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Optimization of wind farm layout with complex land divisions

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ABSTRACT

The study of wind farm layout optimization considering the decisions of land owners has rarely been reported in literature. In this paper, the common situation of complex land divisions (e.g. unequally-spaced plots) is addressed for the first time. A new constraint handling and fitness evaluation technique is developed to address the more complex wind farm boundaries and integrated into two common wind farm optimization approaches: the grid based method and the unrestricted coordinate method. Enable by the new technique, a numerical optimization study is conducted with the goal of evaluating the impact of the participation of land owners on the economic performance of the wind farm. In particular, two scenarios are considered: 1) the varying land plot scenario, where the land plot availability is included in the decision variables of the optimization, and 2) the sequential land plot scenario, where the land plot availability is fixed prior to optimization. The study reveals that the unrestricted coordinate method under the sequential land plot scenario yields the best optimization results, with the smallest cost of energy and the largest wind farm efficiency.

1. Introduction

Due to the depletion of tradition fossil fuels like coal, oil and natural gas, renewable energy sources have recently attracted great attention. Among the different forms of renewable energy including solar power, tidal power, biomass, etc., wind power serves as an attractive alternative energy source, owing to its abundance and cost-competitiveness [1]. Wind power is primarily used for the electricity generation by wind turbines that are typically clustered in a wind farm [2]. After a wind turbine extracts the kinetic energy from the wind, the air speed behind the wind turbine decreases drastically. This reduced velocity zone forms a highly turbulent flow field called the wake region and its recovery to the free stream wind can take dozens of kilometers [3]. Inevitably, some turbines are located in the wakes of others leading to power losses. This is a common issue for wind farm development. Through the optimization of wind farm layout, the power losses due to the wake interaction between turbines can be mitigated and the wind farm power output can be maximized for improved profitability [4,5].

Currently, wind farm layout optimization methods can be categorized into two groups: (i) grid based method, which discretize the wind farm area into uniform grids where each wind turbine can only be placed at the center point of the grid; and (ii) unrestricted coordinate method, which directly employ the Cartesian coordinates to represent the wind turbine locations in the wind farm. Mosetti [6] first studied the optimization problem for a 2 km × 2 km dimension square wind farm by dividing it into one hundred 0.2 km × 0.2 km even cells. Subsequently, many papers were published targeting the same topic with most of them employing the same 10 × 10 grids regardless of the wind farm dimensions studied [7–9]. Wang [10] applied three types of grids to optimize the wind farm layout. He found that 20 × 20 grids yield the best optimization results. The unrestricted coordinate method was first used by Beyer [11] to investigate the optimization of three wind farm layouts with different sizes. He found that better results are achieved for all wind farms by using the optimized wind farm layout compared with the empirical design.

Nevertheless, almost all the wind farm layout optimization studies have been conducted based on the assumption that a continuous piece of land is readily available before developing a

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wind farm. In reality, the willingness of landowners to participate in the wind farm project plays a crucial role in the success of developing the wind farm. Therefore, it is extremely important to study the impact of land plots' availability on the wind farm design when doing the wind farm layout optimization. By assessing this impact, the wind farm developer can make a rational decision on the acceptable compensation for different landowners (e.g. the most important land plots can be compensated with more money). Chen [12–14] studied the wind farm layout optimization by considering the factor of landowners' decision. Since then, no studies on the wind farm layout optimization with different landowners have been reported.

The aforementioned studies typically consider only simple land plot divisions, while the complex land plot divisions have been reported in only one study [15]. The difference between simple and complex land divisions is illustrated in Fig. 1. The bold solid lines indicate the wind farm boundaries and the bold dash lines indicate the land plot divisions. The distinction between simple and complex land plot divisions are made as in Ref. [16]: simple divisions refer to equally-spaced square plots while the complex divisions allow for unequally-spaced rectangular plots, as illustrated in Fig. 1. Clearly, the wind farm complying with the above strict rules of simple divisions is quite restrictive and likely overly-simplistic. It is obvious that the wind farm with complex land divisions is more common in the real situation, and hence it is of great significance to develop the method for its study. In light of the above discussion, the study of wind farm optimization with complex land divisions is extremely crucial to facilitate the application of the research for a real commercial wind farm design. To the authors' best knowledge, the sole study to address the complex land divisions is reference [15], in which only the single grid based wind farm design method is applied. However, this study utilized a standard penalty method to penalize infeasible solutions which the authors of the current paper have shown is typically outperformed by repair infeasible solution (RIS) method [16].

In this paper, different optimization approaches, including three optimization methods and two kinds of land plot scenarios, are considered and compared to investigate the effectiveness of different approaches. A new RIS constraint handling technique developed to handle the optimization constraints of complex wind farm divisions, together with the means of fitness evaluation. The remainder of the paper is organized as follows. Section 2 establishes the fundamental models for wind farm layout optimization study applied in this paper. It contains the Weibull wind scenario model, wind farm wake model, wind turbine power and cost model, and the objective function calculation. Section 3 describes the optimization solution encodings, optimization constraints, feasible solutions generation techniques, fitness evaluation process, and finally the optimization algorithm. Section 4 compares and discusses the wind farm layout optimization results with different approaches. Conclusions are drawn in Section 5.

2. Modelling

2.1. Wind characteristic

Realistic wind descriptions are based on wind data measured on site with continuous wind speed and wind direction. It is widely accepted that wind scenarios in most areas of the world can be represented by the two-parameter Weibull distribution, whose probability density function is given by

$$p(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{1}$$

where $p(v)$ is the probability density of occurrence of wind speed v, c is the scale parameter and k is the shape parameter. The cumulative Weibull distribution, $P(v)$, giving the probability of the wind speed less than or equal to a certain value v, is given by

$$P(v) = 1 - \exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{2}$$

In this paper, the wind condition of Weibull distribution used in Ref. [5] is applied and the detail of the wind scenario can be referred in the literature.

2.2. Wake model

To describe the properties of wind after passing through the wind turbine rotor quantitatively, a simple wake model called the PARK model is utilized in this paper, which was based on N.O. Jensen theory [17]. It was then tuned for applying the improved model to optimize the wind farm configuration as discussed in Ref. [18]. Its effectiveness on predicting the wind farm power output considering the wake effect has been validated by comparison to the real wind farm observational data and computational simulation results [19].

As shown in Fig. 2, the PARK model assumes a linear expansion of the wake. Based on the theory of momentum conservation, the velocity in the wake of an upstream wind turbine at a distance of x along the wind direction can be obtained, it is given by:

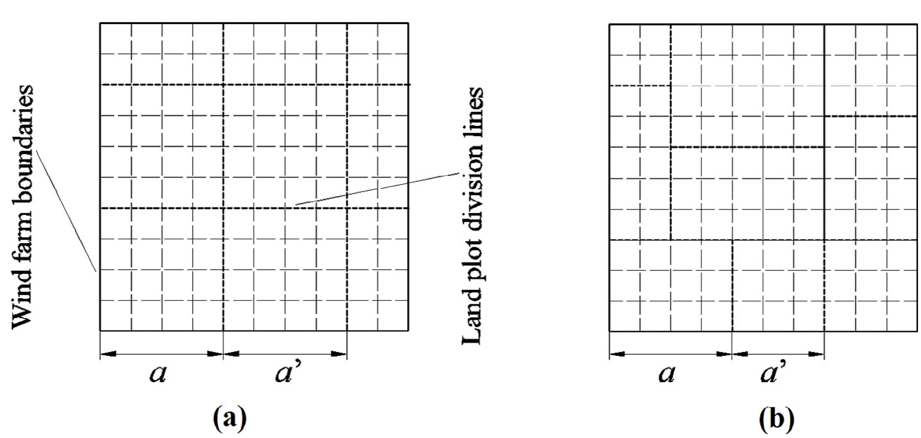

Fig. 1. Illustration of the wind farm model with: (a) simple land plot division and (b) complex land plot division.