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Data mining techniques for performance analysis of onshore wind farms

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HIGHLIGHTS

- Indicators are formulated for monitoring quality of wind turbines performances.
- State dynamics is processed for formulation of two Malfunctioning Indexes.
- Power curve analysis is revisited.
- A novel definition of polar efficiency is formulated and its consistency is checked.
- Mechanical effects of wakes are analyzed as nacelle stationarity and misalignment.

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ABSTRACT

Wind turbines are an energy conversion system having a low density on the territory, and therefore needing accurate condition monitoring in the operative phase. Supervisory Control And Data Acquisition (SCADA) control systems have become ubiquitous in wind energy technology and they pose the challenge of extracting from them simple and explanatory information on goodness of operation and performance. In the present work, post processing methods are applied on the SCADA measurements of two onshore wind farms sited in southern Italy. Innovative and meaningful indicators of goodness of performance are formulated. The philosophy is a climax in the granularity of the analysis: first, Malfunctioning Indexes are proposed, which quantify goodness of merely operational behavior of the machine, irrespective of the quality of output. Subsequently the focus is shifted to the analysis of the farms in the productive phase: dependency of farm efficiency on wind direction is investigated through the polar plot, which is revisited in a novel way in order to make it consistent for onshore wind farms. Finally, the inability of the nacelle to optimally follow meandering wind due to wakes is analysed through a Stationarity Index and a Misalignment Index, which are shown to capture the relation between mechanical behavior of the turbine and degradation of the power output.

1. Introduction and motivation

Wind energy conversion into dispatchable energy is on the long term driven by the distribution of the source and on the short term by its variability, predictable only within a certain extent.

Wind turbines are therefore a energy conversion system having a low density on the territory, needing a careful assessment before installation as well as accurate condition monitoring in the operative phase, in order to plan convenient maintenance programs, to optimize performances, to prevent faults and machine deterioration.

For the above reasons and for the complexity of the machines, in the latest years, Supervisory Control And Data Acquisition (SCADA) control systems have become ubiquitous in wind turbine technology and have provided more and more insight on why actual productivity is lower than theoretical.

SCADA control systems spread on ten minute time basis a vast amount of measurement about the wind flow, its conversion into power output, the mechanical, thermal and vibrational behavior of the machine. Information on the status of the machine is also provided, in the form of time counter on the same time basis as SCADA measurements, or in digital form (incoming and phasing out of states at certain time stamps).

Extracting simple and explanatory answers from such huge amount of information is a far from trivial task, requiring sophisticated methods: SCADA analysis and techniques have therefore

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become a rapidly growing and fertile subject in the scientific literature.

The dynamics of machine states encodes sudden operational phase shifts: it is an abrupt evolution, which gives the basic information (what or why) on the turbine but tells nothing, or almost nothing, about the slow evolution which leads to a certain behavior. The history of the system in its details is encoded in the SCADA measurements: they evolve smoothly, they are more complex and they therefore "encrypt" the information. Yet, complexity of SCADA measurements can be turned from a limitation into a power: at the cost of employing sophisticated methods on a vast amount of data [1], decrypting the information contained in the SCADA is the keystone for a granular knowledge of each machine and of the farm. Therefore, an efficient performance optimization [2] cannot disregard SCADA data analysis.

Due to their intrisically different time scale, machine state dynamics and SCADA analysis are usually treated separately and with different techniques. For an exhaustive survey on the state of art on condition monitoring, fault detection and forecast techniques, we refer to [3]. In this review, a bird's eye view on the state of the art about prediction, operation and condition monitoring in wind energy is provided, with a discussion of pro's and con's of each approach. Concerning forecast, statistical methods, physics methods based on Numerical Weather Prediction techniques [4], data mining models (such as tree based regression algorithms, k nearest neighbor, support vector machine reggression) with their capability in codifying both linearity and non-linearity, hybrid methods, Montecarlo methods [5] are reviewed. Condition monitoring and fault detection has been addressed by several point of views, which are summarized: vibration analysis, lubrication analysis, analysis of aerodynamic asymmetry and yaw misalignment, bispectrum techniques for condition monitoring of blades. A further survey of performance monitoring, as an alternative to condition monitoring, is proposed: peculiar interest is deserved to temperature measurements monitoring. In [6] a survey of modern large wind turbines technology and suppliers is provided and, most of all, the most common condition monitoring techniques are listed, moving from their motivations: in particular, gearbox failures have a high cost and long downtime, and for this reason the most widespread condition monitoring technique is vibrational analysis for gearbox fault prevention. In [6] a comprehensive list is provided of condition monitoring techniques (thermocouple, oil particle counter, ultrasonic testing, vibro-acoustic measurement, torsional vibration, thermography, and so on), their cost, their possible capability of early fault diagnosis, the components which are overseen by each of them. For a review of commercially available condition monitoring systems, see [7]. Further, in [6], SCADA condition monitoring techniques are also addressed, and it is highlighted that they are becoming widely diffuse for their low cost, but they cannot replace a professional purpose-designed wind turbine condition monitoring system: the reasons are mainly lack of information, the 10-min sampling basis, which cannot meet the wide bandwidth needs of condition monitoring, the fact that an abnormal SCADA data change is considered a late-stage indication of a fault. Nevertheless, sophisticated data-mining techniques come at hand for SCADA-based condition monitoring: in [8,9] an Adaptive Neuro-Fuzzy Interference Systems (ANFIS) is proposed for monitoring wind turbine SCADA signals, in [10] SCADA data are pre-processed and then interpreted through statistical estimators to detect wind turbine anomalous behavior. In [11] it is instead shown that rather straightforward temperature measurements monitoring is indeed capable of fault detection at a sufficiently early stage in order to prevent severe faults. In [12] SCADA data are analyzed to quantify energy losses associated with loss in availability of turbines and it discussed if availability should be computed according to the criterion of productive time, or instead basing on the amount of produced energy on the total producible amount.

Previous works of the authors [13–15] provided some supporting arguments on the fact that SCADA data mining can be fruitfully used to investigate the real performances of a wind farm and to understand the behavior of each wind turbine.

Peculiar attention has been devoted to the analysis of wake interactions, in order to quantify power losses, through SCADA data analysis, and to simulate them through numerical models: in [16] power losses due to wakes have been investigated for offshore Horns Rev and Nysted wind farms in Denmark. In [17] SCADA data mining techniques are used for quantifying power and speed losses due to wakes: appreciable analysis is also devoted to misalignment and yawing under downstream wake angles. In [18] the test case of Horns Rev is studied and a systematic analysis is carried in order to highlight dependency of power deficit on wind rose, wind speed, turbulence intensity and stability of the atmosphere.

Numerical models for simulating wake power losses are investigated in [19,20] and are employed in [21,22] to investigate how orography and atmospheric stability affect wind profile, especially for non-neutral atmospheric regimes. Wake assessment is so crucial that an online open access resource, named Virtual Wake Laboratory [23], provides meteorological and wind farm data for use in wake characterization and wake model evaluation exercises. Recently [24] mean annual energy production of wind farms, including losses due to wakes, has been estimated through Geographic Information System (GIS) on the test case of four wind farms in Kansas, with encouraging results.

In the present Paper, post-processing methods are proposed and indicators are formulated for innovative assessment of goodness of operational behavior and performances of onshore wind farms. The methods are tested on two wind farms owned by Sorgenia Green and sited in southern Italy on gentle hilly terrains. Section 3 exploits the information of state dynamics to formulate indexes of malfunctioning: we demonstrate that they are as solid as the metrics commonly employed for operational assessment, which are energy or contractual availability [12] and amount of downtime. In Section 3 it is further discussed that the proposed indexes lie their innovativeness in the easy exportability of the approach to wind turbines of any size, and with any control system supplier, and even to other machines having non-trivial state dynamics.

Further, in Sections 4 and 5 the focus is shifted on power output production in the operative phase: power curve analysis, which is a widely investigated method in SCADA literature [25,26], is revisited. This provides a supporting tool for our innovative formulation of polar efficiency plot: polar efficiency is a powerful metric for quantifying farm homogeneity and highlighting how power losses depend on wind direction. Yet, the definition commonly employed in the literature (see for example [27]) for offshore wind farms is not consistent for onshore wind farms, due to effects from terrain complexity: the novelty of our proposal therefore consists in a new definition of polar efficiency, of which we demonstrate consistency, of which we provide ex-post validation through the discussion of the results on the two wind farms.

Finally, in Section 6 the focus is shifted to the interpretation of the quality of power output production in terms of mechanical effects, manifesting when significant wake effects arise. In previous valuable works [17,27,19] wakes are mainly analyzed mainly by the point of view of power losses and of inability of optimal yaw alignment to wind direction. The novelty of our approach is the inclusion of a related, yet unexplored, point of view: since wake effects usually result in meandering wind, which the nacelle of the turbines under wake cannot follow optimally, symptoms include anomalous and protract nacelle blockage while the wind