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Solving the wind farm layout optimization problem using random search algorithm

Ju Feng*, Wen Zhong Shen

Department of Wind Energy, Technical University of Denmark, DK-2800 Lyngby, Denmark

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ABSTRACT

Wind farm (WF) layout optimization is to find the optimal positions of wind turbines (WTs) inside a WF, so as to maximize and/or minimize a single objective or multiple objectives, while satisfying certain constraints. In this work, a random search (RS) algorithm based on continuous formulation is presented, which starts from an initial feasible layout and then improves the layout iteratively in the feasible solution space. It was first proposed in our previous study and improved in this study by adding some adaptive mechanisms. It can serve both as a refinement tool to improve an initial design by expert guesses or other optimization methods, and as an optimization tool to find the optimal layout of WF with a certain number of WTs. A new strategy to evaluate layouts is also used, which can largely save the computation cost. This method is first applied to a widely studied ideal test problem, in which better results than the genetic algorithm (GA) and the old version of the RS algorithm are obtained. Second it is applied to the Horns Rev 1 WF, and the optimized layouts obtain a higher power production than its original layout, both for the real scenario and for two constructed scenarios. In this application, it is also found that in order to get consistent and reliable optimization results, up to 360 or more sectors for wind direction have to be used. Finally, considering the inevitable inter-annual variations in the wind conditions, the robustness of the optimized layouts against wind condition changes is analyzed, and the optimized layouts consistently show better performance in power production than the original layout, despite of considerable variations in wind direction and speed.

1. Introduction

A wind farm is a group of WTs located at a site to generate electricity, which is also called as “plant”, “cluster”, “array” and “park” in literature. The world's first onshore WF was installed in 1980 on the shoulder of Crotched Mountain in southern New Hampshire, USA, with a capacity of 0.6 MW, consisting of 20 WTs with a rated power of 30 kW [1]. In 1991, the world's first offshore WF, Vindeby offshore WF was erected off the north coast of the Danish Island Lolland, which marked the beginning of offshore wind energy. It has a total capacity of 4.95 MW consisting of 11 Bonus 450 kW WTs [2]. Nowadays, the progress of technologies, such as power electronics [3], wind speed forecasting [4], coordinated control [5], together with the increased experience of WF construction and operation have enabled the development of modern WFs, i.e., larger, smarter WFs, which are typically consisting of hundreds of utility-scale (multi-MW) WTs and with a total capacity of hundreds MW. In parallel with this trend, the efforts for increasing the percentage of wind power in the total electricity consumption have led to the proliferation of modern WFs.

Due to the multi-disciplinary nature and the evolution towards larger size, smarter control and more advanced capabilities, the development of WF is becoming a highly complex process which pursues multiple and in many cases conflicting objectives under different constraints. It involves different design and engineering tasks, which may come from technical, logistical, environmental, economical, legitimacy and even social considerations [6].

Among all these tasks, the optimization of WF layout is a critical one. In literature, WF layout usually refers to the placement of WTs inside a certain area. Therefore, WF layout optimization is to determine the positions of WTs inside the WF in maximizing and/or minimizing some objective functions, such as maximizing the energy production and minimizing the cost, while meeting various constraints, which may include WF boundary, WTs proximity, noise emission level, initial investment limit, and so on. In general cases, i.e., considering the selection of WT number, WT type, discrete hub height, WF layout optimization is a multi-objective mixed integer-discrete-continuous nonlinear constrained optimization problem without analytical formulation. It is mathematically complex and

* Corresponding author. Tel.: +45 45251397.
E-mail address: jufen@dtu.dk (J. Feng).

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can't be solved by using classical analytical optimization techniques.

In the last two decades, this complex problem has received more and more attention. Different problem formulations have been proposed and various optimization algorithms have been used to tackle this problem. Previous works are based on various simplified formulations, such as array of equally spaced turbines [7,8], array of unequally spaced turbines [9], aligned or staggered grid like (row-column) layout [10,11], pre-divided discrete grid points [12], continuous searching space [13,14], using a range of algorithms, such as Monte Carlo [8,15], GA [12,16], simulated annealing (SA) [14], particle swarm optimization (PSO) [17] and local search algorithm [18]. Different kinds of objectives are used, e.g., maximizing the power [9], annual energy production (AEP) [14,18], profit [8,13], net present value (NPV) [11], or minimizing the cost of energy (CoE) [12,15–17], levelized production cost (LPC) [19]. More comprehensive survey of published works can be found in several papers [20–22].

The random search (RS) algorithm for WF layout optimization in our previous study [23] was based on a continuous formulation and used to refine results obtained by GA [16] for an ideal test problem [12]. In this study, the algorithm is improved by adding some adaptive mechanisms and applied first for the same ideal test problem and then for the Horns Rev 1 WF. To save the computation cost, a strategy to evaluate the layouts, which is similar with that adopted by Wagner et al. in Ref. [18], is also applied. It is found that the improved method can achieve better optimization results than its old version for the ideal test problem with the same number of evaluations. For the Horns Rev 1 WF, it also can improve the power production by using optimized layouts. Besides, the preprocessing of wind resource data and the robustness of the obtained layouts against wind change are discussed in this paper. In the meanwhile, the same algorithm was used in a preliminary study to optimize a WF layout in complex terrain and obtained steady improvements over expert guess layouts for a WF on an ideal Gaussian shape hill [24].

2. Problem formulation

2.1. Wind modeling

Appropriate wind modeling is the starting point for accurate predicting wind farm power production. In Mosetti's study [12], three simple wind cases were constructed and applied to his test problem. Although it is valid to use this kind of ideal wind modeling when focusing on algorithm investigation, more realistic wind modeling is required for real-life application.

To assess the wind resource at a planned wind farm site, a wind measurement campaign is usually first carried out at a reference height H_{ref}. The obtained measurement data can be processed by using method of bins [25], and then written in matrix form as

$$\boldsymbol{F} = (F_{wk}), \quad \text{with } w = 1, 2, \ldots, N_{ws}, \; k = 1, 2, \ldots, N_{wd} \tag{1}$$

where $F_{wk} = f_{occ}(v_w, \theta_k)$ denotes the frequency of occurrence of wind speed v_w in direction θ_k; N_{ws} and N_{wd} are number of bins for wind speed and for wind direction, respectively. Furthermore, the summarized wind data can be fitted sector-wisely into a certain probability distribution, typically Weibull distribution, which is governed by

$$p_{Wb}(v, A_k, c_k) = \left(\frac{c_k}{A_k}\right)\left(\frac{v}{A_k}\right)^{c_k-1} \exp\left[-\left(\frac{v}{A_k}\right)^{c_k}\right] \tag{2}$$

Then the wind resource data can be presented as: $[\theta_k, A_k, c_k, f_k]$ with $k = [1, 2, \ldots, N_{wd}]$, i.e., in terms of: direction angle, scale factor, shape factor and frequency of occurrence. In order to predict the power production, the inflow wind speed V_0 at hub height H should be calculated, usually using the logarithmic law:

$$V_0 = v^H(v_w) = v_w \frac{\ln(H/z_0)}{\ln\left(H_{ref}/z_0\right)} \tag{3}$$

where v_w denotes the wind speed at reference height H_{ref}, z_0 is the surface roughness length. Wind modeling form of Eq. (1) is convenient for numerical calculation due to its discrete nature. When the wind data is given in the form of Weibull distribution, it can also be easily converted into a matrix form by discretization. If the directional sector is too wide, i.e., N_{wd} is too small, each sector can also be further divided into smaller sub-sectors with same scale factor A_k and shape factor c_k.

2.2. Wake modeling

In order to calculate the wind field in WFs, the wake effects between WTs have to be modeled appropriately. Due to the nature of optimization problems, a quite large number of layout evaluations must be carried out, which requires simple and reliable wake modeling. In most of the layout optimization works in literature and also in some commercial software such as WAsP, the Jensen wake model [26], also known as PARK wake model or Katic wake model, is used. This model is developed by assuming that momentum is conserved within the wake, and the wake region expands linearly in the direction of wind flow.

Suppose there are N_{wt} WTs in the WF and the layout is represented by $\boldsymbol{X} = [x_1, x_2, \ldots, x_{Nwt}]$, $\boldsymbol{Y} = [y_1, y_2, \ldots, y_{Nwt}]$. Considering WT i at location (x_i, y_i) and WT j at location (x_j, y_j) for wind direction θ_k, the original Cartesian coordinates can first be rotated according to θ_k so that wind blows along the new x' direction. If $x_i' \le x_j'$, WT j is at the downwind of WT i or at the same level, and therefore have no influence on WT i. If $x_i' > x_j'$, wind speed and wake zone radius behind WT j and at the position where WT i is located, denoted as V_{ij} and R_{ij}, are governed by the following expressions:

$$V_{ij} = V_0\left[1 - \frac{1 - \sqrt{1 - C_T(V_0)}}{\left(1 + \alpha\left(x'_{ij}/R_r\right)\right)^2}\right], \tag{4}$$

$$R_{ij} = \alpha \cdot x'_{ij} + R_r \tag{5}$$

where V_0 is the inflow wind speed, $C_T(V_0)$ denotes the thrust coefficient of WT at wind speed V_0, α is the wake decay coefficient, $R_r = D/2$ represents the radius of rotor and $x_{ij}' = x_i' - x_j'$ is the distance between the two WTs along wind direction. Besides, the affected area of WT i's rotor by WT j's wake is calculated as the overlapping area of two circles with radiuses R_r, R_{ij} and centers distanced at $\left|y_{ij}'\right| = \left|y_i' - y_j'\right|$, or zero when it's not in the downstream of WT j, i.e.,

$$A_{ij} = \begin{cases} A_{ol}\left(R_r, R_{ij}, \left|y'_{ij}\right|\right), & x'_i > x'_j, \\ 0, & x'_i \le x'_j. \end{cases} \tag{6}$$

The formula for calculating A_{ol} and its derivation are given in the Appendix. Note that A_{ij}/A_r is used as an effective percentage for the wake effect of WT j on WT i, where $A_r = \pi R_r^2$ is the rotor area.

Based on the mutual wake effects between any two WTs described in Eqs. (4)–(6), the effective wind speed WT i experienced can be derived based on the kinetic energy deficit balance assumption, as