquist sampling theorem affirms that, to be possible to recover all spectral components of a periodic waveform, the sampling rate must be at least twice the highest waveform frequency. So that, the higher the sampling rate the higher the recorded frequencies. With this in mind, and considering that the rotation frequency of wind turbine is 900 rpm (15 rps), the minimum sampling rate to record these signals should be 30 Hz. However, vibration signals are not a single periodic waveform and they have upper spectral components. In addition, the sampling rates offered by oscilloscope is limited. Some of the sampling rates offered are 25, 50, 125, 250 Hz and go on. The first one do not satisfy the Nyquist sampling theorem. In order to avoid missing of those important spectral components to vibration signal analysis, they were recorded at 250 Hz. On the other hand, the recording of frequency beyond the frequencies observed in Fourier spectrum of the signal is unnecessary.

3. Detrended fluctuation analysis

Detrended Fluctuation Analysis, or DFA [31], aims to improve the evaluation of correlations in a time series by eliminating trends in the data. The method assumes a profile that consists of an integrated series y_j

$$y_j = \sum_{i=1}^{j} (u_i - \langle u \rangle) \quad (1)$$

where $\langle u \rangle$ is the overall average of the original series,