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The decision model of 3-dimensional wind farm layout design

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ABSTRACT

This research investigates the maximization of the expected wind farm power output through optimizing the layout of wind turbines as well as their heights. A model for determining the wind farm layout in 3-dimensional (3-d) space is introduced. The objective of the layout design is to maximize the expected wind farm power output. To estimate the wind deficit in 3-d space, a linear 3-d wake loss model is developed and a criterion for identifying wakes affecting on a targeted wind turbine is constructed. The proposed model is complex and, therefore, solved by an evolutionary strategy algorithm. A comparative analysis of the proposed model and a benchmark model is conducted. In the computational study, the design solution offered by the proposed model indicates that the expected wind farm power output could be increased by choosing wind turbines with different heights.

1. Introduction

In a wind farm, wind turbines not only generate energy but also induce wakes behind their swept areas. The wakes will diminish the power generation performance of downstream wind turbines. Due to the wake effect, the layout of a wind farm physically limits the upper boundary of its power generation potential. The research of the wind farm layout design aims to mitigate and even avoid the wake loss through the optimal distribution of wind turbines. The significance of studying wind farm layout is clear as the layout planning impacts the performance of a wind power plant throughout its life-cycle.

The existing studies of the wind farm layout design were mainly conducted based on a 2-dimensional plane [1]. Two systems, the grid system and coordinate system, were utilized to describe a wind farm. The general objective of a wind farm layout design is to maximize the expected wind power output, which is equivalent to the minimization of the wake loss. The grid system modeled a potential wind farm as a grid and each cell of the grid represented a potential location for placing a wind turbine. Based on such setting, the wind farm layout design problem was formulated as a combinatorial optimization model and the genetic algorithm was frequently considered as the solution algorithm. Mosetti et al. [2] modeled the wind farm layout design problem based on a grid system and applied a genetic algorithm to maximize the energy production while minimize the cost. Grady et al. [3] studied placement of wind turbines based on the grid system layout design model and solved it with a genetic algorithm for different wind scenarios. Castro Mora et al. [4] detailed discussed the application of a genetic algorithm in solving the grid system wind farm layout design model in detail. Yet, the wake effect was not sufficiently considered. Chen and MacDonald [5] applied the grid based wind farm layout design model to investigate impacts from landowner participations in the wind farm construction. The grid system based wind farm layout design model has a simple but explicit structure. However, it is highly abstract and lack of flexibility so that the potential of further optimizing the wind farm power generation is limited. For example, the location of wind turbines is restricted to the center of cells. Although Du Pont and Cagan [6] proposed an extended pattern search approach to allow more flexible wind turbine location in cells, extra complexity was added into the grid system based model.

Modeling a wind farm with coordinate system was firstly proposed by Kusiak and Song [7]. In this study, a wind farm was described by a 2-dimensional [2-d] coordinate system with a circular shape and any coordinates within the circular boundary was considered as a potential location for placing a wind turbine.

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Nomenclature

A	the apex of the cone
c	the scale parameter of a Weibull distribution
d	the distance of two positions
E	the optimal value of the objective function
F	the objective in the optimization of the wind farm layout
g	the number of implemented generations
G	the maximal number of generations
h	the height of a wind turbine tower
h_{ref}	the reference elevation
$\mathbf{I}$	the individual in the evolutionary strategy
J	a set of wind turbines whose wakes affecting a target wind turbine
k	the shape parameter of a Weibull distribution
L	the length of a vector
L	a set of feasible 3-d Cartesian coordinates for locating a number of wind turbines
m	the number of parents selected for producing an offspring
M_i	the size of parent set if i = P, the size of offspring set if i = O, and the size of elite set if i = E
N	the number of wind turbines installed in a wind farm
N_v	the total number of intervals with equal width in the discretization of wind speed
N_θ	the total number of intervals with equal width in the discretization of wind direction
O	the origin of a 3-d space
P	the wind turbine power output
P_r	the rated power of a wind turbine
r	the radius of a round wind farm site
R	the radius of a wind turbine rotor
$\mathbf{s}$	the set of parents selected for producing the offspring
$\mathbf{S}_i$	the parent set if i = P, the offspring set if i = O, and the elite set if i = E
$\mathbf{T}$	a set of 3-d Cartesian coordinates of installed wind turbines, $\mathbf{T} = \{T_1, T_2, \ldots, T_N\}$ and $\mathbf{T} \in \mathbf{L}$
T_i	the 3-d Cartesian coordinate, $T_i = (x_i, y_i, z_i)$, describing the position and height of the i-th installed wind turbine
v	the wind speed of a wind farm
v_{ci}	the cut-in wind speed
v_{co}	the cut-out wind speed
v_r	the rated wind speed
v_{ref}	the wind speed at the reference elevation
v_d	the downstream wind speed
v_u	the upstream wind speed
α	the angle between the axis of a cone and any lines on the conical surface
β	the angle between two vectors, $\overrightarrow{AT_i}$ and $\overrightarrow{AT_j}$
δ	the deficit of wind speed
ζ	the friction coefficient
η	the interception of a linear function
θ	the wind direction of a wind farm
λ	the slope of a linear function
κ	the parameter for estimating δ, which is assumed as constant in this study
ξ_{l-1}	the probability mass function of $(\theta_{l-1} + \theta_l)/2$, where $l = 1, 2, \ldots, N_\theta$
ρ	the ratio between the number of wind turbines with higher tower heights and the total number of wind turbines
$\boldsymbol{\sigma}$	the mutation indicator in the evolutionary strategy
$\boldsymbol{\Sigma}$	the set of $\boldsymbol{\sigma}$
φ	the ratio between the reduced tower height and the standard tower height
$c(\cdot)$	a continuous function of determining c based on a wind direction θ
$f(\cdot)$	the linear power curve model
$g_v(\cdot)$	the probability density function (PDF) of the wind speed
$g_\theta(\cdot)$	the probability density function (PDF) of the wind direction
$k(\cdot)$	a continuous function of determining k based on a wind direction θ
$\mathrm{N}(0,\tau')$	a random number generated from a normal distribution with mean 0 and standard deviation τ'
$\mathrm{N}(0,\tau)$	a random number generated from a normal distribution with mean 0 and standard deviation τ
$\mathrm{N}(\mathbf{0},\boldsymbol{\sigma}^k)$	a vector of random numbers generated from a normal distribution with mean 0 and standard deviation $\boldsymbol{\sigma}^k$
$p_v(\cdot)$	the probability density function of a Weibull wind speed distribution
$p_\theta(\cdot)$	the probability density function of the wind direction distribution
$B(\cdot)$	the model for estimating β.
$E(\cdot)$	the expectation of a parameter
$\Gamma(\cdot)$	the gamma function
$\mathrm{int}(\cdot)$	the function returns an integer value

Moreover, a general wake loss model for estimating wind deficit at a wind turbine was proposed. The whole problem was then described as a nonlinear constrained optimization problem and solved by the evolutionary algorithm. Extended studies of planning wind farm layout with coordinate systems have also been widely reported. Benzo and Ramos [8] proposed a stochastic optimization model for planning the layout of offshore wind farms based on the coordinate system. Eroglu and Seckiner [9] applied the Ant Colony Optimization algorithm to solve the same model in Ref. [7]. Chowdhury et al. [10] unrestricted wind turbine types in the wind farm layout design based on the coordinate system based model. The coordinate system based models allow the flexible distribution of wind turbines and fully consider the wake loss under various wind conditions.

The 2-d wind farm layout design models are helpful to scientifically plan the layout of wind farm and key factors of layout design which influence the maximization of wind farm power generation have been investigated [11]. However, it does not consider the opportunities of using space to further mitigate the wake effect and maximize the wind farm power output. In this research, a general 3-d wind farm layout design model is introduced to perform a comprehensive analysis of the opportunity of further improving the expected wind farm power output through optimizing wind turbine locations and heights. A 3-d Cartesian coordinate system is employed to describe the space of a wind farm site and investigate the impact of the wake effect and wind power profile law in the wind farm power generation performance. An evolutionary strategy algorithm is applied to solve the proposed model. An analysis of the influence of mixing wind turbine heights in the reduction of the wake loss and the improvement of the wind farm power generation is conducted. The computational results demonstrate that an optimal mixture of wind turbines with