Applied Energy 229 (2018) 767–777

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Large-eddy simulation of a utility-scale wind farm in complex terrain

Xiaolei Yang[a,b], Maggie Pakula[c], Fotis Sotiropoulos[a,*]

[a] Department of Civil Engineering, College of Engineering and Applied Sciences, Stony Brook University, Stony Brook, NY 11794, USA
[b] Department of Mechanical Engineering, College of Engineering and Applied Sciences, Stony Brook University, Stony Brook, NY 11794, USA
[c] Invenergy, One South Wacker Drive, Suite 1800, Chicago, IL 60606, USA

HIGHLIGHTS

- Large-eddy simulation of the Invenergy Vantage wind farm in complex terrain.
- The computed results show good agreement with field measurements.
- This work shows the possibility of using large-eddy simulation for the site-specific design of wind farms in complex terrain.
- This work underscores the need for developing analytical models that account for terrain effects.

ARTICLE INFO

Keywords:
Large-eddy simulation
Wind farm
Complex terrain

ABSTRACT

Site-specific wind farm design must take into account the effects of site-specific terrain topography. Large-eddy simulation (LES) is a promising approach for simulating the site-specific characteristics of the wind fields and turbine wakes in complex terrain. However, to the best of our knowledge, the capability of LES in simulating utility-scale wind farms in complex terrain has not been systematically evaluated. In this work, we apply the state-of-art LES code Virtual Flow Simulator (VFS-Wind) to simulate the Invenergy Vantage wind farm (located in the Washington state, USA) in complex terrain. The computed power outputs are compared with field measurements and good agreement with the measured data is obtained both in terms of mean power and statistics of power generated by the wind farm. A simple analytical wind farm model without considering the complex terrain effects is also applied to predict the performance of the Vantage wind farm layout. The results show that such a model overestimates the performance of the actual Vantage wind farm and underscore the need for developing analytical models that account for terrain effects to enable wind farm design and optimization in complex terrain. LES can provide the data sets required to calibrate and validate such terrain-specific analytical models.

1. Introduction

Site-specific design of wind farms [1] requires site-specific wind resource characterization and in depth understanding of the physical mechanisms governing the coupled interactions of turbine wakes with each other and the local terrain-topography. Unlike flat terrain, the wind patterns in the complex terrain are inherently heterogeneous and are thus challenging to characterize [2] as measurements at one point may not be representative of the flow state at points located only a few hundred meters away [2]. Characterizing the wind fields over the entire site using measurements is a very time-consuming and difficult task. Computational models provide an alternative approach for characterizing the wind fields in complex terrain. Computational models, however, have to be systematically validated against field measurements before they are applied to the real-world wind farm design. In this work, we evaluate and demonstrate the predictive capabilities of a high-fidelity computational model for simulating wind farms in complex terrain using the field measurements obtained in a utility-scale wind farm.

Practical approaches for simulating high Reynolds number atmospheric turbulent flows are the Reynolds-Averaged Navier–Stokes (RANS) and large-eddy simulation (LES) methods. In the former methods, the Reynolds-Averaged Navier–Stokes equations closed with appropriate statistical turbulence models are solved and thus only statistical descriptions of the turbulent flow fields can be obtained (either steady or time varying). Therefore, in such methods all scales of atmospheric turbulent fluctuations are modeled. The RANS models are typically calibrated using canonical turbulent flows and as a result their

* Corresponding author.
E-mail addresses: xiaolei.yang@stonybrook.edu (X. Yang), mpakula@invenergyllc.com (M. Pakula), fotis.sotiropoulos@stonybrook.edu (F. Sotiropoulos).

https://doi.org/10.1016/j.apenergy.2018.08.049
Received 22 May 2018; Received in revised form 18 July 2018; Accepted 11 August 2018

predictions become less reliable in complex, non-equilibrium turbulent flows, such as flows with adverse pressure gradients and three-dimensional separation. In LES approaches, on the other hand, scales of motions in the atmospheric turbulent flows that can be resolved by the computational grid are directly resolved while subgrid scales (SGS) of motion, which in principle are more isotropic, are modeled using SGS models without empirical parameters e.g. the dynamic Smagorinsky SGS model [3]. A recent literature review on LES methods for wind farm simulations can be found in [4].

Due to the large disparity in spatial scales, the boundary layer flows over the turbine blades and other structures are usually parameterized in wind farm scale simulations. Different turbine parameterizations of varying level of sophistication and physical realism have been proposed in the literature. The actuator disk parameterization represents the whole turbine rotor as a circular permeable disk [5] with distributed forces computed from the one-dimensional momentum theory [6]. The actuator line parameterization [7] represents turbine blades as straight rotating lines with distributed forces computed from the blade-element method [6] using the tabulated geometry (e.g. chord length and twist angle at different radius locations) and aerodynamic data (e.g. lift and drag coefficients as a function of Reynolds number and angle of attack) of the blade. More sophisticated parameterizations of turbine blades as actuator surfaces have been developed by Shen et al. [8] and more recently by Yang and Sotiropoulos [9]. In Shen et al.'s actuator surface model, the distributed forces on the actuator surface are computed using the pressure coefficients at different radial locations. In the actuator surface model by Yang and Sotiropoulos [9], the distributed forces are computed using the blade-element method and are uniformly distributed in the chordwise direction at each radial location along the blade. The turbine nacelle has recently been shown to have significant impact on the structure and dynamics of turbine wakes for different turbine designs and sizes, e.g. a 0.5 m diameter hydrokinetic turbine in [10], a 0.128 m diameter model wind turbine in [11] and a 1.1 m diameter model wind turbine in [12]. A straightforward and computational expedient approach to model the nacelle is to simply extend the blades to the center of the rotor as was done, for instance, by Yang et al. [13]. Another simple approach is to represent the nacelle as an impermeable disk [14]. However, it was shown that such simple models are not able to accurately predict the nacelle wake and its rich dynamics both in the near and far fields [9]. Recently a novel actuator surface parameterization was developed for the nacelle by Yang and Sotiropoulos [9]. It was shown that this model can predict the nacelle wake dynamics both qualitatively and quantitatively with acceptable accuracy on very coarse meshes [9].

Extensive studies on wind fields and turbine wakes in flat terrain or terrain of uniform roughness have been carried out in the literature [15]. Measurements of wind fields and turbine wakes in complex terrain, on the other hand, have only been conducted in few cases, such as the Askervein Hill project [16] and the bolund experiment [17,18]. Wind tunnel experiments have been focused on very simple topography, such as a two-dimensional hill [19] and a three-dimensional hill [20]. Kozmar et al. [21] investigated the wake characteristics of a parked wind turbine model located in the downwind of a mountain model of different topography. Hansen et al. [22] presented the wake data in a wind farm of 25×2 MW wind turbines located in complex terrain in the northern part of China. El-Asha et al. [23] measured turbine wakes in an onshore wind farm. Hyvärinen [24] investigated the wake development of turbines located on sinusoidal hills. RANS models were employed in most computational studies of the wind fields and turbine wakes in complex terrain, e.g. resource assessment in a complex terrain site in western Norway [25], the wake of a turbine mounted on the top of a hill [26,27], and a wind farm of 43 wind turbines located in complex terrain in Spain [28]. Simulations of the turbulent flows and turbines wakes in complex terrain using LES are sparse [4,29]. Yang et al. [30] investigated the effects of the wake of a three-dimensional hill on the wake of a model turbine using LES. In [13] Yang et al. simulated a hypothetical wind farm in a complex terrain site in Minnesota, USA using LES. To the best of our knowledge, the predictive capabilities of LES for a real-world utility-scale wind farm in complex terrain have not been reported in the literature. LES of utility scale wind farms are computationally expensive and usually cannot be directly applied for optimizing wind farm layouts. For that, the state of the art today in wind farm optimization relies almost exclusively on simple and computationally very expedient analytical models. Jensen's analytical model [31], for instance, is widely used for wind farm layout optimization in conjunction with various optimization methods e.g. the evolutive algorithm [32], the ant colony algorithm [33], the gradient-based method [34] and the mixed integer particle swarm optimization algorithm [35]. The shape of the wake profiles from Jensen's model is of top-hat shape, which is different from the wake shapes arising from measurements and simulations. To address this issue, some modified versions of Jensen's model giving Gaussian-like shape wakes were employed in the literature [36–39]. A review of Jensen's model for wind farm layout optimization is given by Shakoor et al. [40]. Other wake models were also employed in the literature for wind farm layout optimization. For instance, Chowdhury et al. [41] adopted Frandsen et al.'s model [41] and the constrained particle swarm optimization method to investigate factors such as turbine rotor diameters and number of turbines influencing wind farm maximum power generation. The Jensen and Frandsen et al. models can take into account the turbine wake interactions using the wake superposition technique. However, they cannot properly model the interaction of turbine wakes with the ambient atmospheric turbulence, which is of critical importance for the wake entrainment in large wind farms. Recently analytical models were developed to better take into account such interaction of turbine wakes with the atmospheric turbulence, such as the models by Stevens et al. [42] and Yang and Sotiropoulos [43], which combine the kinematic wake model (e.g. Jensen's model) with the "top-down" effective roughness length model. The developed models were successfully validated against field and wind tunnel measurements of wind farms in flat terrain. However, none of the above models can take into account the effects of complex terrain, so their validity for optimizing wind farm layout in complex terrain is questionable. Due to their computational expedience, analytical models are still going to play an important role in wind farm layout optimization. In order to develop analytical models for complex terrain, however, the simplifications (e.g. simplified mass and momentum conservation equations [31,6]) and assumptions (e.g. the linear wake superposition rule [31,43]) adopted in such models need to be examined for complex terrain topography. The mechanisms of turbine wakes and their interaction with complex terrain also need to be better understood in order to provide physical insights and the theoretical basis for developing simpler models. LES is in principle able to predict the heterogeneous atmospheric turbulent flows over complex terrain and the interaction of atmospheric turbulence with turbine wakes. However, as discussed in the above literature review, a systematic assessment of the predictive ability of LES in complex terrain simulations has not yet been performed. As the first step towards better understanding the mechanism of turbine wakes in complex terrain and obtaining data sets required for developing analytical models suitable for wind farms in complex terrain, we seek herein to demonstrate the predictive capabilities of LES as powerful tool for simulating utility-scale wind farms in complex terrain. To our knowledge the work reported herein is the first attempt to simulate a utility scale wind farm in complex terrain and validate the numerical simulations with field data both in terms of mean power and statistics of power generation.

This paper is organized as follows. In Section 2, the Virtual Flow Simulation (VFS-Wind) LES code we employ in this work is briefly described. The wind farm we simulate, the Vantage wind farm in the Washington, USA, is discussed in Section 3. Subsequently the computational results from LES and an analytical model are presented and compared with field measurements in Section 4. Finally, a summary and discussion of key findings is given in Section 5.