J. Wind Eng. Ind. Aerodyn. 146 (2015) 1–10

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Comparative study on optimizing the wind farm layout using different design methods and cost models

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ARTICLE INFO

Article history:
Received 10 April 2015
Received in revised form
19 July 2015
Accepted 19 July 2015
Available online 11 August 2015

Keywords:
Layout optimization
Comparative study
Grid density
Grid based method
Unrestricted coordinate method
Mosetti's cost model
Chen's cost model

ABSTRACT

Optimizing wind farm layout is an effective tool to decrease wind power losses caused by the wake interaction between wind turbines. Current researches focus on advancing the optimization algorithms and improving the wind farm models based on two design methods (the grid based method and the unrestricted coordinate method). However, it has been rarely reported for the comparative studies of these two methods. Meanwhile, the topic of how to select a better wind farm cost model for the layout optimization has not been studied in literatures, while it is extremely important to the real wind farm design since the real wind farm cost can be highly uncertain which cannot be represented by a fixed model for different wind farms. Therefore, the wind farm layout optimization using the two design methods is conducted in this paper. Three different grid situations are considered so that the best optimization results with the grid based method can be obtained to compare with the unrestricted coordinate method more convincingly. Two widely acceptable cost models (Mosetti's model and Chen's model) are employed to unveil their influence on the optimization results. It has been found that (i) 20×20 grids should be preferred for the grid based method instead of the previously widely applied 10×10 grids; (ii) compared to using the grid based method, there is a small improvement for the optimization result using the unrestricted coordinate method. Nevertheless, more computation cost is needed for the method when a large number of turbines are optimized and (iii) there is a big discrepancy between the optimization with different cost models. Mosetti's cost model is more accurate than Chen's cost model when the optimized number of turbines is large and vise versa.

1. Introduction

It has been reported that the share of electricity generation through renewable energy sources is vastly increasing in comparison to the conventional fossil fuels such as coals, oils and natural gases nowadays. Among the different types of renewable energy sources, wind energy has exhibited the fastest growing trend due to its abundance all across the world and cost-competitive property, compared to other sources such as solar power, tidal power and nuclear power. Due to the limited energy production of an individual wind turbine, wind power generation usually comes in the form of wind farm, in which numerous wind turbines are installed in a large scale to make the most of the wind power at site. However, clustered wind turbines bring about the problem of wind intervention (also known as a wake effect) from upstream turbines to the downstream turbines, decreasing the power output of downstream turbines. Because of this, reduced wind energy production will greatly affect the profitability of a wind farm project and could even lead to the failure of the project.

Researches show that wake intervention can be weakened with increased wind power output through optimal design of wind farm layout. Mosetti et al. (1994) first studied the wind farm layout optimization problem on a square wind farm of 10 km length. In the study, the wind farm is divided into 10×10 even square grids and all wind turbines can only be placed at the center of the small grids. Binary numbers are utilized to represent if there is the wind turbine in a particular cell or not ("1" indicates yes and "0" indicates no). After the study, a large number of papers have been published with the same wind farm design method (named the grid based method) by employing more advanced optimization algorithms or models (Şişbot, 2010; Pookpunt and Ongsakul, 2013; Bilbao and Alba, 2010). Apart from the wind farm design method, the other method that has been widely applied to the wind farm optimization study is named an unrestricted coordinate method, for which the Cartesian coordinates of wind turbines are used to represent the wind turbine positions. Beyer et al. (1996) first applied the method to the wind farm layout optimization study. In the study, the optimized wind farm layouts are compared with the

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http://dx.doi.org/10.1016/j.jweia.2015.07.009
0167-6105/

empirical layouts. All tested wind farms have shown evident improvement of performance on the profitability of the project and wind farm efficiency. Likewise, other researchers have also focused on advancing the optimization algorithms and improving the wind farm models with the method as can be seen in Sood et al. (2010), Tran et al. (2013) and Wan (2012). However, whatever topic these papers are targeting, they all share some same features, i.e., (i) constant grid density (indicating how many grids a wind farm is divided by) is applied for the study with the grid based method; (ii) only one of the two wind farm design methods, that is either the grid based method or the unrestricted coordinate method, is applied; and (iii) only fixed wind farm cost model is applied to determine the optimal number of turbines and the wind farm layout.

For the grid based method, the selection of grid densities is crucial to the wind farm optimization since it determine the number of potential locations to place wind turbines. The denser grids wind farm is divided by, the more locations are available for placing wind turbines. Therefore, better optimization results can be anticipated in this case. However, a large number of grids lead to the large computational time and increase the optimization costs. It can be imagined that when the grids are extremely dense, the optimization process will proceed too slowly with enormous solution spaces, which will conversely influence the optimization process to find the optimal solutions. Therefore, it is necessary to balance the computation costs and the optimization results when selecting the appropriate grid density for the optimization study. For the unrestricted coordinate method, it is considered to be more superior to the grid based method as reported in literatures (Wan et al., 2009; Wan, 2010), because the wind turbines can be freely placed at any places of wind farm. However, from the authors' standpoint, two aspects are neglected when the conclusion is drawn. One is that the comparison are made based on the optimization using the unrestricted coordinated method and the grid based method with the coarse grid density (10×10 grids), while no results with finer grids are compared. The other is that only the optimization results are compared which is far from comprehensive to judge the effectiveness of different design methods more rationally. The optimization efficiency of the methods needs to be studied as well. For the wind farm cost represented by the approximated expressions, current researchers have only applied single fixed cost model and they may have large uncertainties or deviations from the realistic wind farm data ([Chen and MacDonald, 2014,González, 2010]). For this reason, the comparative study of wind farm optimization employing different cost models is of great importance to shed light on how sensitive the optimization results are to the selection of the wind farm cost models.

The aim of this paper is to fix the aforementioned research gaps accordingly, and the questions to be answered are listed:

1. For the widely applied grid based method, which grid density is the best choice considering both optimization results and optimization efficiency?
2. Compared to the grid based method, what are the pros and cons of the unrestricted coordinate method applied for wind farm layout optimization?
3. What are the effects of selection of wind farm cost models on wind farm layout optimization results?

Three different grid densities are studied by comparing the optimization results and the computational time. The grid based method and the unrestricted coordinate method are compared with respect to the optimal wind farm layout, optimal number of turbines and wind farm efficiency. They are all studied on the basis of two wind farm cost models that are introduced in Section 2.4. The remainder of the paper is organized as follows. Section 2 presents different kind of models applied in the wind farm layout optimization, including the wind condition model, wake model, wind turbine model and wind farm cost models. Section 3 gives the methodology on how the wind farm powers are calculated by considering the wake effect between wind turbines and the calculation of the objective function, cost of energy. The results and discussion are introduced in Section 4. Section 5 draws the conclusion of the study.

2. Wind farm modeling

2.1. The wind condition model

The statistical features of wind scenario are typically described by two factors: the wind speed and the wind direction. When conducting wind farm layout optimization, three different wind conditions are studied, namely, (a) constant wind speed with constant wind direction, (b) constant wind speed with various wind directions, and (c) various wind speeds with various wind directions, which are all regarded as the discrete wind condition.

More realistic wind descriptions are based on measured wind data and hence both wind speed and wind direction should be continuous. It is widely accepted that the wind scenarios of most areas of the world can be represented by Weibull distribution, and it is given by (Seguro and Lambert, 2000):

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

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

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

2.2. The wake model

A simplified wake model is utilized in this paper to depict the property of wind passing through wind turbines quantitatively. Jensen (1983) proposed the wake model first to study a small number of aligned wind turbine wake properties, and it is then tuned to study the wind farm layout optimization (Katic et al., 1986), which is known as PARK model Fig. 1.

The PARK model assumes a linear expansion of the wake. Based on the theory of momentum conservation, the velocity in the wake

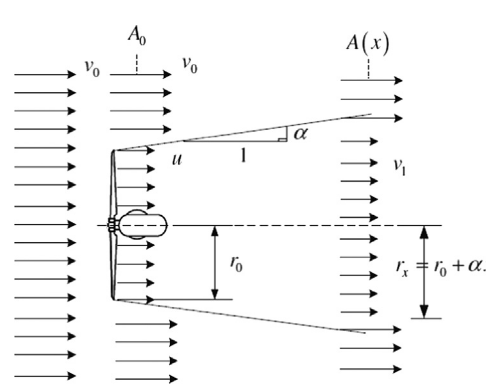

Fig. 1. Diagram of PARK wake model (2014; Available from: http://offwind.eu/Help/EngWindSim).