Statistical analysis of low frequency vibrations in variable speed wind turbines

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Abstract. The spectral content of the low frequency vibrations in the band from 0 to 10 Hz measured in full scale wind turbines has been statistically analyzed as a function of the whole range of steady operating conditions. Attention has been given to the amplitudes of the vibration peaks and their dependency on rotating speed and power output. Two different wind turbine models of 800 and 2000 kW have been compared. For each model, a sample of units located in the same wind farm and operating during a representative period of time have been considered. A condition monitoring system installed in each wind turbine has been used to register the axial acceleration on the gearbox casing between the intermediate and the high speed shafts. The average frequency spectrum has permitted to identify the vibration signature and the position of the first tower natural frequency in both models. The evolution of the vibration amplitudes at the rotor rotating frequency and its multiples has shown that the tower response is amplified by resonance conditions in one of the models. So, it is concluded that a continuous measurement and control of low frequency vibrations is required to protect the turbines against harmful vibrations of this nature.

1. Introduction

During the last years, the interest in the prediction and diagnosis of wind turbine faults is growing because there is a need to reduce maintenance costs and to increase the production rates. Besides, the downtimes for repair and maintenance tasks have to be shortened. For that, a series of condition monitoring (CM) systems are being developed based on the collection and analysis of relevant information from the main wind turbine components [1-5].

The best technology is based on vibration measurements and their analysis in the frequency domain. Such techniques are successfully applied in other types of rotating machinery like hydraulic turbines [6].

In this paper attention is given to the low frequency vibration behavior that variable speed wind turbines exhibit in the drive train system. These vibrations are induced by exciting rotor forces originated from both the flow effects and the mass imbalances during the rotation. Moreover, the wind loads are dynamic and they present fluctuations in time and space. For variable speed machines, care must be taken to ensure that vibrations are not amplified due to the proximity of tower and blade natural frequencies to the rotor rotational frequency or any of its multiples. Particularly, there is a risk that the exciting forces are close to the tower’s first natural bending frequency since many turbines are currently implemented with flexible steel towers to save weight and obtain an economic benefit.
Consequently, excessive vibrations must be controlled to avoid damage to the structure and the drive train components. Besides, their occurrence results in a significant fatigue loading and, in some cases, the turbine performance might be affected [7-9].

2. Experimental set-up and measurements

2.1. Specifications of the wind turbines and monitoring system
The investigated wind turbines belong to two different wind farms. In each wind farm, the turbines are of the same model and power output. Their main characteristics are indicated in table 1. All of them are 3 bladed variable speed upwind machines with pitch regulation. The towers are made of steel with a conical tubular style. The drive trains incorporate 50 Hz 4-pole generators and planetary gearboxes provided by different manufacturers.

|                           | Wind Farm 1 | Wind Farm 2 |
|---------------------------|-------------|-------------|
| Number of units investigated | 7           | 5           |
| Power per unit (kW)       | 2000        | 800         |
| Rotor Diameter (m)        | 90          | 59          |
| Cut-in wind speed (m/s)   | 4           | 3           |
| Cut-out wind speed (m/s)  | 25          | 25          |
| Minimum rotor speed (rpm) | 9.0         | 11.3        |
| Maximum rotor speed (rpm) | 14.9        | 22.6        |

In each wind turbine, an online CM system based on vibrations is installed. The accelerometer signals are forwarded directly to a programmable anti-aliasing filter and then they are digitized and processed by means of a digital signal processor (DSP). The DSP calculates the frequency spectrum from the raw time signals and a series of characteristic values. Two analogue inputs register the wind turbine output power and the main shaft rotating speed at the moment of the measurements. From all the accelerometers installed in the drive train, the sensor of interest in our investigation is mounted in axial direction on the gearbox casing between the intermediate and the high speed shafts. This is an ICP accelerometer specially designed for low speed applications with a sensitivity of 0.1 V/g.

The measuring instruments meet the quality requirements given in the corresponding guidelines. In particular, the accelerometer complies with a ±3 dB tolerance in the frequency range from 0.2 to 15000 Hz and the resolution of the A/D converter is 12 bit. Therefore, it can be guaranteed that the measurement uncertainty of the vibration acceleration lies within the limit ±10%. Regarding the resolution of the output power and of the rotating speed reading instruments, they are of about 1.27 kW and 1·10⁻⁴ Hz for WF1 units and of about 0.49 kW and 2·10⁻³ Hz for and WF2 units.

2.2. Description of the measurements and calculations
The CM system can calculate the frequency content of a vibration signal with user-defined broad band and narrow band characteristic values. The Root Mean Square (RMS) value, \( A_{RMS} \), is calculated from the frequency spectrum of the raw time signal by adding together the squares of the amplitude over a defined frequency range and taking the square root of this halved value as indicated in equation (1):

\[
A_{RMS} = \left( \frac{1}{T} \sum_{n=1}^{N} A^2 \right)^{\frac{1}{2}}
\]
In our case, the acquisition unit is configured to calculate the RMS value of the vibration acceleration in a frequency band, \( \Delta f \), from 0 to 10 Hz. A digitized time signal is low-pass filtered and windowed. The sampling rate is 30 Hz, the cut-off frequency is 10 Hz and 4096 samples are obtained for each measurement. The characteristic RMS value is continuously calculated, saved and checked for machine monitoring. Additionally, a raw time signal and an averaged frequency spectrum computed with the Fast Fourier Transform (FFT) are saved periodically.

The measurements obtained from 7 wind turbines in Wind Farm 1 (WF1) and 5 wind turbines in Wind Farm 2 (WF2) have been considered for the investigations. The period of time with valid vibration data has elapsed approximately half a year for WF1 and one year for WF2.

All the amplitude spectra collected during the period of interest have been post processed with external software in order to obtain various types of statistical results. Previously, the spectra have been digitally integrated to obtain the velocity of the vibration expressed in units of m/s RMS. The first data treatment has consisted in computing the mean and the standard deviation of all the spectra in each wind farm. The maximum standard deviations of vibration velocities estimated for frequencies above 0.1 Hz are of about \( 1.6 \times 10^{-3} \) and \( 2.6 \times 10^{-3} \) m/s RMS for WF1 and WF2 measurements respectively. The second analysis, since we are dealing with variable speed machines, has consisted in computing the estimated powers of given harmonics of the rotor rotating frequency from all the spectra and plotting these estimates as a function of the rotor rotating frequency.

3. Results and discussions

3.1. Power curves
In figure 1 the power outputs of one wind turbine from each wind farm have been plotted as a function of the rotor speeds. These data confirm the minimum and maximum rotor speeds specified in table 1. Expressed in Hz, the range of operation with power generation is approximately from about 0.18 to 0.25 and 0.18 to 0.38 for units in WF1 and WF2, respectively, as indicated in table 2.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Power output as a function of rotor speed for a single unit from WF1 (a) and another one from WF2 (b).}
\end{figure}

3.2. Broad band 0-10 Hz vibration levels
In figure 2 the RMS values of the vibration acceleration from 0 to 10 Hz of one wind turbine from each wind farm have been plotted as a function of the rotor speed. It is observed that the unit belonging to WF2 presents higher vibration levels along the whole operating range than the unit from WF1 in spite of giving less output power. Such behavior is analogous for the rest of units in each farm.
3.3. Average amplitude spectra
In figure 3 the average amplitude spectra, the average plus the standard deviation and the average minus the standard deviation of vibration velocities measured in all the units from WF1 and from WF2 have been plotted as a function of the rotor speed. In WF1 four peaks can be identified at 0.25, 0.29, 0.56 and 0.75 Hz. The second one shows the highest amplitude. In WF2 three peaks can be identified at 0.37, 0.54 and 1.13 Hz. The peak located at 0.54 Hz is significantly higher and broader than the rest.

In order to identify the origin of such frequency peaks, the reference values calculated in table 2 have been used. Given the range of operating rotor speeds from minimum to maximum fundamental frequencies \( f_0 \), the corresponding ranges of the second \( (2xf_0) \) and third \( (3xf_0) \) harmonics have also been calculated.
Table 2. Frequency ranges of rotor speed harmonics.

|               | Wind Farm 1          | Wind Farm 2          |
|---------------|----------------------|----------------------|
| $f_0$ (Hz)    | 0.18 - 0.25          | 0.18 - 0.38          |
| $2xf_0$ (Hz)  | 0.36 - 0.50          | 0.36 - 0.76          |
| $3xf_0$ (Hz)  | 0.54 - 0.75          | 0.54 - 1.14          |

By comparison between the peaks observed in figure 3 and the values in table 2, it can be deduced that the first peak on WF1 corresponds vibrations associated to the rotor frequency, $f_0$, when the unit operates at maximum speed. Then, the third and the forth peaks correspond to the blade passing frequency, $3xf_0$, at both limits of its frequency range. In these cases, the rotor frequency and the blade passing frequency are the sources of excitation that generate the observed vibration peaks. Therefore, the frequency peak around 0.29, that is not associated to any rotating component, should correspond to a tower’s natural frequency.

Meanwhile, on WF2 it can be deduced that the first peak corresponds to the maximum value of $f_0$, the second peak to the minimum value of $3xf_0$ and the third peak to the maximum value of $3xf_0$. In this case, no additional frequency peak is detected. Consequently, it could be assumed that one of them corresponds to the tower’s natural frequency. In this case, the main candidate is the peak at 0.54 Hz because of its significant amplitude and width. And both $2xf_0$ and $3xf_0$ are the exciting frequencies that can match this natural frequency in some operating conditions.

In summary, the estimated first tower natural frequencies for the units installed in both farms are listed in table 3.

Table 3. First tower natural frequency.

|               | Wind Farm 1 | Wind Farm 2 |
|---------------|-------------|-------------|
| 0.29 Hz       |             | 0.54 Hz     |

3.4. Narrow band vibration levels

To verify the assumption of the existence of a tower’s natural frequency in the range of the harmonics of the rotor fundamental rotating frequency for the units of WF2, the power of the vibration velocity at these frequencies has been calculated from all the amplitude spectra available for both wind farms. These power values corresponding to $f_0$, $2xf_0$ and $3xf_0$ have been plotted as a function of the rotor speed at the moment of the measurement in figures 4, 5 and 6 respectively.

In figure 4, very similar trends are found between the units in both farms regarding the vibrations at $f_0$. The amplitudes are similar up to maximum rotor speed. Then they grow up significantly as the power output reaches its maximum during pitch regulation at constant speed.

![Figure 4](image_url)
In figure 5, the amplitude of the vibration at $2f_0$ for WF2 reaches the highest values when $f_0$ is around 0.27 Hz which is approximately one half of 0.54 Hz. So, it indicates that when the excitation originated by the rotor misalignment at $2f_0$ coincides with the tower’s natural frequency the vibration response is significantly amplified.

![Figure 5. Estimated velocity of vibration power of the second harmonic of the rotor rotating frequency peak $2f_0$ as a function of rotor frequency for all the units from WF1 (a) and from WF2 (b).](image)

In figure 6, the amplitude of the vibration at $3f_0$ reaches the highest values when $f_0$ is around 0.18 Hz which is approximately one third of 0.54 Hz. So, it indicates that when the excitation originated by the blade passing frequency at $3f_0$ coincides with the tower’s natural frequency the vibration response is again significantly amplified.

![Figure 6. Estimated velocity of vibration power of the third harmonic of the rotor rotating frequency peak $3f_0$ as a function of rotor frequency for all the units from WF1 (a) and from WF2 (b).](image)

In figure 6, the amplitude of the vibration at $3f_0$ reaches the highest values when $f_0$ is around 0.18 Hz which is approximately one third of 0.54 Hz. So, it indicates that when the excitation originated by the blade passing frequency at $3f_0$ coincides with the tower’s natural frequency the vibration response is again significantly amplified.

![Figure 6. Estimated velocity of vibration power of the third harmonic of the rotor rotating frequency peak $3f_0$ as a function of rotor frequency for all the units from WF1 (a) and from WF2 (b).](image)

Meanwhile, the trends for WF1 units regarding vibrations at $2f_0$ and $3f_0$ show in general low amplitudes in the whole rotor speed range without significant amplifications at any speed.

4. Conclusions
The statistical analysis of low frequency vibrations in two groups of wind turbines has permitted to identify the existence of resonance conditions in one of them that result in significant levels at particular rotor rotating speeds. In this case, the first tower’s natural frequency is located in the frequency range of the second and third harmonics of the rotor fundamental frequency. For the other group, the first tower natural frequency is found well outside the frequency range of any excitation associated to the rotor speed and its harmonics.

As a result, this group of turbines with lower rated power present higher low frequency vibrations than the other ones with larger rated power. For the former turbines, the amplification factors for vibrations at $2f_0$ and $3f_0$ can reach around 6 and 3, respectively, relative to the observed levels outside resonance conditions.

The study of the low frequency vibrations by means of adequate condition monitoring systems is a valuable tool to identify and evaluate vibration problems in operating units. The results of the current
study permit to control and optimize the operation of the wind turbines at specific rotating speeds that present a risk of damage.

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