# Vibration-based tools for the optimisation of large-scale wind turbine devices

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# Vibration-based tools for the optimisation of large-scale industrial wind turbines devices

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## Abstract

Wind turbines (WT) maintenance management must be in continuous improvement to develop reliability, availability, maintainability and safety (RAMS) programs, and to achieve time and cost reductions in large-scale industrial wind turbines. The optimisation of the operation reliability involves the supervisory control and data acquisition to guarantee these correct levels of RAMS. A fault detection and diagnosis methodology (FDD) is proposed for mechanical devices of a WT. The method applies the wavelet and Fourier analysis to vibration signals. The signals collected contain information on failures found in the gearbox-generator set. The information is initially tested by the fast Fourier transform (FFT) to ensure the accuracy of the information. Then, a pattern based on energies that relates each failure with different frequency bands is created. This pattern uses the wavelet transform as the main technique. A number of turbines of the same type were instrumented in the same wind farm. The data collected from the individual turbines was fused and analysed together in order to determine the overall performance. It is expected that data fusion allow a significant improvement since the information gained from various condition monitoring systems can be enhanced. Effort will also focus on the application of dependable embedded computer systems for a reliable implementation.
**Keywords:** wind turbines, maintenance management, vibration, fast Fourier transform, wavelet.

## 1. Introduction

The renewable energy industry is in a constant improvement to cover the current demands. Companies compete to take advantage of any evolving opportunity presented, being some of these competitive advantages focused on maintenance management. Wind turbines (WT) are one of the fastest growing sources of renewable energy production (García *et al.*, 2012). The complexity of the WTs causes a reduction of the systems reliability and raises the maintenance costs due to the occurrence of non-monitored failures (Spinato *et al.*, 2009) and (Pinar *et al.*, 2013). There are several case studies that present maintenance activities on WTs but they all depend on the model considered, the geographic and environmental changes that occur in different wind farms.

Techniques such as condition monitoring (CM) can be introduced to detect and identify these failures at earlier stages. Thereby, the productivity performance is maximised, and

possible downtimes of the WT are minimised. This results in an increasing of the reliability, availability, maintainability and safety (RAMS) levels (García *et al.*, 2010).

CM is implemented from basic operations of the equipment to study (García *et al.*, 2012). The system provides the state of a characteristic parameter that represents the health of the component(s) being monitored. Data acquisition is initially achieved with the optimal type and placement of sensors. Then, data processing, sorting and manipulation according to the objectives pursued, are performed by a digital signal processor. Finally, they are shown via a screen display, stored or transmitted to another system.

As part of some fault detection and diagnosis (FDD) approaches (García *et al.*, 2010), features are extracted via CM. FDD is used to obtain the information needed from these features. This way, mechanical components such as gearboxes or bearings in the case of the WT, can be monitored. The main block function of any FDD must be data acquisition, data processing and data distribution.

A FDD is proposed for mechanical devices according to the above in this case study. A method that applies the wavelet and Fourier analysis to vibration signals is developed. The signals collected contain information on failures found in different gearbox and generator sets. The consortium instruments up to 3 turbines of the same type and from the same wind farm. The information is tested by the fast Fourier transform (FFT) and then, a pattern based on energies is done. This pattern uses the wavelet transform to relate the different failures with the energy of the frequency bands. The data from the individual turbines is fused and analysed together to have the overall reliability of the wind farm. Data fusion can allow a significant improvement since the value of the information gained from the various CM systems is enhanced. Effort will also focus on the successful application of dependable embedded computer systems for the reliable implementation of wind turbine CMs and control technologies.

## 2. Techniques
### 2.1. Fast Fourier transform

The FFT is an algorithm that calculates the Discrete Fourier Transform (DFT) and its inverse from a periodic sequence of complex numbers according to equation (1) (Dickinson, 1982):

$$X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-i2\pi kn/N}$$

(1)

where $i$ is the imaginary unit and $e^{\frac{i2\pi}{N}}$ is the Nth root.

The use of the FFT is focused on the analysis of signals in the frequency domain (Oberst *et al.*, 2007). It is useful when patterns are periodic (Amidror *et al.*, 2009), and provides information of a fault origin and/or its severity (Lahdelma *et al.*, 2007).

There are a large number of publications related to the fault diagnosis for rolling elements employing FFT. Misalignment and unbalances are usually studied with the FFT. They appear due to incorrect machine assemblies (Patel *et al.*, 2009a and 2009b). The different frequency peaks determines the existence of emerging problems besides misalignments or unbalances, e.g., gaps, looseness (Goldman *et al.*, 1999). Al-Hussain and Redmond report vibrations for parallel misalignment at the natural frequency from experimental investigations (Al-Hussain *et al.*, 2002). Other authors suggest the appearance of vibration harmonics from twice to ten harmonics, depending on the signal pickup locations and directions (Nakhaeinejad et *al.*, 2009).

## 2.2.Wavelet transform

The wavelet transform identifies local characteristics of a signal in the time and frequency domain with the use of a series of decomposition coefficients at different frequency bands (Eristi, 2013). The wavelet transform also characterizes and identifies spectral features, unusual temporary behaviours and other properties related to non-standing waves. It can be used as an alternative to the FFT to process the signal from the time domain to the frequency domain without a significant loss of information at specific frequencies (Nieto *et al.*, 2008).

Wavelet transforms are categorized as continuous wavelet transforms (CWT), discrete wavelet transforms (DWT) or wavelet packet transforms (PWT). The CWT provides more detailed information while the DWT is efficient with fewer parameters (Chebil *et al.*, 2010). The PWT is an extension of the DWT using more filtering levels.

The wavelet transform decomposes the signal into several frequency bands. These bands are a linear combination of all the frequency components of the original signal. One of the features of any signal can be the energy. The energy is defined as in equation (2) for the wavelet transform.

$$E_f = \frac{1}{C_g} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left| W_g f(a,b) \right|^2 \frac{dadb}{a^2} \tag{2}$$

where $C_g$ is an admissibility constant used to normalize the energy.

It is important to choose a significant frequency range to use the wavelet transform in every case study. The right selection of the levels of decomposition will provide accurate findings in the signal processing and analysis. Signals are divided into different levels where the approximated decomposition is called $a_n$, being $n$ the highest level of decomposition. It is considered the low frequency component while $d_1$ is the high frequency component. These *approximated* (A) and high frequency *detailed* signals (D), is done using low pass and high pass filters (Figure 1) (Canal, 2010).
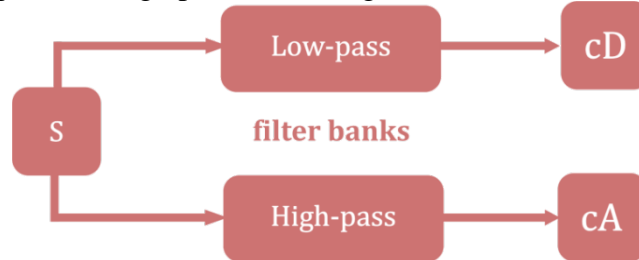


**Figure 1.** Decomposition diagram.

## 3.  Condition monitoring of the mechanical devices

Eight piezoelectric sensors measured the vibration at specific locations for the gearbox and the generator. All the data was captured at 48 KHz, collecting 8192 samples. Table 1 summarizes the information.

**Table 1.** List of installed sensors.

| Signal | Location | Additional information |
|---|---|---|
| Vibration | Gearbox | High speed shaft - Radial |
| | | High speed shaft - Axial |
| | | Planetary stage - Radial |
| | Generator | Drive end - Axial |
| | | Drive end - Radial |
| | | Non-drive end - Radial |

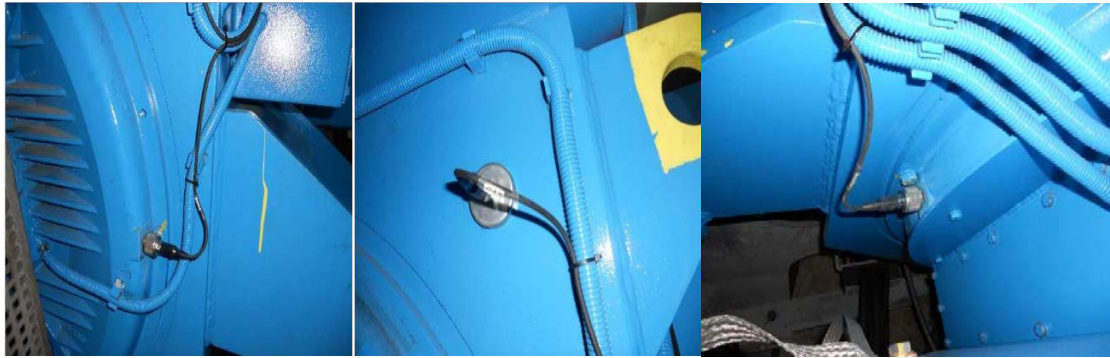The accelerometers were fixed using magnetic bases (Figures 2 and 3)

**Figure 2.** Generator measurements.


**Figure 3.** Gearbox measurements.

The signals were collected in different dates and with different loads. The information is contained in Table 4.

**Table 4.** Measurements.

| Date | 11/04/2014 | 11/04/2014 | 13/04/2014 | 19/04/2014 | 26/04/2014 | 27/04/2014 |
|------|-----------|-----------|-----------|-----------|-----------|-----------|
| Load | 44% | 100% | 50% | 7% | 51% | 26% |

## 4. Vibration analysis employing the Fast Fourier transform

Results depend on the device studied. Section 4 is subdivided in the generator case and the gearbox case.

### 4.1. Generator case study

The bearings are analysed in the case of the generator. Frequencies appear in the high frequency range (kHz) for the first damage phase. The higher frequencies correspond to the natural frequencies. Later, failure modes are observed and harmonic peaks emerge as well as sidebands as the result of the bearing impacts. The amplitude of the natural rotational frequency (1X) and their corresponding harmonics increases due to the emergence of gaps. Finally, the signals show noise accumulations along the spectrum.

Three sources of failure are considered:

- Bearing wear: It presents peaks at non-synchronous frequencies, typically with harmonics, and often sidebands around the 1X.
- Cocked bearing: Peaks are often observed at 1X, 2X and 3X.
- Bearing clearance: The spectrum shows similar characteristics to the rotating loosenesss. There are strong harmonics and half-order and even one-third order harmonics in severe cases.

Figure 4 contains two examples of signals analysed with the sources of failure abovementioned.
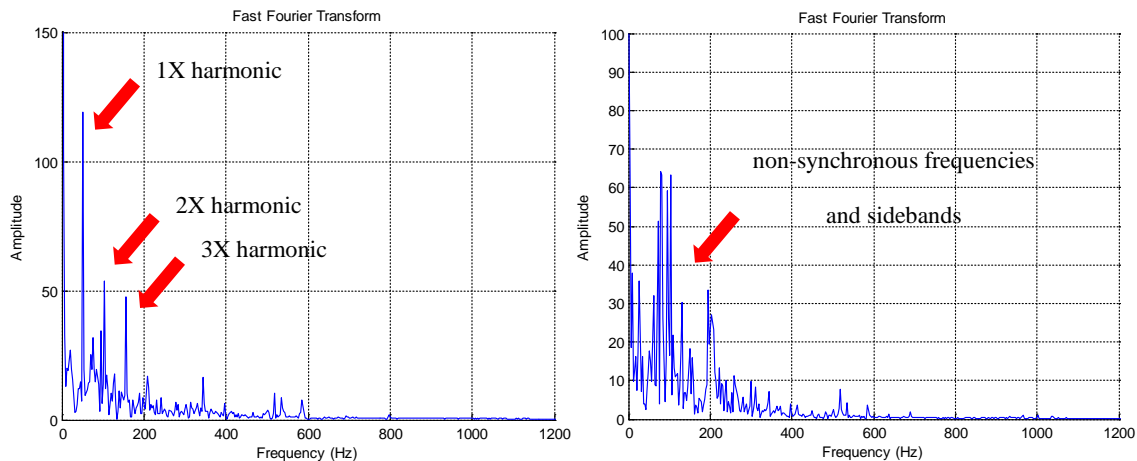
**Figure 4.** Bearing symptoms by the FFT.

### 4.2. Gearbox case study

Gearboxes modify their speed frequency from the gear teeth. Three key frequencies are involved in this process: the input speed, the gear mesh and the output speed. Peaks are usually linked to shaft speeds and the gear mesh frequencies. Peaks at twice the rotation frequency and sidebands around the peaks gear may also exist. Peaks can be found up to 30-40 times the shaft speed because of the gearbox characteristics. These peaks are multiples of the gear mesh frequency. The following problems are identified:

- Gear tooth wear: Sidebands around the gear mesh frequency increase in amplitude for the initial stage. The sidebands are linked to the speed of the worn gear. The natural frequency of the gear will present sidebands.
- Misaligned gear: The misaligned gears have high frequencies amplitudes with sidebands. However, it is also common to find peaks at twice the frequency of the gear.

Due to the nature of these problems, the most accurate information is provided by the sensors placed closest to the planetary stage of the gearbox. The first peak (1X) in Figure 5 (rounded in red, left image) appears because of the rotational speed of the shaft. The following ones correspond to the gear mesh frequencies and are proportional to the rotational speed. The ratio of the amplitudes 1X vs. gear mesh frequency becomes remarkable when the sensors are closer to the failure zone. This fact is observed in Figure 5 where the 1X frequency decrease its amplitude in comparison to the following peaks. It is noteworthy to emphasize that 1X and the gear mesh frequencies usually have sidebands. This performance is expected in this type of failure as well as the appearance of intermediate frequencies between the 1X and the first gear mesh frequency.
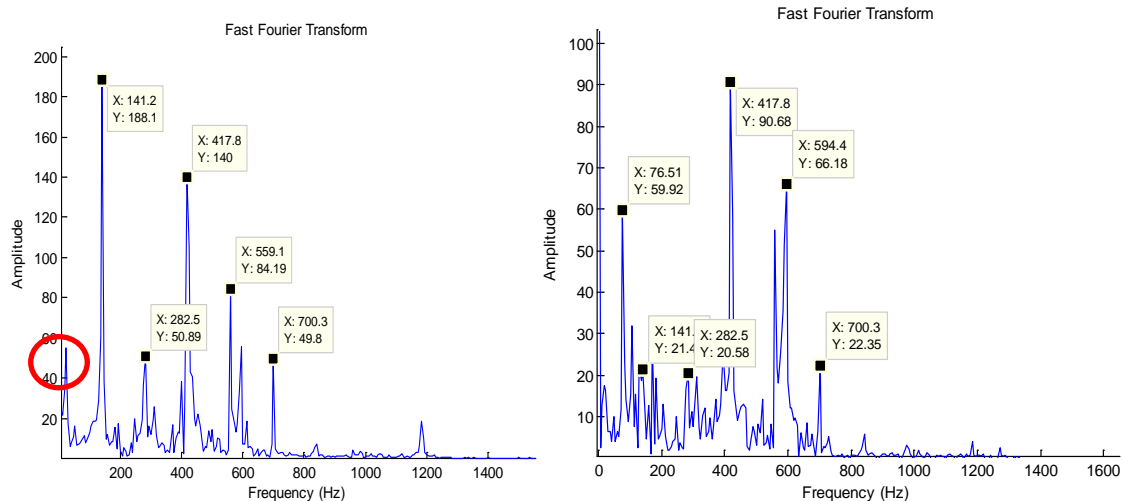
**Figure 5.** Gearbox symptoms by the FFT.

## 5. Vibration analysis employing the wavelet transform

As in Section 4, Section 5 is also divided in the generator and the gearbox case.

### 5.1. Generator case study

The original signal is divided into 12 levels in this case study. The findings were analysed with fewer levels, but the most representative information was usually linked to the natural frequency, giving less importance to any contribution of mechanical nature. The selection of 12 levels shows that there are low frequencies peaks associated to the rotational frequency and significant percentages appear. Discussed frequencies are around the rotational speed and its multiples. Sensors that collect information next to the bearings has a different performance between them (drive end radial and axial). The radial components (drive end radial and non-drive end radial) have a similar behaviour, even with differences, despite their different location regarding to the bearing.

Figure 6 evidences the influence of the load, especially when the set loads are below the 50% of the total. For these cases, the percentage of energy is distributed along different frequencies (from $d_8$ to $d_4$) if the sensor is close to the bearing, while specific peaks are observed at the free fault conditions.

Noise is produced throughout the whole spectrum because the bearing is in an advanced deterioration stage. Gaps, as a result, become evident when the system load is lower. This can be due to the load attenuating this effect.
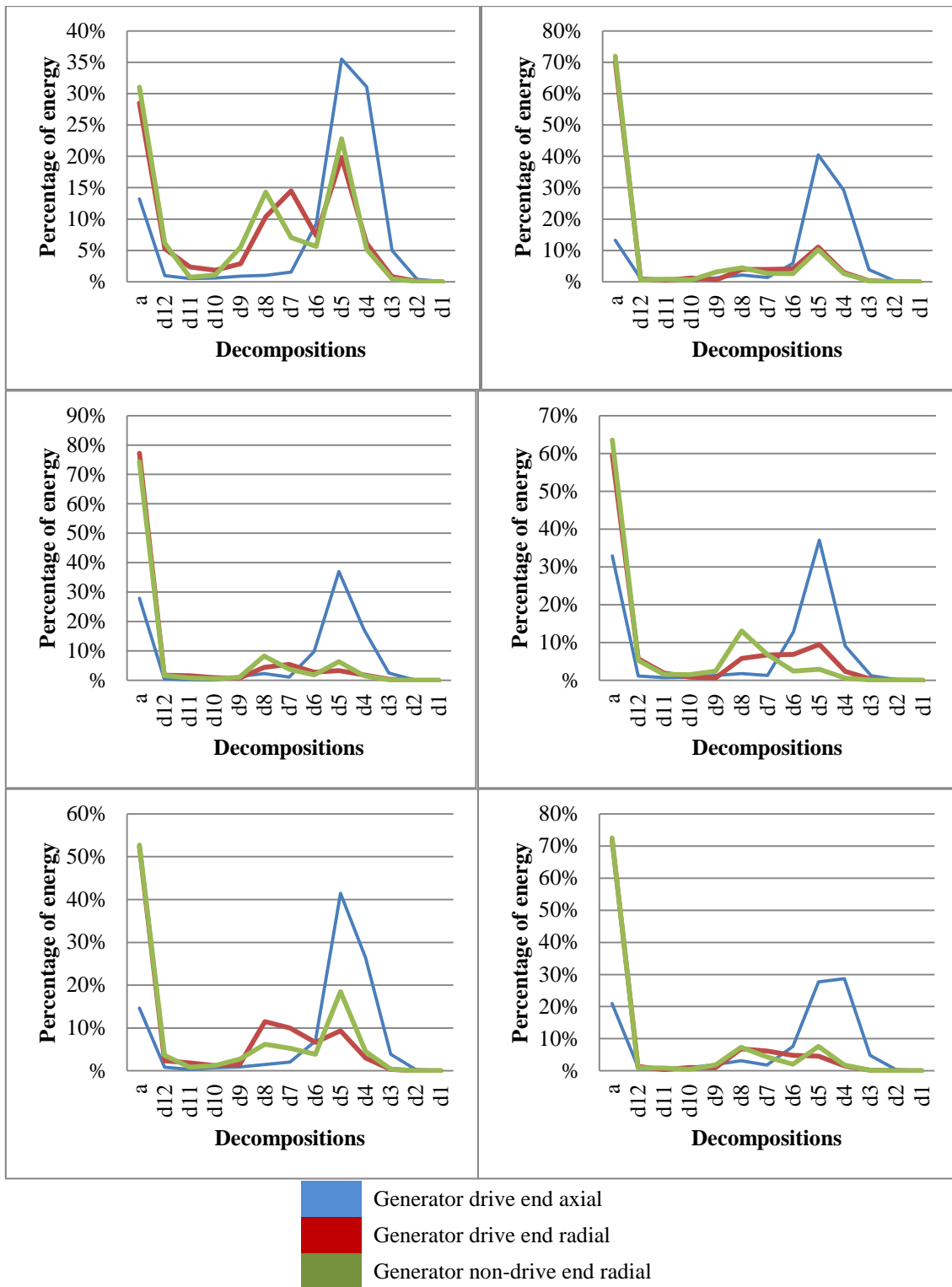
**Figure 6.** 44% load (11th April), 100% load (11th April), 50% load (13th April), 7% load (19th April), 51% load (26th April), 26% load (27th April) (from left to right and from top to bottom).

### 5.2. Gearbox case study

The signals were also divided in 12 energy levels to be consistent with the methodology applied in the previous section. Mechanical contributions are again detected at low frequencies energies. The considerations taken into account in the vibration study through the FFT are also used for the wavelet transform e.g. the selection of the planetary stage to obtain the results. It is observed that the performance of the signals

collected near the failure zone is again completely different to the drive end radial signal.
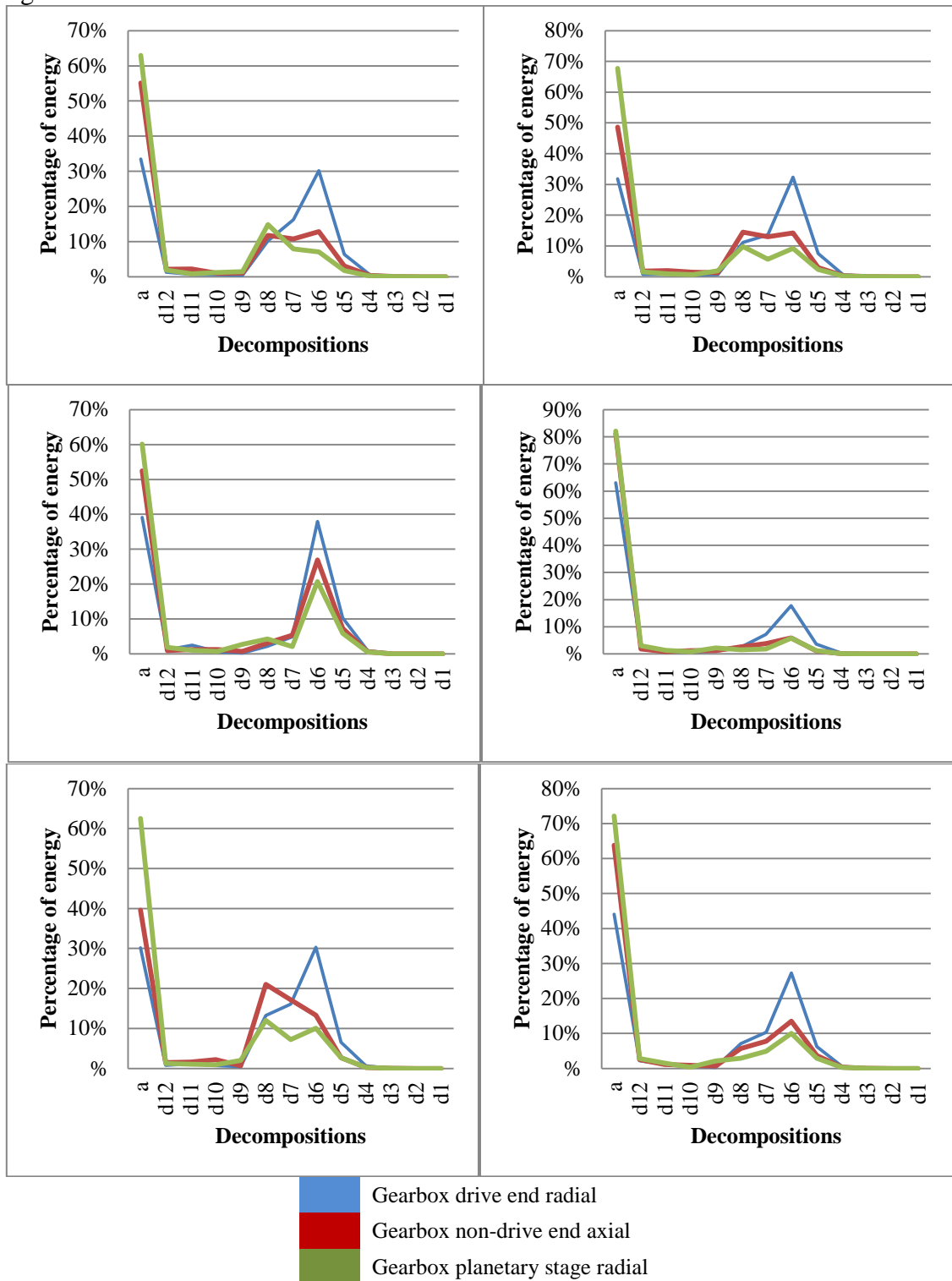


**Figure 7.** 44% load (11$^{th}$ April)**,** 100% load (11$^{th}$ April), 50% load (13$^{th}$ April), 7% load (19$^{th}$ April), 51% load (26$^{th}$ April), 26% load (27$^{th}$ April) (from left to right and from top to bottom).

The percentage of energy is distributed along different frequencies (from $d_8$ to $d_5$) with specific peaks around the speed frequency and the medium range frequency ($d_6$). A second peak energy (medium range frequency) is linked to the gear mesh frequencies as the result of gaps and emerging failures due to the wear and misalignments (See Figure

7). Moreover, regarding the previous case study, it is seen that there are not residual percentages of energies along the remaining frequencies ($d_{12}$-$d_9$ and $d_4$-$d_1$). This situation is not found because the misalignment is not severe and therefore, it does not generate a gap on the set.

## 6. Conclusions

The growth of the renewable energy industry and the needs to reduce costs and increase competitiveness, safety, availability, reliability, forces firms to emphasize to invest and improve areas as the maintenance.

This paper proposes a fault detection and diagnosis methodology for mechanical devices of a WT. The method uses the wavelet and Fourier analysis to vibration signals and a pattern based on energies that relates each failure with different frequency bands is created.

High amplitude peaks are observed in radial and axial directions for the generator. These impacts can be the result of clearances and bearing wear. A slight misalignment and wear is detected in the planetary stage of the gearbox that can be caused by the teeth wear. Other slight defects are not discarded in the gearbox.

As a result, an alarm system can be developed to suggest an immediate inspection for the generator and the monitoring of the gearbox in order to study the degradation of the set. These actions can be introduced within the maintenance management policies of the wind farm. This can be translated into a significant improvement since the information can be enhanced and implemented in dependable embedded computer systems.

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