Wake losses from averaged and time-resolved power measurements at full scale wind turbines

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Abstract. This work deals with the experimental analysis of wake losses fluctuations at full-scale wind turbines. The test case is a wind farm sited on a moderately complex terrain: 4 turbines are installed, having 2 MW of rated power each. The sources of information are the time-resolved data, as collected from the OPC server, and the 10-minutes averaged SCADA data. The objective is to compare the statistical distributions of wake losses for far and middle wakes, as can be observed through the “fast” lens of time-resolved data, for certain selected test-case time series, and through the “slow” lens of SCADA data, on a much longer time basis that allow to set the standards of the mean wake losses along the wind farm. Further, time-resolved data are used for an insight into the spectral properties of wake fluctuations, highlighting the role of the wind turbine as low-pass filter. Summarizing, the wind rose, the layout of the site and the structure of the data sets at disposal allow to study middle and far wake behavior, with a “slow” and “fast” perspective.

1. Introduction
The comprehension of the behavior of wind turbines under wakes is a stimulating subject [1, 2, 3, 4]. Studying wake fluctuations is also a matter of time scales, because it involves the control system and the wind-turbine ability in reacting to the variability of the wind, especially when wake-added turbulence and veering flow are relevant. For the sake of saving space and computational cost, the wind-energy industry commonly employs Supervisory Control And Data Acquisition (SCADA) data sets having 10 minutes of averaging time for performance assessment and condition monitoring. Actually, significant achievements in the comprehension of wakes have been reached by using numerical modeling and 10-minute based SCADA data [5, 6, 7, 8, 9]. On the other hand, some phenomena must still be described only partially due to a too coarse time resolution: for example, the alignment of wind turbines to the incoming wind [10, 11, 12, 13] and mechanical fatigue loads [14, 15, 16]. For this reason, the attention of the scientific community towards high-frequency wind turbine data has recently increased. In [17], for example, SCADA data having 1 minute time resolution are employed for validating LES simulations over the Lillgrund wind farm [18]. In [19], high-frequency time series measurements obtained with remote scanning systems are analyzed, with focus on the identification of wind-turbine wake properties in complex terrain. In [20], high-frequency data are studied and it is shown that the complex
structure of turbulence dominates the power output fluctuation for one single wind turbine as well as for an entire wind farm.

On these grounds, the present work aims at investigating the time-resolved wake dynamics on a wind farm sited in southern Italy over a moderately complex terrain. The test case is particularly valuable because the usual 10-minutes data and time-resolved data, as collected from the OPC (Object Linking and Embedding for Process Control) server, are available. This allows to exploit the large amount of time-wise information to get a statistical description of the wake behavior, with particular focus on the dynamics of the wind turbines. The layout of the test case is characterized by two characteristics inter-turbine distances: approximately 4 and 8 rotor diameters. Therefore, testing grounds are available for observing middle and far wake, with their associated “slow” and “fast” dynamics. The idea is therefore to compare the statistical distributions of wake losses for far and middle wakes, as can be observed through the “fast” lens of time-resolved data and through the “slow” lens of SCADA data. Subsequently, time-resolved data are used for an insight into the spectral properties of wake losses. The structure of the paper is as follows: in Section 2 the test-case wind farm is briefly described, while in Section 3 the data sets and the techniques are introduced. In Section 4 the results are collected, and finally in Section 5 some concluding remarks are proposed and further directions of the present work are discussed.

2. The Wind Farm
The wind farm, selected as test case for the present work, is sited in southern Italy and features 4 wind turbines having 2 MW of rated power each. The layout and the inter-turbine distances (in units of the rotor diameter $D$) are sketched in Figure 1.

![Figure 1. The layout of the test-case wind farm with turbines distance in rotor diameters (blue) and the relative waked direction of minimum distance (red).](image)

From Figure 1, it is highlighted that the subcluster T2-T3-T4 is an interesting test case for investigating the mid-wake regime when the wind blows from approximately $310^\circ$ and $130^\circ$. When the wind blows from approximately $40^\circ$ (respectively $220^\circ$), the far-wake effect of turbine T3 on T1 (respectively, T1 on T3) can be studied.

3. The method
The “slow” (10-minutes based SCADA data) and “fast” (time-resolved) data sets are analyzed in parallel, as follows: a vast data set of 10-minutes SCADA (57168 data, during which all the four
turbine have been all producing) and acquisitions of time-resolved data are filtered on similar wind conditions and the statistics are compared. The two sources are not synchronized: the reason for this is to show the time-resolved “fast” wake fluctuations during certain spot events and the average behavior over a catalog of similar situations (spanned on a much longer period in time), observed through the “slow” lens of SCADA data. This approach has pros and cons: the main pro is that one analyzes time-resolved data during consecutive events and therefore one can appreciate how the wind conditions and the response of the wind turbines evolve in time. The drawback is that one can’t control strictly the wake regime during the time-resolved events: due to the fluctuations, full wakes and partial wakes can occur during the same event. For this reason, peculiar attention has been devoted to understand the wind conditions, especially as regards directions, as shall be explained further on. The wind speed and direction intervals are selected based on the criteria of interest for investigating the near and far wakes. The time series are characterized by low-moderate wind speed, and therefore high thrust.

Couples of turbines are compared by analyzing mainly the statistical distribution of the power ratio between upstream and downstream turbine. The power ratios between upstream and downstream turbine are computed at the same time interval. This is obvious in the case of 10-minutes data, it is less obvious in the case of time-resolved data because at those sampling times (cited in Table 1), the delay between upstream and downstream is a visible phenomenon. The way one considers the transport of the wake from upstream to downstream inevitably includes a certain degree of arbitrariness if approached theoretically. If approached experimentally, a cross-correlation between signals upstream and downstream would in principle detect the delay. There are two reasons why this can’t be applicable in the selected case: the first reason is that the turbulence induced by the turbine upstream alters dramatically the signal downstream and the second reason is that the selected wake events are too short to circumvent the first reason through a large statistics. Therefore, in this work it has been decided to watch unambiguously the picture at the same time. In doing this, one is reassured by the fact that the selected time series all belong to a same “wake event”.

The time-resolved acquisitions, selected for the present work, are summarized in Table 1. The sampling frequency of the time-resolved series depends on buffering issues and must be reconstructed from the data themselves\(^1\). For this reason, in Table 1, for each time series, the sampling frequency is indicated.

| Series | Sampling frequency (Hz) | Wind Speed (m/s) | Wind Speed (m/s) | Wind Speed (m/s) | Wind Speed (m/s) |
|--------|------------------------|------------------|------------------|------------------|------------------|
| FW1    | 0.20                   | 4.7 ± 1.3        | 17.4 ± 20        |                  |                  |
| FW2    | 0.13                   | 5.4 ± 1.9        | 27.4 ± 30        |                  |                  |
| MW1    | 0.57                   | 5.1 ± 1.8        | 318.7 ± 24       |                  |                  |
| MW2    | 0.20                   | 3.8 ± 1.8        | 300.6 ± 48       |                  |                  |

Table 1. Wind conditions (with 2σ interval) at the upstream wind turbine, from the time-resolved data sets employed for the analysis.

A critical issue as regards the objective stated above is filtering the master SCADA data set on reasonably similar conditions with respect to the time series, despite it has different sampling

\(^1\) The “run total” is employed for reconstructing the sampling frequency: it stores the elapsed time, with respect to a reference, according to discrete jumps of 600 seconds (i.e. the averaging time of the SCADA data). Identifying the number of time-resolved measurements inside each block of data, displaying the same “run total” value, allows to compute the actual acquisition rate.
time with respect to the time-resolved series. As regards wind intensity, the procedure is as follows: the standard deviation of each time-resolved wind-intensity series has been computed and the SCADA data are filtered around the average values of Table 1, on an interval having two standard deviations as total amplitude. As regards wind directions, the procedure is as follows: it is based on the standards from the International Electrotechnical Commission [21] defining the amplitude of the wake sector of a wind turbine on a neighboring one, on the basis of their relative distance \( L \) in units of rotor diameter \( D \). The formula is given in Equation 1.

\[
\alpha = 1.3 \frac{180 \arctan \left( 2.5 \frac{D}{L} + 0.15 \right)}{\pi} + 10. \tag{1}
\]

In the case of FW1 and FW2 time series, the focus is on the wake of turbine T3 on turbine T1. By applying Equation 1 between turbines T3 and T1, the amplitude of the waked sector is 48.13°. Therefore, the average wind direction values of the time series FW1 and FW2, as reported in Table 1, are well inside the waked sector. Similarly, as regards the wake between turbines T3 and T4, the amplitude of the waked sector is 64.52° and the average wind direction values for time series MW1 and MW2 are well inside the waked sector too. Basing on this criterion, the 10-minutes SCADA data sets are filtered on wind directions corresponding to the waked sector. The time-resolved fluctuations of wind direction during the four time series of Table 1 are analyzed too: the occurrence outside the waked sector is quantified. On these grounds, despite the different nature of the data sets, it is reasonable to juxtapose the “slow” and “fast” fluctuations and statistics because the regimes are fairly corresponding. In the following Section 4, it is shown that this is indeed the case.

Further interesting information about wakes dynamics can be discovered through the analysis in the frequency domain. The OPC server can give real-time measurement with a good resolution in time. Unfortunately, technical problems regarding the buffering and the transfer rate did not allow a robust and reliable frequency when asking to the system very fast acquisition (up to 2 Hz) for the whole wind farm. The use of “run hour” counter, as explained above, allows anyway to reconstruct the acquisition frequency and this allows to set the scale for frequency-domain analysis. Therefore, the spectral density of wind speed and power production of some sample time series are shown and discussed in Section 4.

4. Results
From the histograms in Figures 2, 4, 6 and 8, it arises that the very vast majority of data from the time-resolved series belongs to the waked sector of, respectively, the T01-T03 and T03-T04 couple of wind turbines. Therefore, the procedure for filtering the 10-minutes SCADA data set (described in Section 3) is ex post supported.

Comparing Figures 3 and 5 to Figures 7 and 9, it arises that the distribution of power ratios of the SCADA data differs more from the one of the time-resolved series in the cases of mid wake. In particular, in the mid-wake cases, for the time resolved data sets, a considerable population at the lower and higher tails of the distribution is evident. In order to have an insight into this phenomenon, for each time series, data have been grouped in tertiles with respect to the downstream - upstream power ratio. For each subset, the distribution of wind directions (relative to the center of the wake) is analyzed. They are shown in Figures 10 and 11 for the FW2 and MW2 time series, respectively. From these Figures, a clear dependency of the power ratio on the wake condition (full or partial) doesn’t arise (except some expected peak of low power ratios around 0°).

In Table 2, the average power ratios between upstream and downstream turbine are shown for the time-resolved series of Table 1 and for each corresponding SCADA milestone: considerable deviations occur in the mid-wake case.
Table 2 suggests that in the far-wake region the results from steady numerical simulation, as RANS (Reynold Averaged Navier Stokes) or linearized models, have more chances of reproducing with a good approximation the wake fluctuations. Actually, the far-wake behavior is less turbulent and more steady and this supports the fact that the distributions of Figures 3 and 5 show a good agreement between “slow” and “fast” data. In any case, the fluctuations observed in Figures 10 and 11 invoke a deeper comprehension on the dynamics of the wake fluctuations and this is why a spectral analysis should be carried on.

Figures 12 and 13 show the spectral density of power production and wind speed for the
upstream T4 and the downstream T3 wind turbines, during the MW1 acquisition time series. The MW1 wake event was chosen for this analysis as it is characterized by the highest sampling rate. It arises that the downstream turbine T3 shows higher oscillation amplitudes and is more noisy in the high-frequency domain, as regards wind speed (Figure 13). This is due to the additional turbulent effects induced by the wake. Comparing Figure 12 to 13, the role of the wind turbine as low-pass filter arises: the turbine cuts out frequencies and absorbs unsteady mechanical loads. Up to the highest frequencies at disposal, the PSD of the wind speed fairly agrees with the $-\frac{5}{3}$ law of turbulence from Kolmogorov [22]. The presence of the wind turbine cuts this behavior and acts as low-pass filter, as the difference between Figures 12 and 13 shows.

Figure 6. Distribution of wind direction: time-resolved data, MW1 time series. Data inside the waked sector between T03 and T04 in gray, in red the data outside the waked sector.

Figure 7. Distribution of power ratios ($P_{T03}/P_{T04}$): time-resolved vs. SCADA, MW1 time series.

Figure 8. Distribution of wind direction: time-resolved data, MW2 time series. Data inside the waked sector between T03 and T04 in gray, in red the data outside the waked sector.

Figure 9. Distribution of power ratios ($P_{T03}/P_{T04}$): time-resolved vs. SCADA, MW2 time series.
Figure 10. Distribution of wind directions of turbine T03, FW2 time series. Data are grouped in tertiles with respect to the $P_{T01}/P_{T03}$ ratio.

Figure 11. Distribution of wind directions of turbine T04, MW2 time series. Data are grouped in tertiles with respect to the $P_{T03}/P_{T04}$ ratio.

| Series | Time-resolved power ratio | SCADA power ratio |
|--------|--------------------------|------------------|
| FW1    | 0.98                     | 0.80             |
| FW2    | 0.95                     | 0.81             |
| MW1    | 0.68                     | 0.75             |
| MW2    | 0.42                     | 0.74             |

Table 2. Average power ratios for the high-frequency time series of Table 1 and their corresponding SCADA milestones.

Figure 12. PSD of power production: upstream T4 and downstream T3 wind turbines, MW1 time series.

Figure 13. PSD of wind speed: upstream T4 and downstream T3 wind turbines, MW1 time series.
5. Discussion and Further Directions

In this work, wake fluctuations have been analyzed through the experimental data of a test wind farm sited in Italy in a moderately complex terrain. The key point of the work is that the analysis has been based on SCADA data, with their usual 10-minute sampling time, and high-frequency time resolved data as well. Thus it has been possible to observe wakes using two lenses: a “slow” one (SCADA) on a catalog of wake events spanned over a long period, and a “fast” one on some spot time series of wake events. Upon filtering the SCADA data in order to resemble reasonably the wind conditions of each spot wake event, the “slow” and “fast” fluctuations have been juxtaposed and analyzed, in order to appreciate their different features. Further, the layout of the wind farm (Figure 1) makes it possible to observe two wake regimes: mid-wake (approximately 4 rotor diameters) and far-wake (approximately 8 rotor diameters). This allowed to observe, for example, the characteristics of power-ratios fluctuation in the mid- and far-wake region. The results of this work are promising about the possibility of employing high-frequency data of wind turbines for validating LES frameworks, that are currently at their early stages especially in complex terrain [23], and for cross-validation against independent averaged informations from the turbines. Figures 12 and 13 suggest another direction of this work, because they highlight the role of the wind turbine in smoothing the high-frequency oscillations coming from the wind: it would be interesting to analyze how the wind turbine, acting de-facto as a low-pass filter, is affected by the unsteady mechanical loads [24].

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References

[1] Matthew J Churchfield, Sang Lee, John Michalakes, and Patrick J Moriarty. A numerical study of the effects of atmospheric and wake turbulence on wind turbine dynamics. *Journal of turbulence*, (13):N14, 2012.
[2] B Subramanian, N Chokani, and RS Abhari. Aerodynamics of wind turbine wakes in flat and complex terrains. *Renewable Energy*, 85:454–463, 2016.
[3] Ann Hyvärinen and Antonio Segalini. Effects from complex terrain on wind-turbine performance. *Journal of Energy Resources Technology*, 2017.
[4] Fredrik Seim, Arne R Gravdal, and Muyiwa S Adaramola. Validation of kinematic wind turbine wake models in complex terrain using actual windfarm production data. *Energy*, 123:742–753, 2017.
[5] Niels Otto Jensen. A note on wind generator interaction. Technical Report Ris-M-2411, Ris National Laboratory, 1983.
[6] Sten T Frandsen, Hans E Jørgensen, Rebecca Barthelmie, Ole Rathmann, Jake Badger, Kurt Hansen, Søren Ott, Pierre-Eloouan Rethore, Søren E Larsen, and Leo E Jensen. The making of a second-generation wind farm efficiency model complex. *Wind Energy*, 12(5):445–458, 2009.
[7] Rebecca Jane Barthelmie, K Hansen, Sten Tronæs Frandsen, Ole Rathmann, JG Schepers, W Schlez, J Phillips, K Rados, A Zervos, ES Politis, et al. Modelling and measuring flow and wind turbine wakes in large wind farms offshore. *Wind Energy*, 12(5):431–444, 2009.
[8] Rebecca Jane Barthelmie and LE Jensen. Evaluation of wind farm efficiency and wind turbine wakes at the nysted offshore wind farm. *Wind Energy*, 13(6):573–586, 2010.
[9] Kurt S Hansen, Rebecca J Barthelmie, Leo E Jensen, and Anders Sommer. The impact of turbulence intensity and atmospheric stability on power deficits due to wind turbine wakes at horns rev wind farm. *Wind Energy*, 15(1):183–196, 2012.
[10] Francesco Castellani, Davide Astolfi, Alberto Garinei, Stefania Proietti, Paolo Sdringola, Ludovico Terzi, and Umberto Desideri. How wind turbines alignment to wind direction affects efficiency? a case study through scada data mining. *Energy Procedia*, 75:697–703, 2015.
[11] Francesco Castellani, Davide Astolfi, Emanuele Piccioni, and Ludovico Terzi. Numerical and experimental methods for wake flow analysis in complex terrain. In *Journal of Physics: Conference Series*, volume 625, page 012042. IOP Publishing, 2015.
[12] Francesco Castellani, Davide Astolfi, Paolo Sdringola, Stefania Proietti, and Ludovico Terzi. Analyzing wind
turbine directional behavior: Scada data mining techniques for efficiency and power assessment. *Applied Energy*, 185:1076–1086, 2017.

[13] Francesco Castellani, Davide Astolfi, Matteo Mana, Emanuele Piccioni, Matteo Becchetti, and Ludovico Terzi. Investigation of terrain and wake effects on the performance of wind farms in complex terrain using numerical and experimental data. *Wind Energy*, 2017.

[14] Torben J Larsen, Helge Aa Madsen, Gunner C Larsen, and Kurt S Hansen. Validation of the dynamic wake meander model for loads and power production in the egmond aan zee wind farm. *Wind Energy*, 16(4):605–624, 2013.

[15] Soo-Hyun Kim, Hyung-Ki Shin, Young-Chul Joo, and Keon-Hoon Kim. A study of the wake effects on the wind characteristics and fatigue loads for the turbines in a wind farm. *Renewable Energy*, 74:536–543, 2015.

[16] Luis Vera-Tudela and Martin Kühn. Analysing wind turbine fatigue load prediction: The impact of wind farm flow conditions. *Renewable Energy*, 107:352–360, 2017.

[17] Wolf-Gerrit Früh, Angus CW Creech, and A Eoghan Maguire. Turbulence characteristics in offshore wind farms from les simulations of lilgrund wind farm. *Energy Procedia*, 59:182–189, 2014.

[18] Jan-Ake Dahlberg. Assessment of the lilgrund wind farm: power performance wake effects. *Vattenfall Vindkraft AB*, 6LG Pilot Report, http://www.vattenfall.se/sw/file/15_Assessment_of_the_Lilgrund_W.pdf, 2009.

[19] Kurt Schaldemose Hansen, Gunner Chr Larsen, Robert Menke, Nikola Vasiljevic, Nikolas Angelou, Ju Feng, Wei Jun Zhu, Andrea Vignaroli, C Xu, Wen Zhong Shen, et al. Wind turbine wake measurement in complex terrain. In *Journal of Physics: Conference Series*, volume 753, page 032013. IOP Publishing, 2016.

[20] Patrick Milan, Matthias Wächter, and Joachim Peinke. Turbulent character of wind energy. *Physical review letters*, 110(13):138701, 2013.

[21] Robert Gasch and Jochen Twele. *Wind power plants: fundamentals, design, construction and operation*. Springer Science & Business Media, 2011.

[22] H Eugene Stanley. Turbulence: The legacy of an kolmogorov. *Journal of Statistical Physics*, 88(1):521–523, 1997.

[23] Nina Zhou, Jun Chen, Douglas E Adams, and Sanford Fleeter. Influence of inflow conditions on turbine loading and wake structures predicted by large eddy simulations using exact geometry. *Wind Energy*, 2015.

[24] C Braccesi, F Cianetti, and L Tomassini. Random fatigue. a new frequency domain criterion for the damage evaluation of mechanical components. *International Journal of Fatigue*, 70:417–427, 2015.