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Numerical modelling for wind farm operational assessment in complex terrain

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ABSTRACT

Wind farm operation in very complex terrains generally involves complicated and severe environment for wind turbines. Strong speedups, extreme wind veer and high turbulence create a harsh environment for turbine safety and durability. A detailed analysis of the wind field can be very useful in order to isolate the most dangerous conditions and prevent exceptional loads. In this study it is investigated to what extent numerical free flow model can give reliable information on the operational behaviour of wind farms. For this reason, two wind farms, having very different features, are selected: the former is sited on a very gentle terrain and its dynamics is mainly driven by wake interactions, while the latter is instead sited on a very complex terrain. The wind field induced by the orography is calculated with two different numerical approaches, CFD (Computational Fluid Dynamics) and mass consistent modelling. Numerical results are compared and validated against experimental measurements from anemometer met-masts and from turbines SCADA (Supervisory Control And Data Acquisition) data sets. The analysis demonstrates that wind field models can give very useful information on rotor alignment patterns and on their influence on the overall park performance.

1. Introduction

Knowledge of wind field features is fundamental to understand the complex behaviour of a wind farm operating in very complex terrains. This is particularly valuable when severe climate conditions (such as icing and lighting) and difficult accessibility might also affect wind farm reliability. In general, the effects of wind flow acceleration induced by high slopes (Castellani and Franceschini, 2005) on the actual production can be difficult to discern. Numerical models play a crucial role in assessing expected performances of wind farms operating in complex terrains: several open scientific challenges are posed by the intertwining of multiple concurring meteorological agents and by the interactions between the main wind field (Makridis and Chick, 2013a) and the wind farm, as for example wakes evolution, turbulence evolution or wind direction spatial variation driven by ridges and valleys. Further challenge is posed by the complex response of the wind turbine to the wind flow: for example, wakes manifest in meandering flow, which the nacelle of a turbine downstream cannot follow optimally, due to the different time scale of the phenomenon with respect to the control system of the turbine. A compromising alignment is therefore established, which nevertheless inevitably manifests in significant power losses. This issue, as well as many others related to the assessment of the actual behaviour of an operating wind farm, has recently received significant boost, thanks to the abundance of Supervisory Control and Data Acquisition (SCADA) control systems, spreading out on 10-minute time basis a vast amount of information on the wind turbines. The challenge is in elaborating SCADA information, processing it into knowledge, and possibly interfacing this knowledge to the control system itself, or to mathematical models, numerical models, forecast techniques. In this study, valuable insight is provided, by SCADA data analysis, on wind turbines and their response to meteorological conditions and terrain. Different application of SCADA approach (condition monitoring, fault prevention, forecast techniques) are reported in Kusiak et al. (2013). In Kaldellis and Zafirakis (2013) economic and technological impact is reviewed of increasing technical availability, to which SCADA data mining methods have provided significant boost.

Due to the scientific challenges, and not negligible technological and economic impact, particular attention has been devoted to the analysis of wake interactions, which is the most investigated testing ground of the interplay of numerical models and SCADA

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data mining techniques. In Barthelmie et al. (2013) power losses caused by wakes are investigated on the test cases of Horns Rev and Nysted wind farms in Denmark. Horns Rev wind farm is analysed also in Hansen et al. (2012), where dependency of power deficit on wind rose, wind speed, turbulence intensity, stability of the atmosphere is studied. In McKay et al. (2013) SCADA data mining techniques are employed for the assessment of power losses due to wakes: the objective is investigating the dynamics of misalignment and yawing dynamics under downstream wake angles. In Gaumond et al. (2013), post processing techniques are employed to demonstrate that mismatch between simulations and operational data of the Horns Rev test case are due to the large wind direction uncertainty commonly contained in the data set, rather than in the wake model itself. In Port-Agel et al. (2013) the Horns Rev test case is studied through large-eddy simulations and it is shown that even small changes in wind direction angle can have strong impacts on the total wind farm power output. For these reasons, precise wake assessment is so crucial in wind farm design that an online open access resource has been built, named Virtual Wake Laboratory (Barthelmie and Pryor, 2013), providing meteorological and wind farm data for use in wake characterization and wake model evaluation. In Subramanian et al. (2015) innovative wind flow measurements techniques, based on instrumented drones, are employed for wake effects assessment and it is shown that the approach can be useful for improving Computational Fluid Dynamics (CFD) modelling. Improving CFD modelling for describing wake effects is an ambitious scientific challenge: in Tian et al. (2015) a new 2D wake model is proposed, based on the Jansen model, which is based on the use of a cosine shape function to redistribute the spread of the wake deficit in the crosswind direction.

In Castellani et al. (2014a) the approach is an upgrade from quantifying misalignment to the wind direction to investigating wind turbine orientation patterns. The idea is that a cluster of turbines affected by multiple wakes should not be considered as a union of single turbines, but rather as a whole: recurrent orientation patterns of the cluster are found, and it is investigated if the most frequent are energetically favorable or not. This approach, tested on two onshore wind farms in southern Italy, would be a valid contribution to the perspective of active yawing control system (Fleming et al., 2013): its underlying principle would be derogating, under certain conditions, from the automatic alignment patterns dictated by the control system, in favor of custom criteria arising from the experience contained in the SCADA measurements. It would in perspective be extremely valuable to upgrade from the "trial and error" approach, based on learning from the SCADA experience of each site, to a connection between wind flow and turbine response to it, provided by numerical models describing the physics of the wind flow and the engineering of the wind turbine in more detail.

Numerical techniques and SCADA data analysis are quite well established on offshore test cases, where farm dynamics is mainly driven by wakes, while instead the challenging complexity of the onshore case has not been exhaustively investigated. Actually, complexity of the terrain induces not negligible additional turbulence and local wind flow acceleration and these effects interplay with meteorological agents and wake interactions. Both numerical simulation techniques and operational assessment methods are stretched to their limit and often even need to be revisited with respect to the offshore case: for example, in Castellani et al. (2014b), it is shown that polar efficiency, which is a common single parameter performance evaluation metric, must be redefined. A novel definition is proposed and its consistency is investigated throughout three onshore test cases, sited on terrains of increasing complexity.

On the grounds of the motivations above discussed, this study is built up of numerical and experimental analysis of two onshore wind farms sited in southern Italy, having very different features: the former lies on a very gentle terrain, the latter lies on a very complex terrain, with slopes up to 60% in proximity of the turbines. In both wind farms, layout and inter-turbine distance are such that considerable wake interactions arise in the main direction sectors of the wind roses. On the latter wind farm, therefore, complexity of the wind flow due to the orography encounters wake effects, resulting in a very stimulating test case. Actually, this wind farm has been one of the testing grounds of IEA-Task 31 Wakebench (Rodrigo et al., 2014) project for the evaluation of wind farm flow models operating at microscale level. This study mainly aims at quantifying how much operational behaviour of wind farms can be captured by numerical free wind flow models, which of course completely neglect the presence of wind turbines. A similar approach is proposed in Makridis and Chick (2013b), where a method for simulating wind turbine wakes in neutral atmospheric wind flow, using Fluent and WAsP, is addressed and validated against a coastal test case sited on a quite complex terrain. The numerical analysis is implemented through two different models. The former is a CFD model and the latter is a mass-consistent model. For CFD simulation, the WindSim (Moreno et al., 2003) numerical tools are used, while the simulations with the mass-consistent model are performed by means of the numerical code WINDS (Burlando et al., 2005, 2007), developed at the University of Genoa (Ratto et al., 1990). The test cases are selected according to the objective above: the wind farm sited on a gentle terrain is affected by severe wakes, whereas wind flow acceleration due to terrain complexity is expected to be the main agent of the operational behaviour of the second wind farm. Therefore, the free flow numerical models are expected to resemble operation behaviour to a different degree on the two test cases. In particular, the presence of the turbines not only affects wind speed field along the wind farm, but most of all distorts undisturbed wind direction. For this reason, a detailed analysis of experimental nacelle orientation patterns is performed, and it is crosschecked how much they agree with free wind directions predicted by the models. The structure of this study is as follows: in Section 2 the wind farms are briefly described. Further, information justifying the simulation regimes on the test cases is provided. In the following Section 3 the methods are described. Further, the SCADA data mining techniques are sketched. Finally, in Section 4 the results are collected, and discussed in Section 5. Conclusions are drawn in Section 6.

2. The wind farms

The wind farms under investigation are placed in Southern Italy, on terrains having very different features: the first wind farm, called WF1 hereafter, consists of 9 wind turbines, having 2 MW of rated power, sited on a very gentle terrain; the second wind farm, called WF2 hereafter, consists of 17 turbines, with 2.3 MW of rated power, sited on a very complex terrain. The terrain of WF2 features very high slopes (up to 60%) close to the turbines; also the layout is complex and large, resulting in the interplay of complex wind flow and wake interactions. The essential information on the two wind farms is summarized in Table 1, while the layouts are displayed in Fig. 1. For WF2, the overall topography of the site is characterized by three ridges with different orientation so that very strong variations in wind intensity and directions can be observed. The site is also characterised by significant icing and lighting effects.

Prior to the installation of the turbines, site assessment was done using met-mast measurements; in both wind farms an