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How wind turbines alignment to wind direction affects efficiency? A case study through SCADA data mining.

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Abstract

SCADA control systems are the keystone for reliable performance optimization of wind farms. Processing into knowledge the amount of information they spread is a challenging task, involving engineering, physics, statistics and computer science skills. The present work deals with the effects on the efficiency of turbine inability of optimal aligning to the wind direction, due to meandering wind caused by wakes. The approach is tested on a judiciously chosen cluster of turbines of a wind farm sited in southern Italy. By a post-processing method based on discretization of nacelle position measurements, a set of dominant patterns of the cluster is identified. The patterns associated to best performances are individuated and it is shown that they correspond to non-trivial alignment to wind direction.

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1. Introduction

The attention on performance optimization of operating wind farms has recently increased, due to the financial crisis discouraging new investments and lowering energy consumption, and due to the increase of the percentage of energy harvested from stochastic renewable sources. Actually, in order to build “smart” grids, judicious balance of electricity coming from renewable and not renewable sources should be estimated: accurate power forecast and performance assessment are therefore precious. Modern wind turbines are therefore equipped with sophisticated SCADA control systems, spreading on 10 minute time

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basis a vast amount of information: details on the wind flow and meteorological conditions, on turbine alignment to the wind, on the conversion of wind kinetic energy into active power, on the vibrational and mechanical status of the machine, on thermal conditions at relevant parts of the turbines, and so on. The scientific and technological challenge is therefore tackling the complexity of SCADA data stream, processing it into novel knowledge and possibly integrating it in the control system itself. Due to the non-trivial physical properties of the source, to the complexity of the machines and of the data flow, the subject lies at the crossroad of engineering, physics, statistics and computer science. Sophisticated techniques have therefore been developed and, for example, ANN's are widely employed for their capability of codifying non-linearity.

The present work deals with a very relevant subject in the literature about SCADA techniques for wind energy: wake interactions and their effects on the quality of turbine power output. Wakes have been investigated mainly for offshore wind farms, since they are the most relevant and intelligible driver of power losses and farm efficiency. In [1] SCADA post processing is used for quantifying power and speed losses due to wakes, and peculiar analysis is devoted to misalignment and yawing under downstream wake angles. In [2] the test cases of offshore wind farms of Horns Rev and Nysted in Denmark are systematically addressed. In [3], [4] and [5] numerical models for simulating dynamics of wake effects are addressed. A related and challenging task is highlighting the agents on which farm efficiency, as a function of the wind direction, depends: in [6], on the test case of Horns Rev wind farm, power deficits are studied as a function of wind rose, wind speed, turbulence intensity and stability of the atmosphere. In [6] a focus on the effects of atmospheric stability on wind profile, and therefore on power output quality, is performed through numerical models.

Previous work of the authors [8] deals with the issue of identifying the drivers of farm efficiency for onshore wind farms: this task is far more challenging with respect to the offshore case, because the layout, and consequently wake effects, non trivially interplay with the complexity of the terrain, causing local wind flow acceleration. Actually, in [8] it is shown that, even for wind farms sited on gentle terrains, the definition of polar efficiency, which is commonly employed for the onshore case, would lead to not consistent results. For this reason a novel and consistent definition of polar efficiency is proposed and test cases, sited on terrains with very different features, are analyzed: the effects of terrain complexity are disentangled and quantified, and a slight dependence of efficiency on atmospheric stability is also highlighted.

The present work focuses on the effects of wakes on farm efficiency. The presence of the rotors alters the wind flow and causes meandering wind: therefore, if machines are sited close one to the other, when a turbine is downstream, it usually suffers of inability of optimally aligning to the rapidly changing wind direction. Misalignment to wind direction is therefore a sharp symptom of wake effects, resulting in decreased performances. For this reason, the present work focuses on the analysis of nacelle positions under meteorological regimes giving rise to significant wakes on a test case wind farm, sited in Italy on a very gentle terrain. Nacelle positions are recorded by the SCADA control system as averages, on 10 minute time basis, of a series of frequent samplings: they represent a time discretization, but the range of values they might assume is a continuous set. Our philosophy is discretizing such continuous measurements with a judicious grain: albeit some information is lost in the discretization process, one ends up with a simplified data set, yet very powerful. As shall be shown later on, the power of the procedure reveals in the fact that the discretization highlights clustering effects: the stronger the presence of wakes is, the sharper is the behavior of the turbines as a whole, rather than as a collection of individualities. Discretizing nacelle positions, further, one obtains a finite subset of typical configurations of the turbines: it becomes possible to investigate if the dominant ones are indeed the most favorable by the point of view of efficiency, or not. The structure of the Paper is as follows: in Section 2 the wind farm

under investigation is briefly described, in Section 3 the details of the method and the results are discussed, in Section 4 some concluding remarks and further directions are briefly sketched.

Nomenclature

SCADA Supervisory Control And Data Acquisition

ANN Artificial Neural Networks

CFD Computational Fluid Dynamics

2. The wind farm

The analysis is performed on the test case of a wind farm sited in southern Italy. It has been chosen because the inter turbine distance is such as resulting in considerable wake interactions when wind, having moderate intensity, blows from West. The wind rose reveals that this is indeed very frequently, and this allows to have at hand a vast data sets for the analysis of the present work. Further, the farm lies on a very gentle terrain and it therefore is a hyphen between the features of offshore wind farms and onshore wind farms, where commonly the effects of orography are not negligible and difficult to disentangle from those of wakes.

The layout of the wind farm is sketched in the following Figure 1, where the elementary grain is 50 meters. The machines have 2 MW of rated power, 82 meters of rotor diameter and 80 meters of hub height.

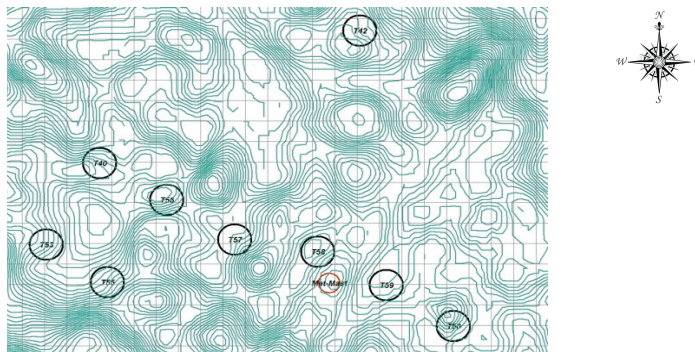


Fig. 1. Wind farm layout.

3. The approach and the results

A data set, built of meteorological conditions (wind direction and intensity at met-mast), turbine power output and nacelle positions from January 2013 to September 2014 has been collected. Data have subsequently been synchronized and filtered on the requirement of simultaneous power output production from turbine T57 to T60. This subcluster of turbines has been chosen for the analysis because they lie symmetrically with respect to the met-mast, and close to it. This makes the met-mast a reliable landmark for wind direction and intensity measurements. Further, inter turbine distance of the T57-T60 subcluster is such as resulting in considerable wake interactions from the West and East sectors. Data have been

filtered according to meteorological conditions: wind speed less than 10 m/s, in order to highlight the effect of wakes, which would be suppressed at high wind intensity both because of the wind profile and of the fact that machines would work at rated power. Further, data have been filtered according to met-mast wind direction, around 270°. Let us briefly recall that our final goal is evaluating the goodness of the orientation of the clusters of turbines T57-T60: therefore the filtering procedure should as much as possible end up with a data set describing the same “external event”, to which we want to evaluate how turbines respond.

For this reason, after having filtered data on wind intensity, the efficiency, as defined in [8], has been considered: it is defined as the ratio between the mean of the 10-minute average powers of the farm and the 10-minute average power of the best performing turbine of the farm. Specified to the subcluster of interest, built up of four turbines, the efficiency reads as in Equation 1, where the subscript runs from 1 to 4.

$$\varepsilon = \sum P_i / (4P_{\max}) \quad (1)$$

The efficiency of the cluster, computed for each 10-minute time step according to Equation 1, has subsequently been averaged on intervals of wind direction having 0.25° of amplitude. A numerical derivative, with respect to the wind direction, of such discrete averaged efficiency measurements has been computed as Newton’s quotient and it has been seen that the interval of maximum stability is centered on 272°, with a 3° total amplitude range. This filtering is particularly valuable because it exactly captures the window expected to result in the maximum effect of wakes and the wind rose is populated as to result in a considerable size of the data set, despite the severe filtering. Therefore, the data set is particularly fit to analyze the effects caused by wakes. Further outliers, due to manifestly incorrect nacelle alignment, have been excluded: if any of the nacelle positions is outside a 60° degree range centered on 270°, the measure is rejected.

This last filtering has been adopted for making more consistent the following analysis, based on the information contained in the nacelle positions, which is exploited for evaluating the optimal configurations. As introduced in Section 1, the philosophy is discretizing the continuous measurements with a fine grain: a bit to each elementary interval of wind direction amplitude is associated, turning from 0 to 1 if the nacelle position measurement falls inside it. The results shown in this Section are obtained with a 3° binning amplitude, but different discretization grains have been tested. This amplitude has been chosen as the finer grain which guarantees that an adequate number of records, providing statistical significance, is associated to at least the most frequent patterns. As discussed later, the results are consistent and do not sensibly depend on the grain. This enforces the reliability of the method and confirms the inspiring idea: turbine alignment of a cluster affected by wakes follows peculiar paths.

Every time step and every efficiency measurement can be associated to a string, describing the orientation of the cluster of turbines. One can subsequently classify the configurations according to the frequency of their occurrence and identify the dominant patterns of the cluster. To every pattern, the corresponding efficiency measurements can be associated and one can thus build N subsets from the native set of measurements, where N is the number of the patterns. The final goal is quantify if the dominant patterns of the subcluster are indeed favorable or not. This sheds light on the quality of turbine alignment to wind direction and might give interesting indications to the perspective of jaw active control systems. The procedure is as follows: all the efficiency measurements passing the filters have been averaged, and the average efficiency has been computed also separately for each subset corresponding to a cluster configuration. These quantities are summarized in Table 1, where the percentage of occurrence is defined as the ratio of the size of the subset for a given configuration to the size of the whole data set. The deviation of each subset average from the global average has been computed. This quantity is

representative of the weight of each configuration on the global average, but a deeper insight on how the population distributes for each configuration would be useful. For this reason, for every subset, also the percentage of records above the global average has been computed. These two quantities therefore provide a two-dimensional plot, allowing not ambiguous evaluation of goodness of a pattern configuration. In Figure 2, the eight most populated configurations are displayed. It has been chosen to analyse and discriminate between a little amount of configurations, in order to ensure each of them having a considerable population, and therefore a statistical relevance.

Table 1. Results for the eight most frequent cluster configurations.

Configuration ranking	Mean Efficiency	Percentage of occurrence (%)
1°	0.58	3.9
2°	0.62	2.21
3°	0.61	1.72
4°	0.63	1.60
5°	0.67	1.47
6°	0.60	1.47
7°	0.57	1.35
8°	0.61	1.10

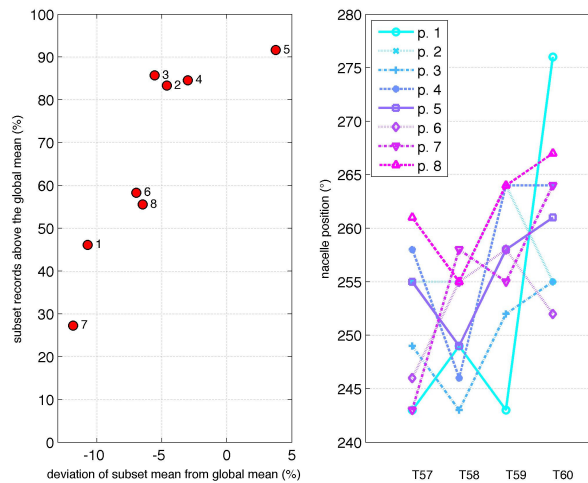


Fig. 2. Pattern Evaluation: 3° binning.

The most populated pattern of Figure 2 lies at the lower-left corner, while the best configuration (the one on the upper-right corner) is the fifth more frequent, occurring 2.5 times less than the dominant one. Further, it arises that the dominant configurations show not negligible performance deviations among them. This strongly justifies the motivations of the present work and the impact that such analysis of turbine alignment to wind direction might have. It is valuable to notice that the best performing

configuration is characterized by a turbine orientation, which is far from trivial if one recalls that the filtering procedure resulted in a data set characterized by anemometer wind direction very focused on 270° . The best orientation vector is the following: $(255^\circ, 249^\circ, 258^\circ, 261^\circ)$, where the first component represents turbine T57, and so on. It is also interesting to notice that the outliers in the lower-left corner of Figure 2 are characterized by an increasing nacelle inclination moving from T57 to T58, while the group of configurations with better performances (from 2° to 5°) is associated to the opposite tendency. Increasing the grain of the discretization, the results do not sensibly vary: if one considers a coarser grain, the best configuration is a deterioration of the one above. Further, if one varies the binning grain, the frequency ratio between the best configuration and the most populated one remains of the same order of magnitude.

4. Conclusion and further directions

In the present work, the effects on power output quality of wind turbine alignment to wind direction have been analyzed through post-processing methods on the SCADA data of a test case wind farm sited in southern Italy on a gentle terrain. A cluster of turbines, lying close one to the other and to the met-mast, has been considered, and the 270° sector has been chosen because very populated and resulting in multiple wake effects on the cluster of interest. By discretizing nacelle position measurements with a fine grain, prevailing pattern configurations are individuated, and it is shown that they are characterized by not negligible average efficiency deviations the one with respect to the other. The most advantageous pattern is individuated and it is shown that it corresponds to a not trivial orientation. Further, it is shown that the most frequent pattern is not one of the most advantageous and the results do not depend on the grain of nacelle position discretization. This strongly supports that perspective of yaw active control for wind turbines, when meteorological conditions and farm layout conspire giving rise to wakes. Further directions of the present work include extending to test cases on complex terrains and possibly parallel include the analysis of turbine wind vane patterns, in order to compare against nacelle position behavior. It would also be valuable to simulate orientation patterns through CFD techniques and compare predicted performances against operational data.

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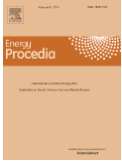
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Biography



Francesco Castellani is an Associate Professor in Machine Engineering at the University of Perugia (ITALY). He is involved in research activities dealing with:

- modelling and control of mechanical systems
- numerical and experimental wind turbines studies;
- numerical simulation of wind flow and wakes on complex terrain sites.;
- condition monitoring.