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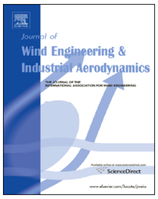

The iteration method for tower height matching in wind farm design

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ABSTRACT

This paper studies the tower height matching problem in wind turbine positioning optimization. Various models are introduced, including the power law wind speed model with height in the wind farm, the linear wake flow model for flat terrain, the particle wake flow model for complex terrain and the power curve model with power control mechanisms. The greedy algorithm is employed to solve the wind turbine positioning optimization at a specified tower height. The optimization objective is to maximize the Turbine-Site Matching Index (TSMI), which includes both the production and the cost of wind farm. Assuming that the optimized layout for each tower height is the same, an iteration method is developed to obtain the approximated optimal height. The convergence of the proposed iteration method is discussed through the mathematical analysis. The proposed iteration method is validated through the numerical cases over both flat terrain and complex terrain. The results indicate that the proposed method can obtain better optimized height in shorter computational time than previous studies.

1. Introduction

Nowadays, energy shortage problem has become one of the serious problems all over the world. In order to mitigate this problem, people start to pay attention to all kinds of renewable energy resources, including solar energy, geothermal, biomass, tide and wind energy. Among these renewable energies, wind energy is an important alternative energy due to the advantages of clean and rich resources (Chen and Zhang, 2007). In China, there are a large amount of wind energy resources. The potential wind power at 10 m height on the land and on the sea are 253 GW and 750 GW, respectively (Tong and Dong, 2012). In the past decade years, wind energy is developing rapidly in China. The total installed capacity of wind turbines reached 75.3 GW up to 2012, which was the largest in the world (Song, 2012).

Wind energy is extracted by wind turbine in wind farm. The power output of the wind turbine increases as the wind speed increases. Meanwhile, the wind turbine will generate a wake region downstream due to the extraction of the wind power and the disturbance of the wind rotor. In the wake region, the wind speed is reduced and the turbulence is increased. Therefore, the wind turbine positions should be designed to reduce the wake effect and increase the total power output of the wind farm.

Much investigation has been done on wind turbine positioning optimization (WTPO). Researchers introduced many optimization algorithms to solve the problem. Genetic algorithm was the first algorithm introduced to solve WTPO by Mosetti et al. (1994). This algorithm simulates the biological evolution process. Bases on the population, the algorithm searches the optimized solution through the selection, crossover and mutation operators. In Mosetti's study, binary coding method was used combined with the linear wake model and 3-order power curve model. The target was to maximize the production per unit cost. The effectiveness of genetic algorithm on WTPO was validated by three numerical cases. Based on Mosetti's study, others have used larger population and more generations (Grady et al., 2005), and more realistic models (Mora et al., 2007; Kusiak and Song, 2010) to improve the optimized results. Wan et al. (2009) used real coding genetic algorithm to optimize the wind turbine positions with the target of maximizing the total power output with the number of wind turbines fixed, obtaining better results than the ones by binary coding genetic algorithm. Another type of optimization algorithms used in WTPO is greedy algorithm. Greedy algorithm is based on a single turbine layout and the turbines are placed in the positions one by one that make the objective value maximum in each step. Compared to genetic algorithm, greedy algorithm requires less computation and the optimized result does not have randomness. Ozturk and Norman (2004) combined greedy algorithm with the adding, removing and moving operators to optimize the wind turbine positioning problem. Based on the submodular property in the optimization problem with linear wake model, Zhang et al. (2011)

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used the lazy algorithm to reduce the computational time of the algorithm. Song et al. (2012) developed a particle wake model that can be used over complex terrain. Based on this particle wake model, the greedy algorithm with repeated adjustment was developed to optimize wind turbine positioning problem over complex terrain (Song et al., 2013). Besides, some other optimization methods were also introduced in WTPO, including simulated annealing method (Rivas et al., 2009), Monte Carlo method (Marmidis et al., 2008) and particle swarm optimization method (Wan et al., 2010).

The wind speed of the wind farm and the cost of the wind turbines will increase with the tower height. Therefore, the tower height of the turbines should match the potential site to achieve maximum power output per unit cost. In the literature, the tower height matching problem has been considered to further improve the turbine layout based on WTPO (Chen et al., 2013a). The Turbine-Site Matching Index (TSMI) was introduced as the objective function, including the production and the cost of the turbine layout. The greedy algorithm with repeat adjustment was introduced to solve WTPO. The optimal height of wind turbine can be obtained through the enumeration method. That is, apply WTPO at each optional tower height. Then the height with the maximum objective value is the optimal tower height. However, it requires a large amount of computational time, especially when the turbine has a large range of optional tower height. In previous study, the fitting method was developed to obtain the optimized height in less computation. When using the fitting method, the normalized power output (L) is defined. The optional height range of the wind turbine is divided into several parts with the same interval and the splitting points are obtained. Then apply WTPO at each splitting point and reproduce the whole L curve using the L values at these points through polynomial fitting. Finally, calculate the extreme points of TSMI using the L curve and obtain the optimized point. The extreme points with the maximum objective value is the optimized height. Three numerical cases were used to test the performance of the fitting method. The results indicated that the fitting method can obtain the approximated optimal height in fewer less times of applying WTPO than the enumeration method (Chen et al., 2013a). However, it needs at least 5-order fitting to obtain the optimized results with the error less than 5% for the multi-direction wind situations. In this paper, the tower height matching for WTPO is studied. Assuming that the optimized layout for each optional tower height is the same, an iteration method is developed to obtain the optimized tower height. The convergence of the iteration method is discussed through the mathematical analysis. The effectiveness of the proposed method is validated by the numerical cases over both flat terrain and complex terrain. The optimized results by three methods are compared for each case, including

- Enumeration method: Apply WTPO at each optional height and take the height with maximum objective value as the optimal one. The result of this method is treated as the optimal result of the tower height matching problem.
- Fitting method: Obtain the optimized height through fitting the L curve, developed in previous study (Chen et al., 2013a).
- Iteration method: Assuming that the optimized layout for each optional tower height is the same, the optimized tower height is obtained by an iteration process, developed in present study.

The remainder of the paper is organized as follows. Section 2 presents the models introduced in WTPO. Section 3 introduces the optimization methodology. Section 4 presents the iteration method for tower height matching problem. Section 5 discusses the numerical results of the test cases. Section 6 presents the conclusions.

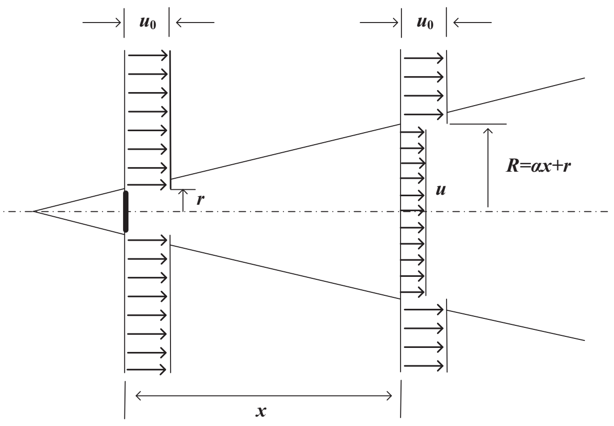

Fig. 1. Schematic of linear wake model (Chen et al., 2013a).

2. Models

2.1. Linear wake model

In this paper, the linear wake model used in the study of Mosetti et al. (1994) is employed to calculate the wind turbine wake effect for the wind farm on flat terrain. The wake model is considered to be a conical area, as shown in Fig. 1. The velocity inside the wake region is calculated by the following algebraic expression:

$$u = u_0\left[1-\frac{2a}{\left(1+\alpha\frac{x}{r_1}\right)^2}\right] \quad (1)$$

where u_0 is the local wind speed without placing the turbine, x is the distance downstream the turbine rotor, r_1 is the downstream rotor radius, a is the axial induction factor and α is the entrainment constant, which are expressed as follows:

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

$$r_1 = r\sqrt{\frac{1-a}{1-2a}} \quad (3)$$

$$\alpha = \frac{0.5}{\ln(h/z_0)} \quad (4)$$

where C_T is the trust coefficient, r is the radius of the wind rotor, h is the tower height of the wind turbine, and z_0 is the surface roughness.

The size of the wake region is described by the wake influenced radius R, which is the radius of the wake region at a specified section in the crosswind direction, expressed as

$$R = \alpha x + r \quad (5)$$

Considering multiple wake interference effect, the velocity of the ith turbine is calculated by Gonzalez et al. (2010)

$$u_i = u_{0i}\left(1-\sqrt{\sum_{j=1}^{N}\left[\frac{A_{ij}}{\pi r_i^2}\left(1-\frac{u_{ij}}{u_{0j}}\right)^2\right]}\right) \quad (6)$$

where u_{0i} and u_{0j} are the local velocities at the ith and the jth turbines' positions without placing the turbines. They are equal to the inlet speed of wind farm over flat terrain. u_{ij} is the wind speed at the wind rotor of $i$the turbine in the wake region of the jth turbine, N is the number of wind turbines, r_i is the rotor radius of