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Optimization of wind turbine micro-siting for reducing the sensitivity of power generation to wind direction

Mengxuan Song [a], Kai Chen [b], Xing Zhang [c], Jun Wang [a, *]

[a] Department of Control Science and Engineering, Tongji University, Shanghai 201804, PR China
[b] Key Laboratory of Enhanced Heat Transfer and Energy Conservation of the Ministry of Education, School of Chemistry and Chemical Engineering, South China University of Technology, Guangzhou 510640, Guangdong, PR China
[c] Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, PR China

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ABSTRACT

In the optimization of wind turbine micro-siting of wind farms, the major target is to maximize the total energy yield. But considering from the aspect of the power grid, the sensitivity of wind power generation to varying incoming wind direction is also an essential factor. However, most existing optimization approaches on wind turbine micro-siting are focused on increasing the total power yield only. In this paper, by employing computational fluid dynamics and the virtual particle model for the simulation of turbine wake flow, a sensitivity index is proposed to quantitatively evaluate the variation of power generation under varying wind direction. Typical turbine layouts obtained by existing power optimization approaches are evaluated for stability. Results indicate that regularly arranged turbine layouts are not suitable for stable power production. Based on solutions from the power optimization, a second-stage optimization using Particle Swarm Optimization algorithm is presented. The proposed optimization method adjusts the positions of the turbines locally, aiming at increasing the stability of wind farm power generation without damaging its advantage of high power yield. Case studies on flat terrain and complex terrain both demonstrate the effectiveness of the present local adjustment optimization method.

1. Introduction

Among all the renewable energy sources, wind energy is the one with the most mature technologies of utilization. As the traditional energies are gradually depleted and the environmental problems are becoming urgent, increasing attention has been paid to wind energy in recent years. To utilize wind energy efficiently, it is essential to optimize the wind turbine positioning on a wind farm by reducing the wake flow effect. Several optimization approaches have been studied for generating optimized layouts of wind turbines, including binary-coded genetic algorithm (GA) with Cartesian mesh [1,2], binary-coded GA with triangular mesh [3], real-coded GA [4], particle swarm optimization (PSO) [5,6], Monte Carlo method [7], greedy algorithm [8,9], lazy greedy algorithm [10,11] and bionic method [12]. The target of these optimization methods is either to maximize annual energy yield or to minimize the cost of a wind farm to its energy yield. However, the annual energy yield consists of a sum of factors which concern the total quantity of energy production only. It ignores the power generation performance due to the varying wind conditions. Especially on complex terrain, because of the nonlinearity of the flow field, power output of wind farm may change drastically even when the incoming wind direction varies slightly. Ali et al. [13] studied the performance of power output of wind farms when the wind direction is changing. It is noticed that for the least stable case, power output drops rapidly from 13.0 MW to 7.3 MW when wind direction changes within 10°. González-Longatt et al. [14] studied the steady-state and dynamic behavior of turbine wake flow in wind farms. They also discovered the non-negligible differences of wake flow influences for different inlet angles of wind. However, the existing optimization approaches are unable to consider the stability of power generation. The sensitivity of power output of wind farms to incoming wind direction should be accounted for during the process of wind farm micro-siting in order to achieve a more stabilized

* Corresponding author.
E-mail address: junwang@tongji.edu.cn (J. Wang).

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power generation.

In this paper, the overall power generation performance of the wind farm is studied through evaluations and analyses of several cases on both flat and complex terrains. Computational fluid dynamics and the virtual particle model [15,16] for the wake flow simulation are employed to calculate the power output for a specified wind turbine layout under a certain incoming wind condition. Results indicate that, although turbine layouts optimized by existing power optimization approaches have high average power outputs under the condition of multiple wind directions, they may perform poorly on stability when wind direction is varying, especially for those with regularly arranged turbines. A second-stage optimization is then proposed in this paper. By conducting a local adjustment process optimized by PSO, solutions from existing power optimization approaches can be significantly improved. Sensitivity of power output to wind directions can be greatly reduced, and in the meantime, the average power generation hardly drops.

2. Numerical methods

2.1. Computational fluid dynamics

Solving the state of airflow above the terrain is a problem of fluid dynamics with high Reynolds Number and low Mach Number. The Reynolds Averaged Navier–Stokes equations of incompressible flow are used as the governing equations. The following equations are conservation equations for mass, momentum component, turbulent kinetic energy and turbulence dissipation rate, respectively.

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu_t \frac{\partial u_i}{\partial x_j}\right) \tag{2}$$

$$\rho u_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\mathrm{Pr}_k}\frac{\partial k}{\partial x_j}\right) + \frac{\mu_t}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)^2 - \rho\varepsilon \tag{3}$$

$$\rho u_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\mathrm{Pr}_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right) + C_1\frac{\mu_t}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)^2\frac{\varepsilon}{k} - C_2\rho\frac{\varepsilon^2}{k} \tag{4}$$

where u_i and u_j are velocity components, x_i and x_j are coordinates, ρ is the density of air, p is pressure, k is turbulent kinetic energy, ε is turbulence dissipation rate. μ_t is turbulent viscosity, which is calculated by

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{5}$$

According to Palma et al. [17], the values of the constants are chosen as: $C_1 = 1.44$, $C_2 = 1.92$, $\mathrm{Pr}_k = 1.0$, $\mathrm{Pr}_\varepsilon = 1.85$, $C_\mu = 0.033$.

The terrain following grid system is employed to discretize the 3D domain, and the governing partial derivative equations are solved numerically on the discretized domain. Fig. 1 shows an example of the grid system. The terrain altitudes are generated using the diamond-square algorithm [18]. The outer edges of the terrain surface are expanded to flat horizons in order to maintain flux conservation for inlet and outlet. Boundary conditions on the outer edges of the expanded flat horizons are specified according to the commonly used logarithmic profile of atmospheric boundary layer [19]:

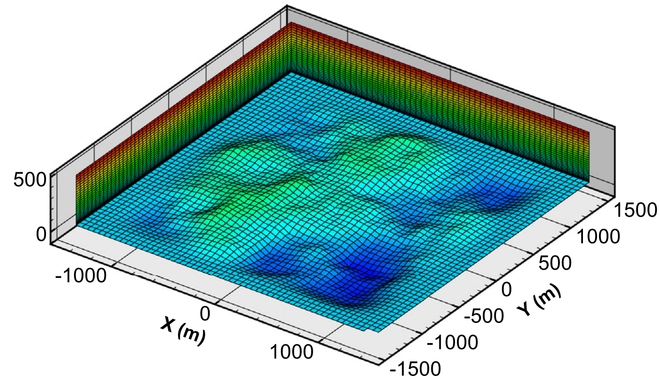

Fig. 1. Terrain following mesh of the calculation domain above complex terrain.

$$u(z) = \begin{cases} u_r \dfrac{\ln(z/z_0)}{\ln(z_r/z_0)}\cos\theta, & z \geq z_0 \\ 0, & z < z_0 \end{cases} \quad v(z) = \begin{cases} u_r \dfrac{\ln(z/z_0)}{\ln(z_r/z_0)}\sin\theta, & z \geq z_0 \\ 0, & z < z_0 \end{cases} \quad w(z) = 0 \tag{6}$$

where z_r is the reference height to the ground, u_r is the reference velocity, z_0 is roughness length, which is 0.3 m in the present study, and θ is the direction of the incoming wind. Grids near the ground are concentrated in the vertical direction in order to increase the spatial accuracy near the surface. The boundary condition for the ground surface is specified using the high Reynolds Number approximation [20]. Velocity and turbulent kinetic energy near the wall are:

$$u_{\mathrm{wall}} = v_{\mathrm{wall}} = w_{\mathrm{wall}} = 0, \quad \frac{\partial k}{\partial \mathbf{n}}\Big|_{\mathrm{wall}} = 0 \tag{7}$$

For the grid nodes adjacent to the ground surface, turbulent viscosity is calculated by Ref. [21]:

$$\mu_t = \frac{y^+}{u^+}\mu, \quad y^+ = \frac{yC_\mu^{1/4}k^{1/2}}{\mu/\rho}, \quad u^+ = \frac{uC_\mu^{1/4}k^{1/2}}{\tau_{\mathrm{wall}}/\rho} \tag{8}$$

if the node is outside the viscous sublayer, where y is the distance from the grid node to the ground surface. Turbulent energy dissipation rate is calculated by Ref. [22]:

$$\varepsilon = \frac{C_\mu^{3/4}k^{3/2}}{\kappa y} \tag{9}$$

where κ is the von Karman constant whose value is chosen to be 0.41 in the present study. The terrain and mesh in this figure will be used in the calculation and discussion for complex terrain scenario in this paper.

2.2. Virtual particle model for turbine wake flow

The calculation of wake flow of wind turbines is critical to the assessment of wind farm power yield. For near wake region, solving the full 3D Navier–Stokes equations with locally refined grids is one of the most accurate numerical ways to simulate wake flow characteristics. However it requires large quantity of computer memory and calculation time, it is not suitable when applied to wind farm optimizations [23]. Some simplified analytical models, such as the ones proposed by Katic et al. [24] and Larsen [25], have