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Wind turbine layout optimization with multiple hub height wind turbines using greedy algorithm

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ABSTRACT

Wind turbine layout optimization in wind farm is one of the most important technologies to increase the wind power utilization. This paper studies the wind turbine layout optimization with multiple hub heights wind turbines using greedy algorithm. The linear wake model and the particle wake model are used for wake flow calculation over flat terrain and complex terrain, respectively. Three-dimensional greedy algorithm is developed to optimize wind turbine layout with multiple hub heights for minimizing cost per unit power output. The numerical cases over flat terrain and complex terrain are used to validate the effectiveness of the proposed greedy algorithm for the optimization problem. The results reveal that it incurs lower computational costs to obtain better optimized results using the proposed greedy algorithm than the one using genetic algorithm. Compared to the layout with identical hub height wind turbines, the one with multiple hub height wind turbines can increase the total power output and decrease the cost per unit power output remarkably, especially for the wind farm over complex terrain. It is suggested that three-dimensional greedy algorithm is an effective method for more benefits of using wind turbines with multiple hub heights in wind farm design.

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1. Introduction

In recent decades, traditional fossil fuel shortage and the serious environmental pollution raise much public concerns. As one of the effective ways to mitigate these problems, renewable energy has been taken worldwide attention. Among various kinds of renewable energies, wind energy is one of the most important ones as it is clean to environment, and rich in resources. In China, wind energy utilization develops rapidly in recent years. The total installed capacity of wind turbines is 318.1 GW all over the world up to 2013, while in China it has reached 91.4 GW, accounting for 29% of the total.

Wind energy is usually extracted and converted into electricity by wind turbine in wind farm. The power output of wind turbine is usually determined by the local wind speed. Large wind speed usually generates large power output, so local wind speed is desirable for maximum. However, due to the extraction of wind power and the disturbance of the wind rotor, there generates a speed decay region called wake region after wind turbine. The power output of one turbine will reduce when the turbine is inside the wake regions of other turbines. Therefore, the positions of the wind turbines should be arranged carefully to reduce the wake decay effect and increase the total wind power output of wind farm for more benefits. This procedure is called wind turbine layout optimization.

Wind turbine layout optimization is a critical topic in wind energy utilization research. Much research has been done on wind turbine layout optimization problem and some optimization methods have been developed. Genetic algorithm (GA) is one of the most popular optimization methods, which was first introduced in wind turbine layout optimization by Mosetti et al. [1] in 1994. GA is based on the mechanics of genetic and evolutionary. Wind turbine layouts are changed into chromosomes, and genetic operators including crossover, mutation and selection are implemented to

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search better solution when performing GA. In Mosetti's study, binary coding GA was employed and the wind speed deficit effect was calculated by linear wake model for wind farm design over flat terrain. After optimization with the objective of minimizing cost per unit power output, both the best number of wind turbines and the optimized layout were obtained. Later, some researchers improved the optimized results of GA through adopting better coding methods [2–4], introducing more realistic models [5–10], using various shapes of grid cells [11,12] and exchanging some individuals among multiple small sub-populations [13]. Greedy algorithm is another popular optimization method for wind turbine layout optimization. Greedy algorithm starts from an empty turbine layout and the turbines are placed into wind farm one by one. At each step, greedy algorithm chooses the position with the best objective value for this step to place the wind turbine. Compared to GA, greedy algorithm operates on a single layout and incurs lower computational costs. Ozturk and Norman [14] combined greedy algorithm with the adding, removing and moving operators to improve the optimized results. Zhang et al. [15] found that the wind turbine layout problem had the “submodular” property. Based on this property, the lazy algorithm was developed to reduce much computational costs when performing greedy algorithm. Chen et al. [16] developed the incremental calculation method, revealing the property that the wake flows of the original turbines did not need to be calculated again when adding a turbine into the wind farm. This method was combined with greedy algorithm, saving much computational time. Later Chen et al. [17] studied the tower height matching in wind turbine positioning problem. In the study, the wind turbines with identical tower height was considered. The height was optimized to maximize the power output per unit cost. A fitting method was developed to obtain the best height, which can save much computation compared to the enumeration method. The results showed that the objective value can be improved significantly through choosing appropriate tower height of wind turbines. In further study, an iteration method was developed to obtain the best tower height in shorter computational time for the problem [18]. Besides, more heuristic optimization approaches are introduced to solve wind turbine layout design problem, including Monte Carlo simulation [19], simulated annealing algorithm [20], particle swarm optimization [21], extended pattern search [22], ant colony algorithm [23], particle filtering approach [24], random search algorithm [25], sequential convex programming [26], and the hybrid algorithms [27,28].

In the above studies, the wind turbines considered were with identical hub height. Some scholars found that the total power output of the wind farm can be further increased through using wind turbines with multiple hub heights. Herbert-Acero et al. [29] investigated the situation that the turbines with two different hub heights were placed in a straight line. The results indicated that more power output can be extracted through using wind turbines with different hub heights. Mora et al. [30] treated the hub height of wind turbine as a variable in the coding of GA, which can be used to optimize the wind turbine layout problem with multiple hub heights. Chowdhury et al. [31] optimized the placement and the selection of wind turbines using an advanced mixed-discrete particle swarm optimization algorithm. The results showed that the normalized power output of the wind farm can be increased dramatically through using various types of wind turbines. Chen et al. [32] used the GA that contained two stages to optimize wind turbine layout with multiple hub heights. The positions of the wind turbines were determined through the first stage GA and the hub heights of the wind turbines were optimized using the second stage GA. However, in the existing studies, the linear wake model was employed and only flat terrain was considered. Furthermore, the optimization of hub height increased the number of optimization variables remarkably and high computational costs were needed.

In this paper, the wind turbine layout optimization with multiple hub height wind turbines is studied. Greedy algorithm is combined with three-dimensional grid system for the optimization problem. The problems over flat terrain and complex terrain are considered and optimized, respectively. The wake flow over flat terrain is calculated by linear wake model and the one over complex terrain is calculated by particle wake model. The effectiveness of greedy algorithm for wind turbine layout optimization with multiple hub height wind turbines is validated through comparing the results to the existing optimization results by GA. Two numerical cases both over flat terrain and complex terrain are implemented to further discuss the benefit of using multiple hub height wind turbines in wind farm.

The remaining parts of the paper are organized as follows. Section 2 presents the mathematical models used in the wind turbine layout optimization problem. Section 3 introduces the three-dimensional greedy algorithm. Section 4 discusses the numerical results of the test cases. Section 5 presents the conclusions.

2. Mathematical models

2.1. Wind speed profile in wind farm

Normally, wind speed will increase with the height from the ground in wind farm, which is commonly modeled by power law or logarithmic law [33]. In this paper, the logarithmic law is used, shown as

$$u = u_{\mathrm{ref}} \log(h/z_0)/\log\left(h_{\mathrm{ref}}/z_0\right) \tag{1}$$

where u_{ref} is the wind speed at the reference height h_{ref}, named the reference wind speed. z_0 is the ground roughness. As the wind speed increases with the height, the wind turbine with higher hub height can usually operate at larger power output.

2.2. Linear wake model

Wake effect is a critical factor that influences the wind resource distribution in wind farm, which should be considered for more accurate evaluation of the total power output. Computational Fluid Dynamics (CFD) is one of the most accurate methods for wind turbine wake flow calculation [34]. CFD method obtains the detail wake flow information of wind turbine through solving the governing equations of the air flow numerically. However, fine grids are needed to guarantee the calculation accuracy and the total calculation of CFD method is quite large. As wind turbine layout is altered during wind turbine layout optimization process, the wind turbine wake flow calculation needs to be implemented for hundreds of thousands of times, costing unacceptable computational time. Thus, CFD method is not efficient for wake flow calculation in wind turbine layout optimization. In order to reduce the computational time, some simplified wake models are developed. Among all the wake models, the linear wake model is the most popular one for wind turbine layout optimization over flat terrain. The linear wake model was developed by Jensen [35] in 1983. The wind speed inside the wake region was calculated by algebraic expression in this model. Later other researchers developed similar linear wake models and combined them with different optimization methods for wind turbine layout optimization [1,32,36]. In the present study, the linear wake model used by Chen et al. [32] is introduced for wake flow calculation over flat terrain. Ignoring the turbulent intensity of the near wake flow caused by the rotor blade, the shape of the wake region in the linear wake model can be simplified as a

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