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# Analyzing wind turbine flow interaction through vibration data.

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**Abstract.** Wind turbines commonly undergo non-stationary flow and, not rarely, even rather extreme phenomena. In particular, rough terrains represent a challenging testing ground, because of the combination of terrain-driven flow and wakes. It is therefore crucial to assess the impact of dynamic loads on the turbines. In this work, tower and drive-train vibrations are analyzed, from a subcluster of four turbines of a wind farm sited in a very complex terrain. The main outcome of the study is that it is possible to start from the analysis of wind conditions and interpret how wakes manifest in the vibrations of the turbines, both at structural level (tower vibrations) and at the drive-train level. This wind to gear approach therefore allows to build a connection between a flow phenomenon and a mechanical phenomenon (vibrations) and can be precious to assess loads in different working conditions.

## 1. Introduction

Wind is a non-stationary phenomenon and therefore wind turbines, extracting its kinetic energy in exploitable form, are dynamically loaded along all the chain transforming the slow rotation of the main shaft into power output to be fed into the grid. The degradation of gearboxes is an elusive phenomenon; nevertheless gearbox faults are the most common cause of wind turbine breakdowns. In [1], it is estimated that a sudden failure of a 1.5 MW wind turbine during winter (when wind intensity is usually higher) leads to around €50,000 of missed production. This amount is up to 5 times greater than the missed production due to a wisely planned maintenance program. For this reason, there is a vast literature about drive-train condition monitoring (CM), for extending the lifetime of wind turbines [2]. The main sources of information are two: Supervisory Control And Data Acquisition (SCADA) data, which are commonly stored on 10-minutes time basis, and vibration signals acquired by turbine condition monitoring (TCM) systems. These vibration data are captured from several sensors placed on the turbine drive-train housing at high sample frequency (several kHz). Due to the different timescale of SCADA and TCM data sets, the techniques for elaborating them are commonly very different (in particular, feature extraction and denoising are challenging as regards vibrations [3, 4]) and so is the diagnostic power. In [5], oil temperature rises as recorded by SCADA control system are used for detection of incoming gearbox failures. In [6], it is shown that intuitive SCADA data mining techniques help in diagnosing and preventing faults and in [7], in particular, it is shown that the analysis of SCADA temperature measurements has a considerable diagnostic



power as regards gearboxes. Concerning vibrations, in [8], the k-means clustering algorithm is employed for condition monitoring of vibrations recorded on 10-seconds time scale. In [9], a comparative study on condition monitoring is conducted at the National Renewable Energy Laboratory (NREL). A full-scale baseline wind turbine drive train and a drive train with several gear and bearing failures are tested. In [10], some instructive methods are proposed for facing a very common situation: scarcity of information. The number of teeth in all the gears of a wind turbine gearbox with one planetary and two helical parallel stages is reconstructed and this allows to successively calculate toothmesh frequencies and rotational speeds of all shafts. On top of this very briefly summarized state of the art on condition monitoring, further inspiration for this work comes from the experience about operational analysis of onshore wind farms in complex terrain. In particular, the test case of this work is a subcluster of four turbines from a wind farm sited in southern Italy in a very complex terrain, which has also been a test case of the IEA-Task 31 Wakebench project [11, 12] for the evaluation of wind flow modeling at microscale level. Several studies [13, 14, 15, 16] are devoted to the investigation of the challenging combination of terrain-driven flow and wake effects, characterizing this wind farm. In particular it has been observed that the selected subcluster, when the wind blows from West, is characterized by a severe wake of the upstream turbine on the first downstream, and by an unexpected wake recovery at the site of the other downstream turbines, which is difficult to interpret in the framework of the most common wake models [17, 18]. It has been observed that this behavior is related to the directional response of the turbines to the terrain-driven distortion of the flow. The aim of the present work is studying this puzzling underworld as regards vibrations. The approach is what might be called "wind to gear", in this sense: the vibration spectra are analyzed and interpreted on the grounds of the statistical analysis of the collective response (yaw positions) to wind flow from the subcluster, in particular when considerable wakes between nearby turbines arise. The first step is analyzing tower structural vibrations, because they are expected to be sharply responsive to wind flow and to the onset of turbulence due to wakes. Subsequently, a study is conducted in order to inquire if wakes manifest also at the level of vibration spectrum at the drive-train. This is motivated by the fact that the drive-train acts as a velocity multiplier, and therefore it might be a useful testing ground for studying wakes at rated power, when sharp symptoms (as power collapse) fade away. The objective of this study therefore slightly shifts the focus with respect to the most diffuse vibration analysis: from fault prevention to performance analysis. This has a twofold value: on a practical level, it might be useful for understanding stress distribution under particular regimes, and in perspective it might therefore inspire management strategies of groups of turbines. On a scientific level, it constitutes an upgrade in our understanding of wind turbines under complex flow, because a connection is built between the response to a flow phenomenon (in the form of yaw positions) and a mechanical phenomenon (structural tower vibrations and drive-train vibrations). The structure of the study is therefore as follows: in Section 2, the test case and the data set are described. The methods are introduced in Section 3, and the results are collected and discussed in Section 4. The conclusions are drawn and some further direction is sketched in Section 5.

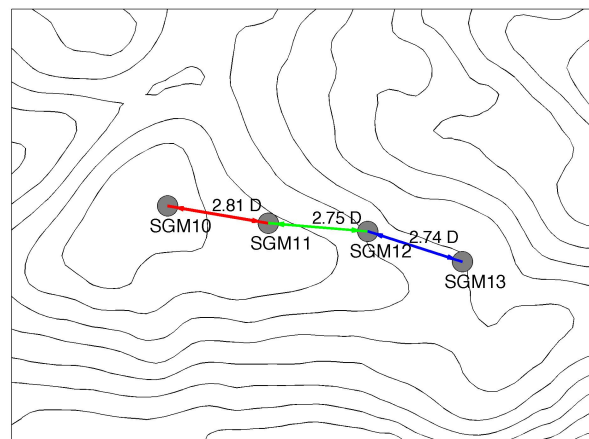
## 2. The test case and the data set

The wind farm features 17 turbines having 2.3 MW of rated power, 80 meters of hub height and 93 meters of rotor diameter. The terrain is very complex. Slopes up to 60% can be found in proximity of the turbines. In Figure 1, the subcluster selected for the analysis is sketched and, in Table 1, the complexity of the terrain at turbines site is estimated through the Ruggedness Index (RIX Values) [19, 20]. Inter-turbine distance (as can be seen in Figure 1) and slopes cause a very challenging combination of wakes and terrain effects, when the wind blows from East or West. For this reason, this wind farm, and especially this particular subcluster, have been a test

case of IEA-Task 31 Wakebench project[11, 12].

Turbine	RIX value (%)	height a.s.l. (m)
SGM10	24.9	1078
SGM11	23.1	1056
SGM12	21.7	1047
SGM13	20.4	1014

**Table 1.** Ruggedness Index and height at turbine site.



**Figure 1.** The layout and the inter-turbine distance of the subcluster under investigation. The terrain is represented with a contour line resolution of 20 m.

The data sets employed for the analysis basically come from two sources:

- Supervisory Control And Data Acquisition (SCADA) control system, recording measurements on 10-minute time basis,
- Turbine Condition Monitoring (TCM) system, recording vibration time-series, through several accelerometer sensors placed on the drive-train housing (the sampling frequency reaches the kHz scale).

Concerning the TCM system data, particular focus is devoted to the first downstream turbine: SGM11. Eleven time-series (TS) of the turbine SGM11 main bearing acceleration are analyzed. Table 2 describes the main working parameters of the turbine SGM11 during TS recording.

Each TS is acquired with a sample frequency of 2557.5Hz for an extent of 64100 points. In particular, the TS5 was acquired in a time period during which turbine SGM11 was suffering of turbulent flow induced by the wake of turbine SGM10 (see discussion in Section 4.2), whilst all the other TSs are acquired during normal turbine working conditions. As regards tower vibrations, instead, the approach is based on comparing each turbine against the others: several time series, as stored and automatically analyzed by the TCM system, are collected, as well as the information about the working parameters during the vibration sampling.

Time-series (TS)	Active Power [kW]	Generator rotation speed [rpm]	Yaw Position [deg]
TS1	2303	1463	252
TS2	2309	1456	244
TS3	2286	1444	246
TS4	2279	1441	354
TS5	2294	1446	265
TS6	2312	1453	255
TS7	2308	1451	25
TS8	2224	1431	9
TS9	2310	1458	250
TS10	2333	1458	7
TS11	2294	1473	29

**Table 2.** Working condition of turbine SGM11 during TS recording

### 3. Methods

The structural vibrations are investigated as follows: the data processed from the TCM system are collected and interpreted. They are in the form of statistical indexes about vibration time series. Each sampling is associated to a set of SCADA data, recorded simultaneously to the vibration time series, describing what the wind turbine was doing, how and why: wind speed, active power, yaw position, pitch angle, slow and fast revolutions per minute and so on. Further, data are organized in groups according to the percentage of rated power produced during the vibration measurement: this is particularly valuable for the purpose of this study, because different power regimes correspond to different thrust and load conditions. The focus is devoted to the statistical analysis of each TS: in particular, normalized root mean square is a global metric describing the power of vibration signal. In our approach, this information is crossed against the yaw position of each turbine, contextual to the vibration measurement. Crossing these two quantities is meaningful because in the patterns of yaw positions information is encoded about the response of the turbines to wind flow and wakes. Actually this has been studied exactly for our test case, in [13, 14, 15] and in an another study in press [21]: the directional behavior of the selected subcluster is investigated and the regimes associated to severe wakes or, in the converse, to wake recovery are highlighted. The TCM system records the statistical indexes about vibration sampling at different power regimes, but it doesn't store the original time series, except for the rated power regime. Therefore, the more challenging pre-treatment required for investigating drive-train vibration can be carried only at rated power (see the time series of Table 2). Concerning the gearbox vibration, therefore, the phase of the planet carrier is analyzed [22] in order to highlight the phase variation which could be related to the turbulent flow due to the wake effects. In particular, the Crest Factor of the extracted phase is evaluated and compared over eleven TSs. The results of this operation are then expanded to the analysis of the residual signal of the planetary annulus gear in order to highlight the modulation phenomena due to the turbulent flow.

In this way, a bridge should be established between the response (alignment patterns) of the turbine to the flow phenomenon and the vibrations. In the following Section 4, it is shown that this is indeed the case.

## 4. Results

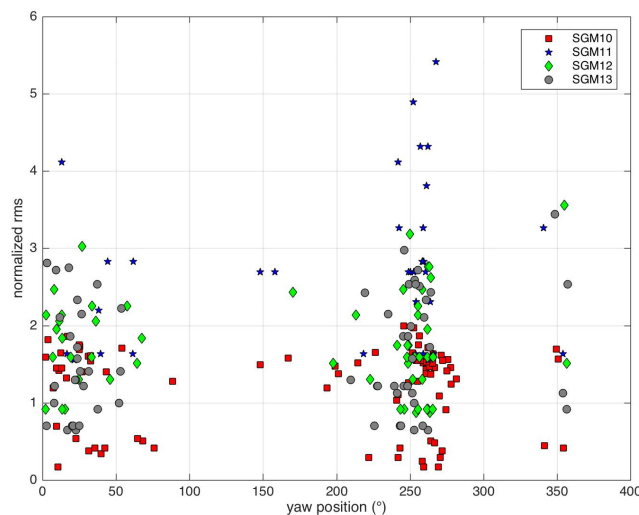
### 4.1. Tower vibrations

The TCM system records the structural accelerations through a bi-axial sensor placed on the top of the tower. In this way both the fore-aft and later accelerations can be measured (the two components of the acceleration on a plane parallel to the ground). In order to estimate the power of the horizontal oscillations, the RMS of the tower vibration is calculated using the following equation:

$$RMS = \sqrt{\frac{1}{N} \sum_{n=1}^N (|a_x[n]|^2 + |a_y[n]|^2)} \quad (1)$$

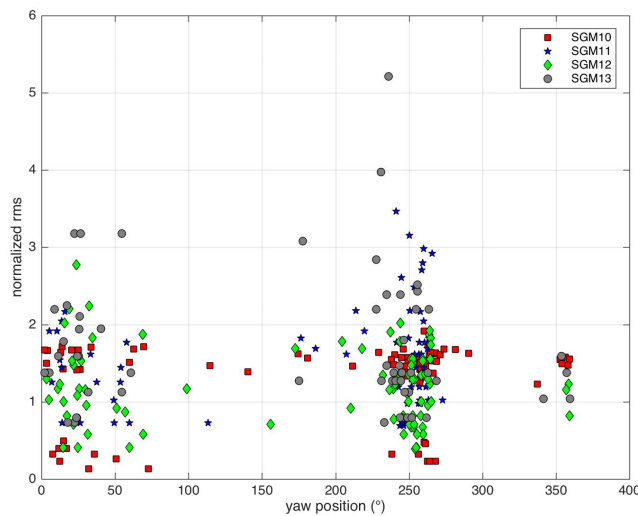
where  $a_x$  and  $a_y$  are the two components of the plane vibration. In figure 2 and 3 the RMS values are normalized using the average value of the measurements of each turbine.

The results about tower vibrations are collected in Figures 2 and 3. Figure 2 displays the dispersion of normalized root mean square against yaw position of each turbine when it is producing in the range of 75% of rated power, Figure 3 instead concerns the rated power regime.



**Figure 2.** Normalized root mean square vs yaw position (75% Rated Power).

From Figure 2, it arises that the turbulent flow induced by the wake of turbine SGM10 causes severe and very clearly observable vibrations to SGM11, when it is oriented at  $260^\circ$ . From [13, 14, 15] and another work in press [21], it arises that SGM11 yaw inclination at around  $260^\circ$  often corresponds to SGM10 orientation at  $270^\circ$ : this configuration is a clear manifestation of the relevant wake between SGM10 and SGM11, affecting the performances of SGM11 [13]. This expectation has been crosschecked against experimental SCADA measurements: two years of data have been filtered on the request that SGM11 is oriented at  $260^\circ$ , with a  $5^\circ$  tolerance because it corresponds to two typical standard deviations. On this filtered data set, it arises that mean and standard deviations of SGM11 yaw position measurements are respectively  $259.72^\circ$  and  $1.3^\circ$ , while for SGM10 one respectively obtains  $268.71^\circ$  and  $4^\circ$ . Therefore, further evidence is collected that SGM11 orientation at  $260^\circ$  is a response to wind blowing from West, and SGM10 oriented at  $270^\circ$ . As expected, the phenomenon arising in Figure 2 fades away approaching rated power, because the thrust lowers and wakes are mitigated. The terrain becomes the main driver



**Figure 3.** Normalized root mean square vs yaw position (Rated Power).

of the flow. Figure 3 is consistent with this interpretation: when the wind blows from West, the level of tower vibration of SGM11 is comparable to the rest of the subcluster, and peaks are observed at turbine SGM13, which is the turbine most affected by wind flow acceleration due to the terrain and in this regime is even the best performing of the subcluster. Summarizing, then, the proposed approach allows to interpret very consistently the behavior of the subcluster at the level of tower vibrations. Further, an issue is raised: do wake effects manifest in the vibration spectra even at rated power (when manifest symptoms are weaker)? Is drive-train analysis useful at this aim, in virtue of the nature of the drive-train itself as a velocity multiplier? In the following, it is shown that this is indeed the case.

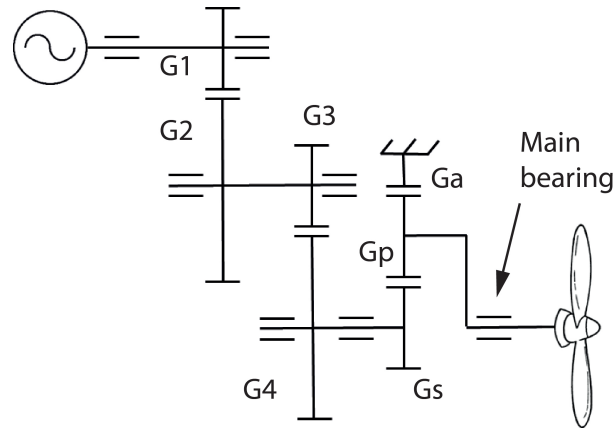
#### 4.2. Main Bearing

In order to understand the effect of the wake of turbine SGM10, analyzing the vibration of the the gearbox of turbine SGM11, the main bearing spectra of SGM11 are hereafter processed. Figure 4 depicts the schema of the turbine gearbox. This is a three stage gearbox; the first stage is a planetary one, whilst the last two stages are ordinary. Table 4 depicts the meshing frequencies of each stage for a generator speed of 1445.8 rpm.

Gear pair	Meshing frequency [Hz]
G1/G2	530.13
G3/G4	110.96
Planetary	22.98

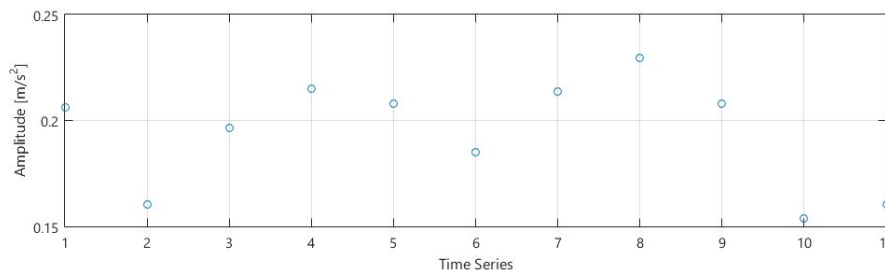
**Table 3.** Meshing frequencies of each gearbox stage.

Figure 5 depicts the RMS of the eleven main bearing TSs. The RMS values of main bearing vibration don't give any information about the turbulent flow acting on turbine SGM11 due to



**Figure 4.** Gearbox schema.

the wake effect. De facto, the RMS value of the TS5 is comparable with all the other RMSs. Therefore, deeper analysis has to be carried out for highlighting the behavior of the gearbox.



**Figure 5.** Time-series RMS values. Each signal is acquired with a sample frequency of 2557.5Hz for an extent of 64100 points.

The spectra of three TSs are depicted in Figure 6. It is possible to see that the main bearing spectra are dominated by the meshing frequencies of the three gearbox stages and its harmonics. In particular, no interesting information can be obtained by comparing the meshing component amplitudes. However, by looking at the planetary meshing frequency (Figure 6 (b)), a huge frequency spread is visible for the TS5 compared to TS6 and TS8. This strong phase variation of rotor rotational speed is therefore due to the turbulent flow induced by the wake effect.

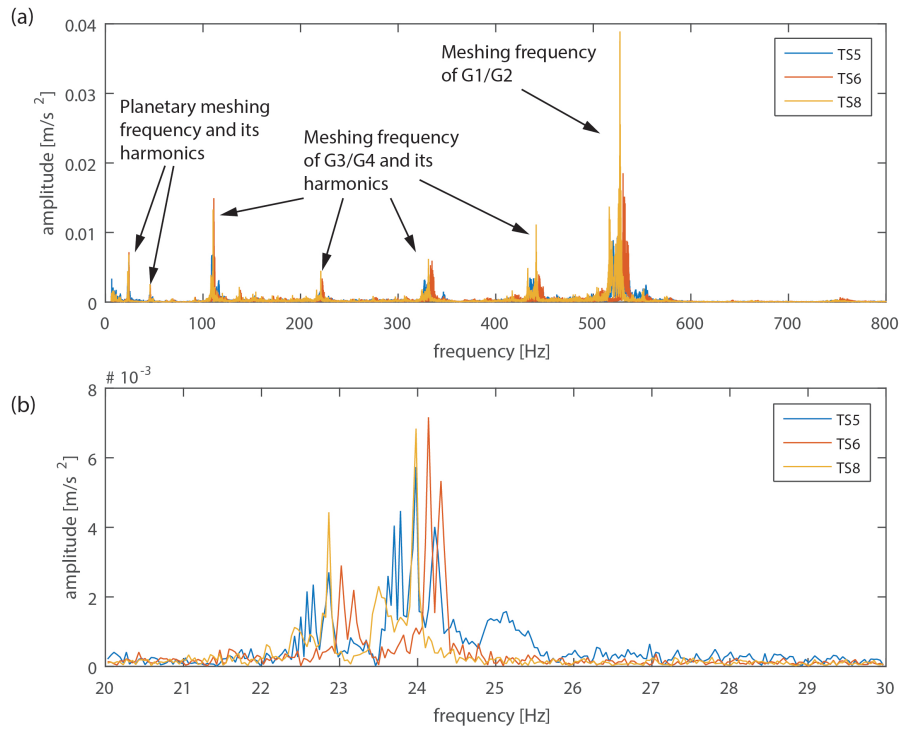
In order to keep track of this variation, the phase should be extracted from the main bearing vibration signal. To do so, the phase-demodulation technique [22] is used. In particular, the main bearing vibration signals are firstly filtered around the planetary meshing frequency and its harmonics. After that, the analytic signal is computed and the phase of such a signal is extracted.

The analytic signal is a complex function, computed as follows:

$$x_a(t) = x(t) + j\tilde{x}(t) \quad (2)$$

where  $x(t)$  is the time signal itself,  $j$  the imaginary unit and  $\tilde{x}(t)$  is the Hilbert transform of the time signal  $x(t)$ . Equation (2) evaluated on a filtered signal around a meshing frequency  $f_m$  becomes:

$$x_a(t) = X_n(t)e^{j(2\pi f_m t + \phi_n(t))} \quad (3)$$



**Figure 6.** (a) Spectra of TS 5, 6 and 8, (b) zoom around the planetary meshing frequency.

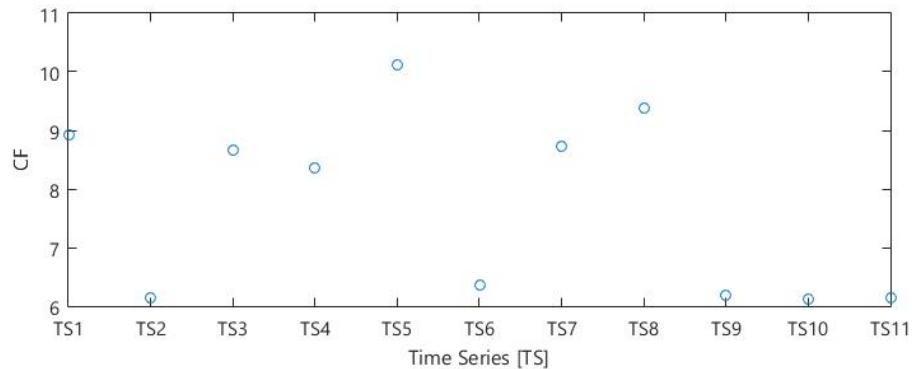
where  $X_n(t)$  accounts for the amplitude of the meshing components and possible modulation, and  $\phi_n(t)$  is the phase angle. Therefore, from the phase of the analytic signal filtered around a meshing component, it is possible to reconstruct the gear phase. In this work, in order to take into account the phase variation induced by the turbulent flow, the Crest Factor (CF) is evaluated on the detrended phase extracted from the planetary meshing frequency and its two harmonics. The Crest Factor (CF) is defined as the peak amplitude of the acceleration waveform divided by the RMS value:

$$CF = \frac{|a|_{peak}}{RMS} \quad (4)$$

where  $a$  is the acceleration measured by the main bearing accelerometer. As expressed by equation 4, the Crest Factor is a relative measure of the spikiness of a waveform: therefore the CF is sensitive to strong amplitude changes (with small energy) inside the waveform. The results of this process are shown in Figure 7.

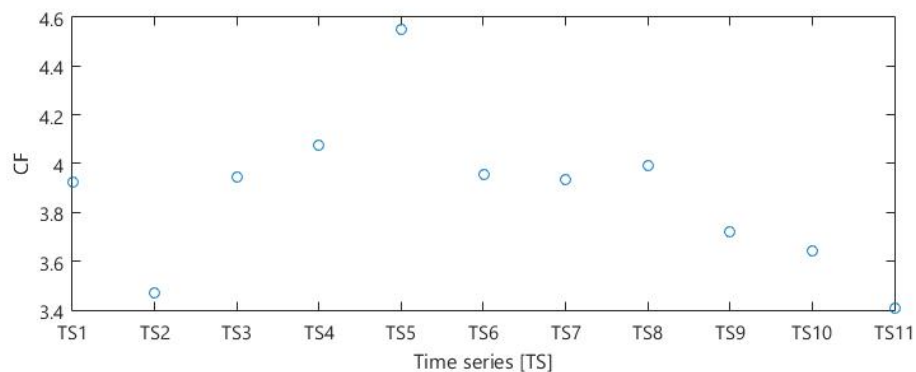
It is possible to see from Figure 7 that the TS5 shows the highest CF among all the TSs considered. Basically, the CF indicates how extreme the peaks are in a waveform, and so it is a measure of the phase variation of the planet carrier. These results highlight a strong variation of the rotational regime due to the turbulent flow induced by the wake effect.

De facto, phase shaft variations are related to modulations. In particular, sidebands around the meshing frequency and its harmonics arise in the spectrum of the time synchronously averaged signal. Therefore, in order to better highlight this phenomenon, the time synchronous average (TSA) [23] of the planetary annulus gear is extracted from the main vibration signal and its residual signal is taken into account. The residual signal is obtained by removing from the TSA the meshing components and its harmonics: therefore the residual signal carries the information related to the modulation effects. As done beforehand, the CF of the residual signal



**Figure 7.** Sum of the Crest Factor of the phases extracted from the planetary meshing frequency and its two main harmonics for each time-series.

is evaluated and the results of this operation are depicted in Figure 8.



**Figure 8.** Crest Factor of the annulus residual signals each time-series.

The CF of the residual signals, Figure 8, highlights the strong modulation phenomenon of the TS5 which could be related to the turbulent flow induced by the wake effect. Actually, the SGM11 yaw position recorded during the measurement of TS5 is typical of a wake configuration. This statement is supported by experimental data, exactly as for tower structural vibrations in Section 4.1. From two years of SCADA data, it arises data when SGM11 yaw position is averagely  $264.73^\circ \pm 1.4^\circ$ , SGM10 yaw position is averagely at  $273^\circ \pm 4^\circ$ . As a result, therefore, the turbulent flow associated to a wake configuration manifests also at the level of gearbox vibrations; however this procedure involves more challenging pre-treatment of the vibration signal itself with respect to the case of tower vibrations. Further, the proposed methods turned the structure of the data set (availability of raw time series only at rated power) from a limitation into a pro, because it has been possible to identify vibration effects of wake interactions when more intuitive symptoms are less evident, by zooming into the transmission of the slow rotation into fast.

## 5. Conclusions and further directions

In this work, the vibration effects of wind flow over complex terrain on large wind turbines are investigated. The work is inspired by a very challenging test case, sited in southern Italy, which has also been analyzed for the IEA-Task 31 Wakebench project [11, 12]. In [24, 13, 14, 15, 16],

this wind farm has been studied, on the grounds of the methods developed in [25, 26, 27]: in those works, the 10-minute based SCADA data sets are exploited as much as possible in order to extract knowledge about the wind field in this site and about the behavior of the turbines. In particular, it is observed that the performances of the turbines can be consistently interpreted only taking into account the considerable role of the terrain in distorting the wind flow. The subsequent step, in order to study the dynamics of the turbines, is employing data sets having very shorter time scale with respect to SCADA: for this reason, the vibration signals coming from the TCM control system have been analyzed in this work. Vibrations and SCADA measurements have been analyzed simultaneously and a step by step philosophy has been adopted. This is the core of a "wind to gear" approach: starting from the SCADA (describing the response to the flow from each turbine), then moving to the vibrations more directly related to the flow (tower structural), and finally arriving to the analysis of the drive-train. In particular, the interpretative capability of the approach is strengthened by the statistical analysis of the wind and of the collective response to it coming from the subcluster. This actually allows, for example, to have considerable arguments for interpreting SGM11 yaw position at around  $260^\circ$  (analyzed in Section 4) as a response to the wake of SGM10 when free wind blows from West. In general, therefore, the lesson from the analysis and from the results of Section 4 is that wakes manifest in observable effects at the level of vibration spectra. The power of the method further is in the fact that the drive-train acts a velocity multiplier and then its vibrations take trace of a phenomenon like wakes even in the regime (approaching rated power) where macroscopic symptoms (power collapse) fade away and structural response is less evident. A reverse approach ("gear to wind"), that is starting from vibrations and moving towards the interpretation of the flow phenomenon, would be much more challenging. It would probably need, as input for interpreting what's going on, a careful modeling of rotor, drive-train and wind field for wake and non-waked operation. This therefore supports the philosophy of the present work: conjugating different scales of information (SCADA and vibrations), in order to connect the macroscopic response to a flow phenomenon from the turbines (yaw positions) to vibrations (at the level of tower structural and at the drive-train level). Several are the further directions of this work, from the particular to the general. The first upgrade is shifting attention to regimes where the terrain-driven flow acceleration is more relevant: this is the case, for example, of turbine SGM13 (as discussed in Section 1). This subsequent achievement, as well as the results of this study, would constitute a building block of a more general picture about the exploitation of vibration analysis for performance assessment, rather than strict fault prevention. Information about loads, stresses, possible long term degradation of drive-train components under peculiar regimes could be used for wind farm optimization, for individuating advantageous sector management at the aim of wake mitigation, and so on.

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