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Wind farm layout optimization using area dimensions and definite point selection techniques

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ABSTRACT

Wind turbines are the biggest rotating machines on earth, operating in the lowest part of the earth boundary layer. Designing the layout scheme of wind farms is a challenging job to researchers, as there are many design objectives and constraints due to the multiple wake phenomena. This paper proposes an area rotation method to find the optimum dimensions of the wind farm shape, where maximum area could face the free stream velocity. Afterwards, a novel method called Definite Point Selection (DPS) is developed to place the turbines in order to operate at maximum, while providing obligatory space between adjacent turbines for operation safety. This method can be used to identify the zero wake effect points at wind farm. The result from this study shows that the proposed method is more effective to increase the overall power of a wind farm than the previous methods. Also, the power output of the wind farm by using combined area rotation and DPS methods was increased even when using the same number of wind turbines.

1. Introduction

The wind energy has experienced a remarkable growth from the previous decade. Because of this continuously increasing demand, the use of single wind turbine is converted to the installation of wind farms having large number of wind turbines placed together [1]. The power production from a wind farm is usually proportional to the total number of wind turbines installed. However, the relative position of the turbines has a great influence on the energy yield. This is because of the wake effect, which reduces the wind speed behind the rotor. This greatly decreases the power output of downstream wind turbines. Thus, it is necessary for wind farm developers to fully understand that altering the wind farm layout affects not only wake losses but also the power production of wind farm.

Mosetti et al. [2] were the first who addressed wind farm layout optimization. They used the genetic algorithm (GA) for three different wind scenarios. To enable the encoding of a 0–1 type solution, they divided the wind farm into a square grid for wind turbine installation. Following from Mosetti et al.'s work, Grady et al. [3] engaged 600 individuals and 3000 generations in a genetic algorithm to find out the improved layout of a wind farm. Mittal [4] also employed the GA to propose the micro-siting of wind turbines in order to achieve perfect locations in the wind farm. In his research, the grid size was assumed $1m \times 1m$, which was significantly smaller than $200m \times 200m$ grid used by Refs. [2] and [3]. Compared with the results of [3], Mittal's results showed that the cost per unit power could be reduced by increasing the number of cells in a specific wind farm area. Reference [5] also used GA for optimal layouts; while for optimal line connection, they utilized the Ant Colony System algorithm (ACS). Chen et al. [6] explored the effect of hub height of wind turbine on the power output of the wind farm. The results demonstrated that the overall efficiency of the wind farm was increased.

Besides genetic algorithm, Marmidis et al. [7] utilized Monte Carlo Simulation (MCS) for wind farm layout optimization in the case of constant wind speed and direction. However, the wind turbine arrangement on a specific terrain selection was randomly done using this method. Chowdhury et al. [8] used particle swarm optimization (PSO) and found that the energy yield from the wind farm became greater when the wind turbines had different size of

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rotor diameters. Turner et al. [9] developed Mixed Integer Linear (MIL) and Quadratic Optimization (QO) formulations and applied them to several example layout cases from the literature. However, they considered an additive deficit in the kinetic energy, which lead to underestimating the wake losses.

An important parameter which changes the wind speed, direction and turbulence effect is the landscape while siting the wind turbines at the top of the hills. Different models for hilly areas have been discussed in Refs. [10], such as the bell shaped Gaussian cosine, squared sinusoidal and sinusoidal etc. Han et al. [11] studied the effect of terrain on wind speed and wind direction using Monte Carlo simulation. They proposed a quadratic interpolation method (QIM) to optimize the location of wind turbines corresponding to maximum power output. The reference [12] evaluated the wind farm for maximum power output while considering the terrain effect on the wind direction. They found that the power output of the wind farm increases due to the hilly land within the wind farm in comparison with the flat wind farm. Song et al. [13] was employed the lazy greedy algorithm for optimization in complex terrain field. The reference [14] investigated the impact of complex terrain on the power output of the wind farm and found that the uniform arrangement of wind turbines causes the power output to fluctuate for irregular complex terrain.

A literature review of wind farm layout optimization highlights that most researches in this field focused only the placement of wind turbine within some given boundaries of the wind farm [15]. This field also has very limited amount of research regarding area of wind farms and its impact on the power production. The authors in Ref. [16] concentrated on the optimization of land area per unit power production for wind farm. They also investigated the effect of total number of wind turbines used, their relative distance and influence of setback distance on power production of wind farm; but they did not investigate the effect of area shape of wind farm on its power production.

The maximum power potential with corresponding optimal wind farm layout strongly depends on the specific area dimensions of the farm site. Therefore, the power production from a certain wind farm area dimension will be considerably different from the wind farm with different area dimensions though with identical wind resource and total area. An alteration in the area boundaries can change the overall performance of wind farms; hence it is more beneficial to first get the best area dimension and then to optimize the layout of the wind farm. Such type of two-level optimization can give tremendous increase in the overall efficiency of the wind farm. In the literature to date, two-level optimization is still lacking in wind energy community.

In this paper, a novel mathematical modelling of two-level optimization is proposed to solve the wind turbine layout problem. The rest of this paper is arranged as follows: Section 2 describes the modelling of wind farms and explores the proposed formulation of area dimension and Definite Point Selection (DPS) methods for the wind farm layout problem. Section 3 demonstrates the flow chart and optimization steps taken to get optimized layout for the wind park. Section 4 presents the comparative results for various wind scenarios as to validate the effectiveness of the proposed methods. Section 5 gives the conclusion and recommendations for the directions of future research.

2. Problem formulation and methodology

The modelling of the wind farm layout is based on some assumptions, given as follows. However, these can be easily changed to site conditions.

- The total area of the wind farm is fixed which is equal to $2km \times 2km$ and divided into cells of same size for wind turbine installation.
- All the turbines used are homogeneous, having the same rotor radius, hub height and power curve characteristics. It is also assumed that the turbine nacelle is fully controlled and can move the rotor towards the predicted wind direction.
- The wind turbine location within the farm is characterized by its Cartesian coordinates(x_i, y_i); $\forall i = 1, \ldots\ldots N_T$, (where N_T represents the total number of wind turbines) and are described by the decision vector $x \in \Re_{N_T * 2}$ as follows;

$$x = \begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ \vdots & \vdots \\ x_{N_T} & y_{N_T} \end{bmatrix} \tag{1}$$

- The Probability density function for wind speed 'v' follows a Weibull distribution and is given by

$$p_v(v, k, c) = \frac{k}{c}\left({}^{v}\!/_{c}\right)^{k-1} e^{-\left({}^{v}\!/_{c}\right)^{k}} \tag{2}$$

where c is the scale parameter and k is the shape parameter.

- The process of optimization essentially ensures that all the wind turbines are installed within a specific area in the wind farm, and that the distance between the position of two wind turbines must also be limited to four rotor diameter ($d_{min} = 4D$) for safety reasons. This constraint can be expressed mathematically as follows:

$$\frac{(x_l - x_w)^2 + (y_l - y_w)^2}{4D} \geq 1; \quad \forall l = 1, 2, \ldots. (N_T - 1); \ \forall w > l \tag{3}$$

- The characteristics of the wind farm used in the present research are given in Table 1. The total area of the wind farm and the parameters of wind turbines were same as used in previous studies [2,3,7,9].

Table 1
Parameters and characteristics of the wind farm.

Parameters	Values
WT hub height (m)	60
WT rotor diameter (m)	40
Thrust coefficient	0.88
WT swept area (m^2)	5080
Wind farm area (km^2)	4
Grid size	100
shape parameter 'k'	2
Scale parameter 'c' (${}^{m}\!/_{s}$)	10.2
Length of surface roughness (m)	0.3
Air density (kg/m^2)	1.2253
Entrainment constant α	0.1