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Optimization of wind farm micro-siting for complex terrain using greedy algorithm

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ABSTRACT

An optimization approach based on greedy algorithm for optimization of wind farm micro-siting is presented. The key of optimizing wind farm micro-siting is the fast and accurate evaluation of the wake flow interactions of wind turbines. The virtual particle model is employed for wake flow simulation of wind turbines, which makes the present method applicable for non-uniform flow fields on complex terrains. In previous bionic optimization method, within each step of the optimization process, only the power output of the turbine that is being located or relocated is considered. To aim at the overall power output of the wind farm comprehensively, a dependent region technique is introduced to improve the estimation of power output during the optimization procedure. With the technique, the wake flow influences can be reduced more efficiently during the optimization procedure. During the optimization process, the turbine that is being added will avoid being affected other turbines, and avoid affecting other turbine in the meantime. The results from the numerical calculations demonstrate that the present method is effective for wind farm micro-siting on complex terrain, and it produces better solutions in less time than the previous bionic method.

1. Introduction

As the fossil energies are nearly depleted nowadays, great attentions have been increasingly concentrated on developing renewable energies. Wind energy is one of the fastest developing clean and renewable energies. The World Wind Energy Association reported that the worldwide wind power capacity has reached 296 GW by the end of June 2013. The main difficulties in utilizing wind energy are its spatial non-uniformity and temporal instability. Two significant factors that cause the spatial non-uniformity is the terrain topography and the wake flow of wind turbines. In a wind farm, wind turbines generate wake flow regions where wind speed decreases. The wake flow influences the downstream turbines, reducing their power output and the efficiency of the wind farm. And the influences of terrain topography makes the problem even more complicated. Many efforts have been paid previously on developing methods to accurately assess wind resources. For flat terrain, the logarithmic velocity profile [1], Weibull distribution and statistical models [2] are effective. For terrains with larger slopes, physical models such as computational fluid dynamics (CFD) [3] are more suitable for the evaluation and optimization. As for its temporal instability, many studies have been conducted about the prediction and forecast technologies of wind velocity and power output of wind farm. Statistical methods for wind speed prediction include the measure-correlation-prediction (MCP) method [4], the ARMA algorithm [5], the Gaussian process regression approach [6], etc. Similarly, for complex terrain scenarios, physical models or combined models [5] are essential for reliability. This paper concentrates on discuss the wind turbine positioning problem, which is related to the spatial non-uniformity. The aim of optimizing wind farm micro-siting is to optimize the layout of turbines to reduce wake flow influences, and to increase overall energy yield of the wind farm.

Many optimization approaches have been introduced to the wind farm micro-siting problem, including the binary-coding [7] and real-coding [8] genetic algorithm, particle swarm optimization [9,10], Monte Carlo method [11], greedy algorithm [12], simulated annealing [13], lazy greedy algorithm [14], etc. But in most of these studies, the linear model is employed to simulate turbine wake flow, which is first proposed by Jensen [15,16]. The linear model is a simplified model that is valid only on flat terrain. On complex terrain where airflow is complicated, the linear model is unable to describe the deformation of wake flow affected areas.

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In order to perform turbine layout optimization on complex terrain, it is necessary to simulate the influences of wake flow interactions of wind turbines. The effectiveness of CFD method to aid the wind farm micro-siting has been demonstrated in many previous studies [17,18]. Although CFD calculations solve the related problems very accurately as reported in many previous literature [19–21], it takes much computation time even when calculating the flow field around one single wind turbine. The quantity of computation is not acceptable for engineering application of the wind farm optimization cases, where multiple wind turbines with various possible layouts should be evaluated separately. Therefore, the virtual particle model is introduced for turbine wake flow simulation. The virtual particle model is presented in the previous study [22]. The model simulates wake flow as if it is composed by multiple particles, which move convectively and diffusively according to the pre-calculated flow field. The virtual particle model describes the characteristics of wake flow more accurately and realistically than the linear model, especially for non-uniform flow fields, and it takes much less computation time than detailed numerical calculation using fluid mechanics.

In this paper, the virtual particle model is employed, and the greedy algorithm is used for optimization of turbine layout. The greedy algorithm implements the short-sighted strategy. In each step, it adds a turbine to the position that will bring maximum power increment to the wind farm. The newly added turbine shall avoid other turbines' wake flow, and in the meantime, avoid influencing existing turbines. In the previous study of bionic optimization method [18], only the former avoiding rule is considered. In the present study, a *dependent region* technique is presented to find the best position for the new turbine in each optimization step quickly, with the consideration of both avoiding rules. The algorithms and steps are presented in the following sections. The numerical results demonstrate that the present method is effective for turbine layout optimization on complex terrain, and is much faster than the previous bionic method.

2. Wake flow model

The virtual particle model is employed for wake flow simulation on complex terrain. The flow field with no turbines should be pre-calculated using computational fluid dynamics. Based on the pre-calculated flow field, the virtual particle model simulates the turbine wake flow and superimposes the wake flow effect to the pre-calculated flow field. During the simulation, the wake flow is treated as a kind of virtual matter that develops according to the pre-calculated flow field. The convective and diffusive behaviors of the virtual matter are simulated using particle tracking. The concentration of the virtual matter is transformed into the velocity decrement caused by wake flow, which is then added to the pre-calculated flow field, obtaining the wake influenced flow field. The detailed steps of applying the particle model to complex terrain are stated below.

The pre-calculated flow field is the flow field that is only influenced by the terrain topography, but not by the turbines. For a certain terrain, the pre-calculated flow field can be calculated using the models of Computational Fluid Dynamics (CFD). The flow field contains information about the non-uniformly distributed wind speed and direction in the three-dimensional domain of the wind farm. For a specified turbine layout, the wake flow is treated as multiple convective and diffusive virtual particles.

During the simulation process of the wake flow, the virtual particles are continually released within the area of each turbine rotor. The releasing rate is denoted as p, which stands for the number of particles generated in unit area and unit time span. In each simulated time step, the motion of each particle is calculated by adding the convective and diffusive displacements to its coordinate:

$$\Delta x = u\Delta t + \sigma\sqrt{-2\Delta t \log R_1}\cos 2\pi R_2 \tag{1}$$

where u is the local velocity at the position of the particle, R_1 and R_2 are two independent random numbers of uniform distribution in [0,1), σ is the diffusive coefficient which is suggested to be 0.3 in the previous study [22]. The first term on the right is the convective displacement. The local velocity u can be calculated by interpolating the pre-calculated flow field in each step. The second term on the right is the diffusive displacement, which is a Gaussian random number generator suggested by Box et al. [23].

At the hub of each turbine, a cubic area is defined to count the particles that pass through the turbine rotor. The side length of the cubic area is equal to the diameter of the turbine rotor. The averaged number of particles inside the cube (denoted by n) represents the intensity of wake flow influence. The number of particles is normalized to be the relative concentration by:

$$c = \frac{nu_0}{p} \tag{2}$$

where u_0 is the local velocity at the hub of the turbine, p is the rate of particle releasing. The relative concentration is then transformed into the velocity decrement. The wake influenced velocity is calculated by:

$$u' = u(1 - \beta c) \tag{3}$$

where u is the velocity in the pre-calculated flow field, β is a constant which is suggested to be 0.65 in the previous study.

Within a wind farm, the power output of the ith turbine is approximately calculated using the following function [7]:

$$F(u_i') = 0.3(u_i')^3 \tag{4}$$

where u_i' is the wake influenced velocity at the hub of the ith turbine, calculated by the virtual particle model. The total power output of the wind farm is calculated by:

$$P = \sum_{i=1}^{N} F(u_i') = \sum_{i=1}^{N} 0.3(u_i')^3 \tag{5}$$

3. Optimization algorithm

3.1. Greedy algorithm

The optimization problem studied in this paper is as follows: A fixed number of turbines are to be sited within a rectangular area with complex terrain. The characteristics of the incoming wind are specified, and the target of optimization is to maximize the total power output. The greedy algorithm is employed to determine the optimal positions for the turbines. The core concept of greedy algorithm is to perform a short-sighted action in each step. It starts from an empty wind farm with its pre-calculated flow field. In each step, a new turbine is added at the position which provides maximum increment to the total power output. The adding step is repeated until the specified limit of turbine number is reached. The detailed steps of the optimization process are listed as follows:

1. Calculate the pre-calculated flow field using CFD method, according to the terrain geometry and wind characteristics.