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Analysing Wind Turbine States and SCADA Data for Fault Diagnosis

Nicola Bartolini*, Lorenzo Scappaticci**‡, Alberto Garinei**, Matteo Becchetti*, Ludovico Terzi***

* Department of Engineering, Faculty of Mechanical Engineering, University of Perugia, via Duranti 67, 06125 Perugia

**Dept of Sustainability Engineering, Faculty of Science and Technology, Marconi University, via Plinio 44, 00193 Roma

*** Renvico srl, Via San Gregorio 34, 20124 Milano

(nicola.bartolini@hotmail.it, l.scappaticci@unimarconi.it, a.garinei@unimarconi.it, matteobecchetti@alice.it, ludovico.terzi@renvico.it)

‡ Corresponding Author; Lorenzo Scappaticci, via Plinio 44, 00193 Roma, Tel: +39 075 585 3945,

Fax: +39 075 585 3770, l.scappaticci@unimarconi.it

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Abstract- The diffusion of Supervisory Control And Data Acquisition (SCADA) systems has revolutionized the management of wind farms. Advanced performance optimization can lead to considerable improvement of power extraction, and therefore might also extend the possibilities for exploiting the wind resource. The price to pay is the challenge in elaborating vast amount of information into knowledge and visualizing them intuitively. Further challenge lies in the stochastic nature of the wind resource and in the complex mechanical structure of wind turbines: the optimization task therefore lies at the crossroad of physics, statistics, mechanical engineering, data visualization. This has led to fruitful collaboration between academy and industry, as the present work is. In this study, a mathematical and graphical method for elaborating wind turbine dynamics is formulated. Its key points are intuitiveness and versatility: the method can be used for a bird's eye view on a portfolio of wind turbines, for diagnosing and preventing fault onsets. The output doesn't depend on the nature of the single SCADA supplier and is potentially universal. In this work, some examples of applications to a wind farm owned by Renvico s.r.l are discussed.

Keywords Wind energy, wind turbines, SCADA control system, fault diagnosis.

1. Introduction

Power generation in the age of information is currently facing new and stimulating challenges. On one side, public opinion and governments are becoming more and more demanding by the point of view of lowering environmental impact and integrating renewable and non-renewable energy sources into smart grids. Farm owners are commonly charged with fees if they can't predict with accuracy the energy to be dispatched into the grid with 24 hours of advance. When the source has a stochastic nature, as is the case of wind, the power forecast is non-trivial and requires sophisticated methods, which can be purely statistical [1] or might couple machine learning to deterministic methods [2-4]. Although the performance of energy extraction are determined by the characteristics of the machines [5, 6] and by their relative positioning [7], in the age of information, the world of renewable energy is endowed with a whole scenery of new possibilities. Economic sustainability of wind farms can substantially be improved in the short term, by preventing damages, and in the long term, through performance optimization. In both cases, the turning point is exploiting information provided by Supervisory Control And Data Acquisition (SCADA). The stochastic nature of the wind resource and the complex technology of wind turbines are the main reasons why SCADA-based optimization is a multi-disciplinary subject, involving mechanical engineering, physics, statistics, data visualization. For comprehensive reviews on SCADA data analysis, we refer to [3, 4]. In [8], the correlations among SCADA data is employed for detecting incoming faults. In [9], three SCADA-based condition monitoring techniques (signal trending, self-organizing maps and a physical model) are presented, and their capability in preventing drivetrain faults is discussed. In [10], oil temperature rises are used for detecting incoming gearbox failures. In [11], it is shown that monitoring temperatures is a simple and powerful tool for detecting incoming mechanical failures, and for controlling wind turbines path back to normal operation after maintenance. The border between fault prevention and performance assessment is fleeting, as severely degraded performances might be the indicator of a problem or, on the long term, slightly degraded performances might be due to particular load conditions jeopardizing the health of the wind turbine. In [12], indicators are defined to detect the malfunctioning of a wind turbine and to select meaningful data to investigate the causes of the anomalous behaviour of a turbine. In [13-15], the dynamics of wind turbine states is processed for formulating indexes for performance evaluation. Further, the most straightforward global tool for performance assessment can be revisited: characteristics curves, in particular power curve. For other issues about power curve analysis, see for example [16] and [17]. Some of the agents determining wind farm efficiency [18] are: wake effects, terrain complexity (which causes local wind flow accelerations) and atmospheric stability. There is a vast literature on these issues: for some basic references, see [19-31]. Previous work of the authors concerns the stimulating intertwining of wake effects and terrain-induced flux acceleration, and its effects on the mechanical response and on the performances of the wind turbines. In particular, the main recent line of research of the authors is about the comprehension of the directional distortion of the wind flow, and its relation with turbine yawing [31-35]. On the grounds of the brief discussion above, it clearly arises that each wind farm owner might develop its own tools for SCADA analysis aimed at condition monitoring and performance evaluation: what commonly happens is that fruitful collaborations arise between academy and industry. The research improves our understanding of the wind and of the wind turbines, and the scientific results are embellished by validation against real test cases. This study actually follows this exact script: a mathematical method is formulated for codifying the dynamics of large wind turbines and this is subsequently translated in a versatile graphical output. The universality and intuitiveness of the method suggest that it might be useful for several tasks:

- a bird's eye of view on a portfolio of wind turbines
- fault diagnosis and prevention
- investigation of the quality of wind farm management

Therefore, the approach is useful if wind farm management and ownership coincide, and also if they don't coincide, and the owner needs to control, possibly dialogue, with the management. The proposed method is tested on a wind farm owned by Renvico s.r.l. The structure of the Paper is as follows: Section 1 is devoted to the description of the data sets and how they are processed in order to produce the output. Further, the test case is described. In Section 2, the results are collected and discussed. Finally, in Section 3 the conclusions are sketched and some further directions are indicated.

2. Materials and Methods

The data set is composed of two sources of information, having different structure and nature:

- The SCADA system stores data on 10 minute time basis, including minimum, maximum, average and standard deviation for each channel. They cover all the basic aspects of turbine behaviour, including wind conditions and consequent response of the machine (nacelle position, pitch angle and so on), electric, mechanical and thermal aspects.
- Turbine states: they provide the basic information about what the turbine is doing (producing output, being in fault, and so on) and why. Their codification depends on the language of each SCADA supplier, but a general demarcation can be established. Operating states describe what the turbine does: producing, waiting enough wind speed, restarting, being in error and so on. Therefore they must be mutually exclusive, i.e. in every moment one and only one state can be activated. SCADA systems provide also alarm and warning logs: these are naturally non-exclusive, i.e. more than one of them can be activated at a given time. Each wind turbine supplier records this information according to its own codification: the dynamics of operating states might be recorded in its continuous motion, or operating states can be recorded as counters of activation time on 10-minute time basis. Whatever is the case, the point is that the time grain of operating states and alarms is not regular as the one of SCADA data. States can have much shorter time scale, and vary even in few seconds (the start-up phases, for example). Or, on the converse, a wind turbine can remain in the same operating state (producing or waiting enough wind speed) for several hours.

The philosophy of the method we propose is combining together these two sources of information. In order to do so, one should convert the irregular grain of the operating states of the turbine into the same basis of the SCADA data: the turning point is associating to each 10-minute interval a unique number, describing what the turbine has done in majority during the same interval (producing, error, and so on). The "state number" is therefore a number representing the state that has been activated longer during the interval.

The "state number" is somehow like a fictitious SCADA channel, in the sense that it is constructed through data mining, but it has the same features and the same time grain of a regular SCADA channel. By a certain point of view, it is much more powerful than the regular SCADA, because it contains the most urgent information: what the wind turbine does. The idea of our method is now juxtaposing the "state number" to the real SCADA, 10 minutes by 10 minutes in such a way that the time evolution is evident and explanatory. Actually, a SCADA measurement (for example, turbulence intensity or rotor temperature) typically doesn't contain decisive information by itself, but its evolution might do. Further, its evolution juxtaposed to the information of what the turbine is doing might very explanatory.

Therefore, for each 10-minute interval, we propose to couple the "state number" to a meaningful SCADA measurement, which is customizable, in the sense that whatever channel can be chosen.

According to this criterion, for each wind turbine, two numbers are employed for each 10-minute interval. These two numbers evolve: they vary in time. Their evolution can be converted into graphics, and in the following a convenient representation is proposed. Each turbine during a period is represented with a bar, which is filled with an evolving colour and a black line which can move from left to right and viceversa inside the bar. It is built as follows: the time evolution proceeds along the y-axis and the resulting bar is the juxtaposition of slices, made by a black dot on a horizontal colour segment. Each slice represents a 10-minute interval. The dot represents the "state number" of each 10-minute interval, and the position of the dot depends on the value of the "state number". The right-most position is the "natural" state, power production. Moving to the left, one finds start-up phases and brake programs, as shown schematically in Table 1. The universality of the coding lies in the order: albeit the different number of states (and their names) that each SCADA supplier might provide, the relative placing is meaningful and captures the functioning phases of a wind turbine, which do not depend on the form of the SCADA. From right to left: production, start-up waiting for enough wind intensity, run-up, manual stop, errors-emergency. The rightmost, the most severe and traumatic and unexpected. The horizontal segment of background colour is built as follows: the minimum and maximum of SCADA measurements during the period are recorded, and the interval between these two values is discretized and converted into a colour palette. The lower limit is associated to the blue limit of the palette, the upper to the red limit. Each horizontal slice describing a 10-minute interval, in the end, is therefore constituted by a coloured segment (describing the value of the selected SCADA channel with respect to its range of variability) and a black dot (describing what the turbine is doing). Juxtaposing many of these slices, one obtains an area: a bar whose colour varies vertically, filled with a black line whose horizontal position varies when moving vertically in "reading" the graph. The scale of the y-axis, and therefore the time span of the analysis, is also customizable. If the SCADA system provides alarm logs too, as for the selected test case, they can be processed too. In order for the graph to be readable, we have selected to provide just the basic information: if, for each 10-minute interval, a wind turbine has an alarm log (whatever) activated. This is represented by a pink segment parallel to the main one, as in Fig.s from 2 to 7. In the time juxtaposition, this pink segment might become a pink bar if alarms are activated continuously.

The key points of the method are universality and versatility. It might be used by the farm management for visualizing performances, or as a first method of investigation, conjugating zero cost (it comes just from SCADA analysis) and simplicity. It might be useful as an intermediation between wind farm ownership and management: boost in contractual power of wind farm ownership with respect to management, obtained through low cost knowledge from SCADA data analysis, is actually a powerful driver to performance optimization.

The present work deals with an onshore wind farm, owned by Renvico s.r.l. and sited in northern France on a terrain with gentle slopes. The main features of the turbines are summarised in Table 2 and the layout is sketched in Fig. 1. This peculiar wind farm has been selected as test case for the present work mainly for two reasons. The first is that some turbines (T1, T2, T5, T6) suffer from a certain number of reoccurring unexpected stops. The second is that the SCADA system is very basic and it standard techniques are not capable of extracting the explanation for the reoccurring anomalous stops. Therefore, this wind farm provides a very stimulating testing ground for our method: the objective is inquiring if the approach is valuable in extracting some sense from the scarcity of data. In the following Section, it is shown through some sample results that this is indeed the case and the method is useful for analysis, diagnosis and interpretation of fault onsets.

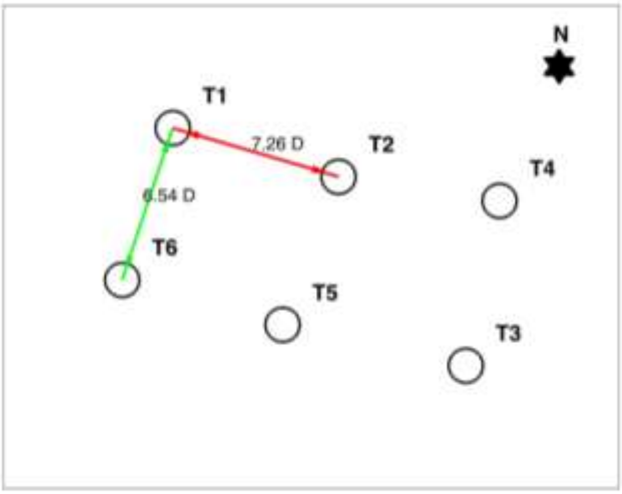

Fig. 1. The layout of the wind farm.

Table 1. The sequence of the states from left to right in the graphical codifying strategy. This table represents the position of the dot for every 10-minute interval, which in the long period builds the motion of the black line.

Stop	Test	Man. Op	Brake Release	Run Up	Start Up	Prod

Table 2. Main turbine characteristics.

Number of turbines	6
Rotor diameter	82 meters
Hub Height	80 meters
Rated Power	1.5 MW
Terrain	Flat

3. Results

Fig.s 2, 3, 4 and 5, 6, 7 show some sample results for two different days from two very different periods. The y-axis in each plot runs from 0 to 24, the number of hours. The pictures represent the time evolution of the farm along the day by the point of view of wind speed (Fig.s 2 and 5), wind speed standard deviation (Fig.s 3 and 6) and wind direction (Fig.s 4 and 7). The alarm log database doesn't provide univocal information about the causes of turbine stops, as one can see from the Fig.s. On the right of the bar of each turbine, actually, a pink bar is plotted representing the time periods during which an alarm is activated: during the sample days selected for the analysis, all the turbines had an alarm activated for all the 24 hours long. Therefore, this information is useless to extract knowledge about the dynamics, and it is therefore valuable to try to reconstruct it through the present method. From the Fig.s, the following pattern arises: during the day, the wind turns from southern to western or northern-western (Fig.s 4 and 7), simultaneously it becomes more intense (Fig.s 2 and 5) and more variable and therefore turbulent (Fig.s 3 and 6). From the Fig.s, it is evident that some turbines (most of all, T5 and T6) switch to emergency or error state and stop as wind variability increases. This phenomenon lasts few hours and then, when wind intensity decreases (Fig.s 2 and 5) and the wind becomes less turbulent, the turbines start producing again.

It is particularly valuable, in the example above, to notice that the conditions under which the turbines stop are not extreme: T5 and T6 are not expected to stop so long, according to wind conditions as recorded by the SCADA control system. Therefore the proposed method is able to highlight an incorrect, or at least too conservative, management of some turbines of the wind farm. In particular, it causes severe energy losses because it occurs for wind intensities associated to rated power. From the selected validation case, it arises that the approach of this study is particularly precious when applied to scarcity, i.e. to wind turbines whose SCADA control system does not provide plenty of information. Through zero cost SCADA data mining, a first picture of the dynamics of the turbines is provided, having a remarkable explanatory power, conjugating intuitiveness to universality. It can be used to stimulate a better wind farm management or as a starting point for ad hoc deeper analysis.

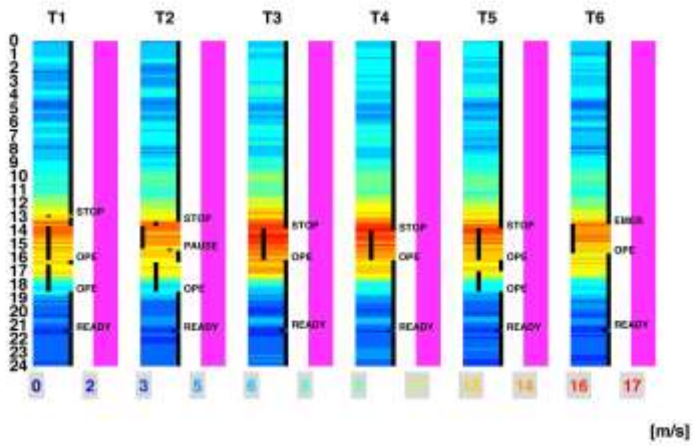

Fig. 2. Sample day 1. Abrupt machine stop during intense wind speed regime. Wind speed in background. The pink bar corresponds to the time of alarms activation.

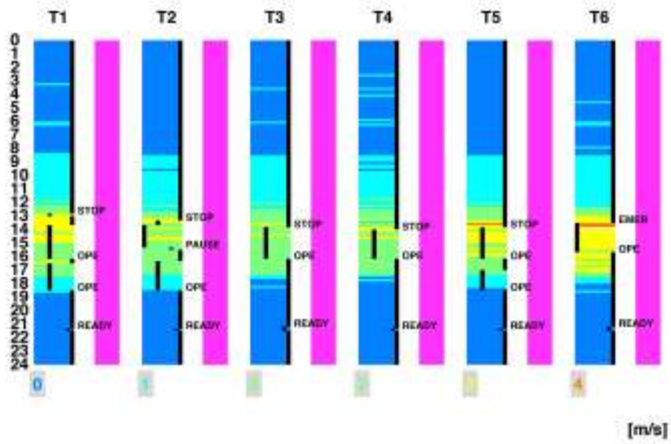

Fig. 3. Sample day 1. Abrupt machine stop during intense wind speed regime. Wind speed standard deviation in background. The pink bar corresponds to the time of alarms activation.

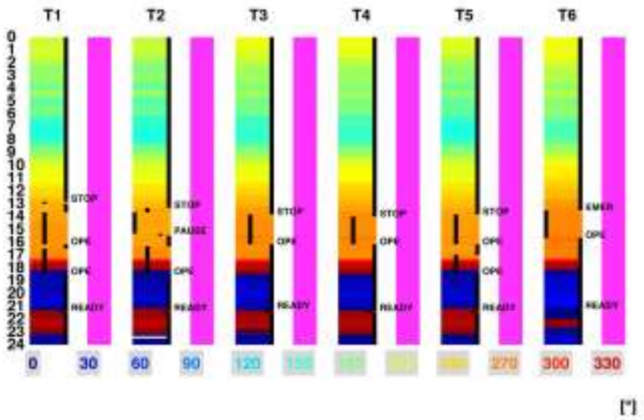

Fig. 4. Sample day 1. Abrupt machine stop during intense wind speed regime. Wind direction in background. The pink bar corresponds to the time of alarms activation.

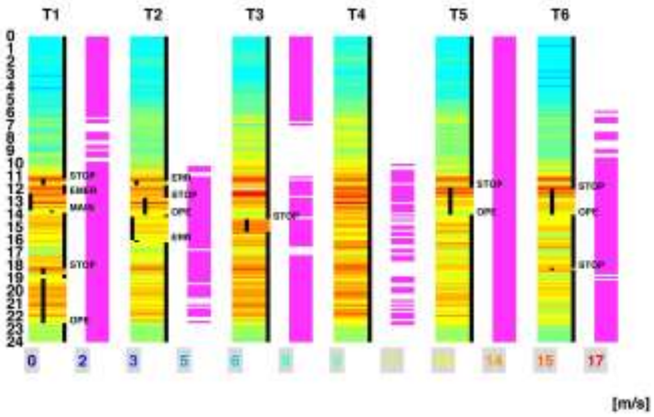

Fig. 5. Sample day 2. Abrupt machine stop during intense wind speed regime. Wind speed in background. The pink bar corresponds to the time of alarms activation.

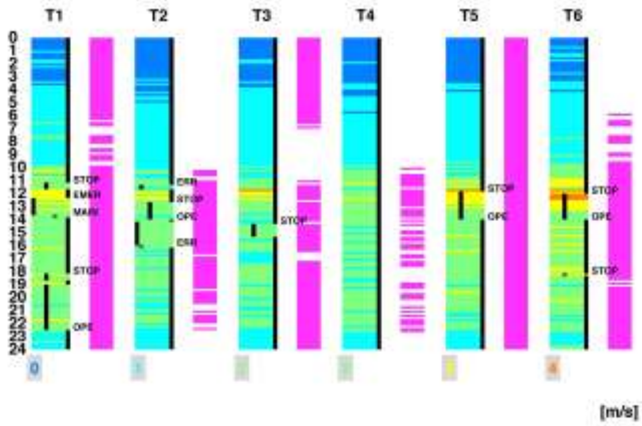

Fig. 6. Sample day 2. Abrupt machine stop during intense wind speed regime. Wind speed standard deviation in background. The pink bar corresponds to the time of alarms activation.

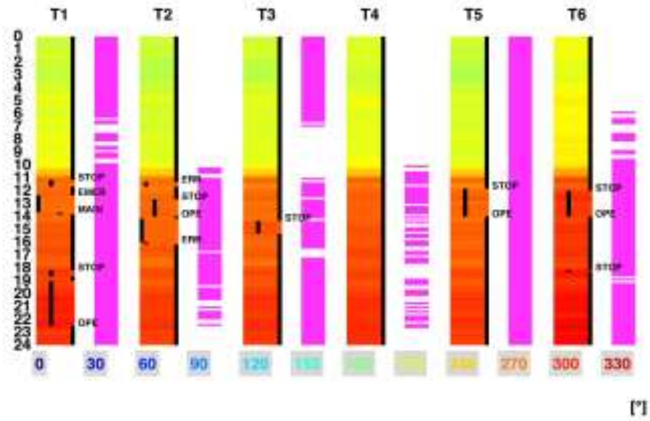

Fig. 7. Sample day 2. Abrupt machine stop during intense wind speed regime. Wind direction in background. The pink bar corresponds to the time of alarms activation.

4. Conclusion and Future Work

The conclusion section should emphasize the main contribution of the article to literature. Authors may also explain why the work is important, what are the novelties or possible applications and extensions. Do not replicate the abstract or sentences given in main text as the conclusion. In this work, a mathematical and graphical method has been formulated for processing wind turbine states and SCADA measurements. From the brief discussion in Sections 1 and 2, it arises that these two sources of information have intrinsically a much different dynamics and it is valuable to process them in a combined way. An aggregate dynamic visualization is useful for several objectives: most of all, analysing fault onsets and preventing them, evaluating wind farm performances and management. The final output of this work is a two-dimensional plot, encoding what a wind turbine does in the position of a moving line on a coloured background representing the evolution of a customizable SCADA channel. This approach has been tested for a wind farm sited in northern France. In Section 3 it is shown on the test case that the proposed method is preciously insightful and helps in the diagnosis of turbine stops. The main result, coming from the application of the proposed method, is that some wind turbines of the test case wind farm have undergone a too conservative management in reacting to increasing turbulence.

An interesting further direction of this work is testing the method when there is ambiguous super-abundance of information. We are confident that also in this regime, that is when information is too much and needs to be simplified, an aggregate dynamic graphical output might help at zero cost the wind farm ownership and management in keeping control of wind turbines portfolio. Another possible development is endowing memory to the method: processing a vast amount of historical data, possibly through Artificial Neural Network techniques, it might be possible to highlight critical regimes, whose recurrence should represent a wake-up call for wind farm manager. Or, one can endow the method of knowledge acquired through theoretical considerations and numerical modelling, as for example the estimated power production taking into account the effect of wakes [36].

References

[1] Brusca, S. “A new statistical based energetic-economic methodology for wind turbine systems evaluation”Energy Procedia, Vol. 45, pp. 180-187, 2014. (Article)

[2] Castellani F, Burlando M., Taghizaded S., Astolfi D., Piccioni E. “Wind energy forecast in complex sites with a hybrid neural network and CFD based method” Energy Procedia, Vol 45, pp. 188-197, 2014. (Article)

[3] Hashimoto, A., Kanougi, R., Hayasaki, N., Yamaguchi, A., Kajihara, F., & Arakawa, C. “Inter-comparison of the meso scale meteorological models for wind power prediction” Journal of Wind Engineering, Vol 35, No. 1, pp. 17-26, 2010. (Article)

[4] Castellani, F., Astolfi, D., Mana, M., Burlando, M., Meißner, C., & Piccioni, E. “Wind Power Forecasting techniques in complex terrain: ANN vs. ANN-CFD hybrid approach” In Journal of Physics: Conference Series, Vol. 753 No. 8, p. 082002. IOP Publishing. (Conference Paper)

[5] Brusca, S., Lanzafame R., Messina, M. “Design and Performance of a Straight-Bladed Darrieus Wind Turbine” International Journal of Applied Engineering Research, Vol. 10, No. 5, pp. 3979-3982, 2015. (Article)

[6] Scappatici, L., Bartolini, N., Castellani, F., Astolfi, D., Garinei, A., Pennicchi, M. “Optimizing the design of horizontal-axis small wind turbines: From the laboratory to market” Journal of Wind Engineering and Industrial Aerodynamics, Vol. 154, pp. 58-68, 2016. (Article)

[7] Brusca, S., Lanzafame, R., Messina, M. “Wind turbine placement optimization by means of the Monte Carlo simulation method” Modelling and Simulation in Engineering, Vol. 35, 2014. (Article)

[8] Yang W., Court R., Jiang J. “Wind turbine condition monitoring by the approach of SCADA data analysis” Renewable Energy, Vol 53, No. 0, pp. 365–376, 2013. (Article)

[9] Wilkinson M., Darnell B., van Delft T., Harman K. “Comparison of methods for wind turbine condition monitoring with SCADA data” Renewable Power Generation, IET, Vol. 8, No. 4, pp. 390–397, 2014. (Article)

[10] Feng Y., Qiu Y., Crabtree C.J., Long H., Tavner P.J. “Monitoring wind turbine gearboxes” Wind Energy, Vol 16, No. 5, pp. 728–740, 2013. (Article)

[11] Astolfi D, Castellani F., Terzi L. “Fault prevention and diagnosis through SCADA temperature data analysis of an onshore wind farm” Diagnostyka, Vol. 15, 2014. (Article)

[12] Castellani F., Garinei A., Terzi L., Astolfi D., Moretti M., Lombardi A. “A new data mining approach for power performance verification of an on-shore wind farm” Diagnostyka, Vol. 14, 2013. (Article)

[13] Astolfi D., Castellani F., Garinei A., Terzi L. “Data mining techniques for performance analysis of onshore wind farms” Applied Energy, Vol. 148, pp. 220–233, 2015. (Article)

[14] Castellani F., Garinei A., Terzi L., Astolfi D., Gaudiosi M. “Improving windfarm operation practice through numerical modelling and supervisory control and data acquisition data analysis” Renewable Power Generation, IET Vol. 8, No. 4, pp. 367-379, 2014. (Article)

[15] Bartolini N., Scappaticci L., Garinei A., Becchetti M., Terzi L. “Analysing wind turbine state dynamics for fault diagnosis” Diagnostyka, Vol. 17, No. 4, pp. 19–25, 2016. (Article)

[16] Roy S. “Performance prediction of active pitch-regulated wind turbine with short duration variations in source wind” Applied Energy, Vol. 114, pp. 700–708, 2014. (Article)

[17] Mikkelsen T., Hansen K.H., Angelou N., Sjholm M., Harris M., Hadley P., Scullion R., Ellis G, Vives G. “Lidar wind speed measurements from a rotating spinner” European Wind Energy Conference and Exhibition, 2010. (Conference Paper)

[18] Castellani F., Astolfi D., Terzi L., Hansen K.S., Rodrigo J.S. “Analysing wind farm efficiency on complex terrains” Journal of Physics: Conference Series, Vol. 524, No. 1. (Conference Paper)

[19] Barthelmie R., Hansen K., Pryor S. “Meteorological controls on wind turbine wakes” Proceeding of the IEEE, Vol. 101, No. 4, pp. 1010-1019, 2013. (Conference Paper)

[20] Barthelmie R., Pryor S., Frandsen S., Hansen K., Schepers J., Rados K., Schlez W., Neubert A., Jensel L., Neckelmann S. “Quantifying the impact of wind turbine wakes on power output at offshore wind farms” Journal of Atmospheric and Oceanic Technology, Vol. 27, No. 8, pp. 1302-1317, 2010. (Article)

[21] Mc Kay P., Carriveau R., Ting D.S.K. “Wake impacts on downstream wind turbine performance and yaw alignment” Wind Energy, Vol. 16, pp. 221-234, 2013. (Article)

[22] Hansen K., Barthelmie R., Jensen J., Sommer A. “The impact of turbulence intensity and atmospheric stability on power deficits due to wind turbine wakes at Horns Rev offshore wind farm” Wind Energy, Vol. 15, No. 1, pp. 183-196, 2012. (Article)

[23] Porté - Agel F., Wu Y.T., Chen C.H. “A numerical study of the effects of wind direction on turbine wakes and power losses in a large wind farm” Energies, Vol. 6, No. 10, pp. 5297–5313, 2013. (Article)

[24] Gaumond M., Réthoré P.E., Ott S., Pena A., Bechmann A., Hansen K.S. “Evaluation of the wind direction uncertainty and its impact on wake modeling at the horns rev offshore wind farm” Wind Energy, Vol 17, No. 8, pp. 1169–1178, 2014. (Article)

[25] Marathe N., Swift A., Hirth B., Walker R., Schroeder J. “Characterizing power performance and wake of a wind turbine under yaw and blade pitch” Wind Energy, 2015. (Article)

[26] Iungo G.V. “Experimental characterization of wind turbine wakes: Wind tunnel tests and wind lidar measurements” Journal of Wind Engineering and Industrial Aerodynamics, Vol. 149, pp. 35–39, 2016. (Article)

[27] Moreno P., Gravdahl A.R., Romero M. “Wind flow over complex terrain: application of linear and cfd models” European wind energy conference and exhibition, pp. 16–19, 2003. (Conference Paper)

[28] Makridis A., Chick J. “Validation of a cfd model of wind turbine wakes with terrain effects” Journal of Wind Engineering and Industrial Aerodynamics, Vol. 123, pp. 12–29, 2013. (Article)

[29] Rodrigo J.S., Gancarski P., Arroyo R.C., Moriarty P., Chuchfield M., Naughton J.W., Hansen K.S., Machefaux E., Koblitz T., Maguire E. “Iea-task 31 wakebench: Towards a protocol for wind farm flow model evaluation. part 1: Flow- over-terrain models” Journal of Physics: Conference Series, Vol. 524, IOP Publishing, 2014. (Conference Paper)

[30] Moriarty P., Rodrigo J.S., Gancarski P., Chuchfield M., Naughton J.W., Hansen K.S., Machefaux E., Maguire E., Castellani F., Terzi L. “Iea-task 31 wakebench: Towards a protocol for wind farm flow model evaluation. part 2: Wind farm wake models” Journal of Physics: Conference Series, Vol. 524, IOP Publishing, 2014. (Conference Paper)

[31] Castellani F., Astolfi D., Garinei A., Proietti S., Sdringola P., Terzi L, Desideri U. “How wind turbines alignment to wind direction affects efficiency? A case study through SCADA data mining” Energy Procedia, Vol. 75, pp. 697-703, 2015. (Article)

[32] Castellani F., Astolfi D., Piccioni E., Terzi L. “Numerical and experimental methods for wake flow analysis in complex terrain” Journal of Physics: Conference Series, Vol. 625. IOP Publishing, 2015. (Conference Paper)

[33] Castellani F., Astolfi D., Sdringola P., Proietti S., Terzi L. “Analyzing wind turbine directional behavior: SCADA data mining techniques for efficiency and power assessment” Applied Energy, 2015. (Article)

[34] Castellani F., Astolfi D., Burlando M., Terzi L. “Numerical modelling for wind farm operational assessment in complex terrain” Journal of Wind Engineering and Industrial Aerodynamics, Vol. 147, pp. 320-329, 2015. (Article)

[35] Astolfi D., Castellani F., Terzi L. “Mathematical methods for SCADA data mining of onshore wind farms: Performance evaluation and wake analysis” Wind Engineering, Vol. 40, No. 1, pp. 69-85, 2016. (Article)

[36] Castellani F., Gravdahl A., Crasto G., Piccioni E., Vignaroli A. “A practical approach in the CFD simulation of off-shore wind farms through the actuator disc technique” Energy Procedia, Vol. 35, pp. 274-284, 2013. (Article)