



Combined optimization of continuous wind turbine placement and variable hub height

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ABSTRACT

This paper aims to systematically study the wind farm optimization with the continuous selection of wind turbine placement (using Cartesian coordinates) and wind turbine hub height (restrained among a predefined range). Two case studies are performed. The first case involves an ideal two-dimensional (i.e., flat terrain) wind farm, and the other is a three-dimensional wind farm with real terrain altitudes. The schemes of simultaneously optimizing the wind farm layout and wind turbine hub heights applying the simplified and augmented PARK wake model are established for the ideal and real wind farm cases, respectively. The results show that applying different wind turbine hub heights for the wind farm layout optimization yields significant improvement: up to a 0.2 MW increase in total power and a 2% increase of the wind farm efficiency for the ideal wind farm. However, for the real wind farm the effectiveness of applying different wind turbine hub heights varies depending on the number of turbines installed. With less number of turbines installed, the impact of varying hub heights is small. However, significant improvements can be achieved as the number of turbines increases. With 39 wind turbines, the wind farm cost of energy can be reduced by \$15000 per megawatt and the wind farm efficiency can increase by up to 0.2%. Given the nameplate capacity and the lifespan of wind farm project, the resulting effect on total energy production can be significant and thus improve the competitiveness of wind power exploitation.

1. Introduction

The study of utilizing renewable energy to produce electric power has attracted extensive attention by academia and industry. Wind energy is one of the renewable energy sources including nuclear power, hydro-power, solar power and others, that has shown the fastest trend of development in the last few decades (Liu et al., 2013). The utilization of wind energy is achieved via wind farms consisting of a large number of wind turbines in clusters to make full use of local wind resources. However, with clustering wind turbines it brings about the problem of wind flow intervention from the upstream turbines to the downstream turbines. As a result, the power production of downstream wind turbines can be greatly reduced, as well as the life expectancy of turbine components caused by fatigue load due to the wake effect (Aho, 2010). As the scale of wind farms have increased, these wake power losses are becoming increasingly prominent (Chen, 2013). In order to mitigate or avoid the wake power losses, significant efforts have been made through

optimizing the wind farm layout. By carefully choosing the best wind turbine positions in a wind farm, the power losses caused by the wake effect can be regained to a large extent (Song et al., 2015; Pookpant and Ongsakul, 2016). Such power increases will not only enhance the financial return of the wind farm development, but also boost the cost-competitiveness of wind power utilization.

The study of wind farm layout optimization started as early as 1994 by applying the grid based method for an ideal square wind farm study (Mosetti et al., 1994). The method employs identical square grids to divide the wind farm area, and each grid is a potential position to place the wind turbines. Significant power output increase has been achieved for the optimized wind farm layouts as compared with those random wind farm layouts for all tested wind conditions. Since then, an increasing number of publications began to emerge on the topic of wind farm layout optimization studies. This includes those which applied the novel wake model (Tong et al., 2012; Bastankhah and Porté-Agel, 2014), wind farm cost model (González et al., 2010, 2011) and wind condition

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models (Wan et al., 2009), while others employed novel optimization approaches (Al-Edaily et al., 2011; Turner et al., 2014; Ituarte-Villareal and Espiritu, 2011). In those references, it is found that most of the research employed identical wind turbines for the wind farm design, though applying different types of wind turbines has the advantage of increasing the total wind farm power and alleviating the wake effect (Chen et al., 2013). When using different types of wind turbines in a wind farm, those with same rotor diameter and different hub heights are preferred to those with different rotor diameters, since the latter is much more costly for operation and maintenance of wind farm development (Ali et al., Milanović).

Only recently have a few papers reported results on the wind farm layout optimization using wind turbines with different hub heights. Chen et al. (2013) applied a single type of turbine with two different hub height options for a wind farm layout optimization using the grid based method. The optimization results were compared with constant hub height turbines. It was shown that the improvement of cost of energy (investment cost per unit power production) for the wind farm is obvious under all wind conditions. Vassel and Archer (Vassel-Be-Hagh and Archer, 2017) carried out the optimizations of wind turbine hub heights with fixed wind turbine positions, under the scenarios of both discrete selection of two optional hub heights and continuous selection from a minimum to a maximum predefined hub heights. They found that by simply optimizing the wind turbine hub heights, it yields 5.4% more power output for the two hub height options and 2% more power production for the continuous hub height options. Abdulrahman et al. (Abdulrahman and Wood, 2017) studied the wind farm layout optimization problem by investigating the power and cost of energy trade-off for a wide selection of commercial wind turbines with different hub heights. They concluded that the taller tower of wind turbines not only reaches higher wind speed, but also facilitates to reduce wake effect for the wind farm by applying different wind turbine hub heights, which is extremely prominent in compact wind farm layouts. By referring to the literature (Vassel-Be-Hagh and Archer, 2017; Abdulrahman and Wood, 2017), it is found that few studies considering continuous variation of hub heights for wind farm layout optimization have been reported, which is believed to be more beneficial to escape the wake effect by more flexible hub height selections. In addition, despite that the unrestricted coordinate method (directly using the Cartesian coordinates to determine wind turbine positions) has shown to yield better optimization results when compared to the grid based method (Wang and TanGu, 2015), no studies on the wind farm and hub height optimizations have employed this more advanced wind farm design method which could possibly lead to a better result. Moreover, the wind farm models applied in the hub height optimization study are either two dimensional neglecting the variation of terrain altitudes (Hou et al., 2016), or employing artificially-defined altitudes which provide little insight on the effect of considering different hub height turbines to real wind farms (Chen et al., 2016).

Therefore, this paper aims to conduct the wind farm layout optimization applying different hub height turbines permitting continuous variation of both the placements (by using the unrestricted coordinate method) and the hub heights of wind turbines (by predefining a minimum and a maximum hub height). Two types of wind farms are studied: a flat terrain (two-dimensional) ideal wind farm and a non-flat terrain (three-dimensional) real wind farm. The objective is to unveil the impact of applying the continuous selection of different hub height turbines on the wind farm optimization results. The optimization variables include the wind turbine positions (represented by x and y coordinates) and wind turbine hub heights. The objective function, which is cost of energy production, is minimized by the genetic algorithm in C++ language. A novel wind multiplier method calculating the wind speed variation on non-flat terrain is extended for wind farm optimization study with different hub height turbines. In this method, the original PARK model is augmented using wind multiplier at constant hub height obtained from CFD simulation of the three-dimensional wind farm model, and the wind multiplier at different hub heights is calculated using the power law of wind profile.

2. Modeling

In this section, different types of models applied for the wind farm layout optimization study are introduced including: the wake model which quantitatively describes the wind speed change in the wake region, the wind farm models, the wind turbine models, the wind condition models and the wind farm cost models for both ideal and real wind farm cases.

2.1. Wake model

Compared to the other simplified wake model such as Larsen model and Frandsen model, the well-established PARK wake model has been most widely used for the wind farm layout optimization study in literature, due to its low computational costs and satisfying accuracy of described wake properties for such research topic which requires enormous computational resources. The model is first proposed by Jensen et al. (Jensen, 1983) and then tuned for the wind farm optimization study by Katic et al. (1986). It is directly applied for the ideal wind farm case in this paper.

The PARK model (see Fig. 1) assumes linear propagation of wake behind the wind turbine rotor. In the figure, A_0 and $A(x)$ are the cross-section areas of downstream rotor and downstream x distance wake, respectively. The wind speed affected by the wake at the downstream x distance towards the dominant wind direction is represented by:

$$v_x = v_0 \left[1 - 2a \left(\frac{r_0}{r_0 + \alpha x} \right)^2 \right] \quad (1)$$

where r_0 is the downstream rotor radius, a is the axial induction depicting the percentage of wind speed reduction relative to the free wind speed, and they are given by (R is rotor radius and u is the wind speed at the downstream rotor place):

$$r_0 = R \sqrt{\frac{1-a}{1-2a}} \quad (2)$$

$$a = \frac{v_0 - u}{v_0}$$

In Eq (1), α is the wake spreading coefficient and it is determined by the surface roughness length (z_0) and wind turbine hub height (H) (Frandsen, 1992):

$$\alpha = \frac{0.5}{\ln\left(\frac{H}{z_0}\right)} \quad (3)$$

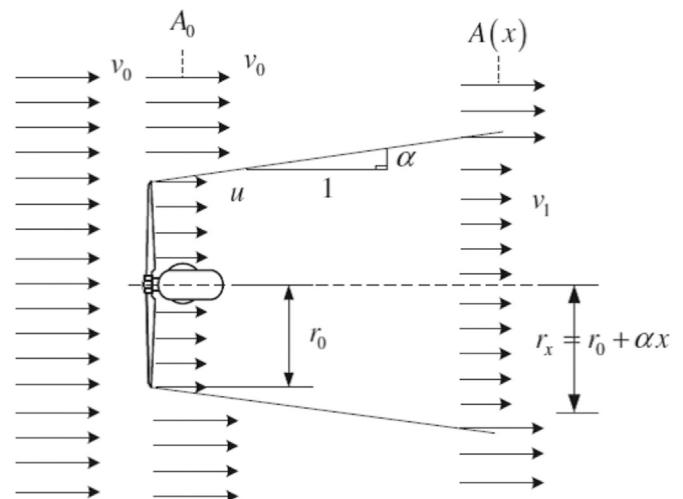


Fig. 1. Diagram of PARK wake model (replicated from (Engineering Model, 2014)).

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