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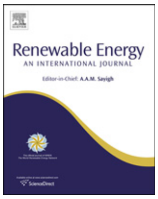

Design of wind farm layout using ant colony algorithm

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ABSTRACT

The wind is a clean, abundant and entirely renewable source of energy. Large wind farms are being built around the world as a cleaner way to generate electricity, but operators are still searching for more efficient wind farm layouts to maximize wind energy capture. This paper presents an ant colony algorithm for maximizing the expected energy output. The algorithm considers wake loss, which can be calculated based on wind turbine locations, and wind direction. The proposed model is illustrated with three different scenarios of the wind speed and its direction distribution of the windy site and, comparing to evolutionary strategy algorithm available in literature. The results show that the ant colony algorithm performs better than existing strategy, in terms of maximum values of expected energy output and wake loss.

1. Introduction

Wind Farm Layout Optimization Problem (WFLOP) is a problem, which has an objective function that tries to minimize wake effects of turbines by each other. Therefore, the expected power production of the farm is maximized [1]. There are many researches show that using heuristics to solve WFLOP is possible [2–10]. Mosetti et al. [3], Grady et al. [4], Huang [5], and Emami and Pirooz [6] used a genetic algorithm to solve WFLOP. The wind farm is divided into a square grid, to facilitate the encoding of a binary solution. The general framework of optimizing the offshore wind turbine layout was presented by Elkinton et al. [11]. Mora et al. [7] also used a genetic algorithm to maximize an economic function. Mora et al. [7] and Gonzales et al. [8] used an evolutive algorithm. Bilbao and Alba [9] worked on the same problem and conditions within ref. [7] and also developed a simulated annealing algorithm. Öztürk and Norman [10] compared discrete with continuous WFLOP and decided that using continuous location model was better than using discrete one. They constructed six test problems with different siting area sizes and used a Greedy Search Algorithm [10]. Kusiak and Song [2] developed an evolutionary strategy algorithm for WFLOP with continuous variable for turbine locations.

The annual energy production was improved by optimizing the wind farm layout design, specifically minimizing the wake loss. From the papers and reviews available in literature [3–11], it has been noted that the use of heuristics to address this problem in practice is intensive. This paper presents a new co-operative agents approach – the Ant Colony Search Algorithm – for solving WFLOP. The main goal of this paper is to investigate the applicability of an alternative intelligent search method in the design of wind farm layout optimization. The effectiveness of the proposed scheme has been demonstrated on the Kusiak and Song's energy output model which calculates the wake loss based on turbine locations [2] and the results were compared with evolutionary strategy algorithm developed by Kusiak and Song [2].

2. Problem definition and methodology

The wind farm layout optimization problem has the following assumptions:

1. The number of turbine is fixed in the farm because; the power capacity of the farm is generally planned at the beginning of the investment. So, in the model, the number of turbines Nt is not variable.
2. The layout representations of the turbines are Cartesian coordinates (x, y) and length of a location of turbine is $\sqrt{x^2 + y^2}$. The surface roughness of the terrain can be negligible and the optimal solution is represented with Cartesian coordinates (x_i, y_i), $i = 1, 2, \ldots, \mathrm{Nt}$

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3. All wind turbines have the same specifications (i.e., the theoretical power, the power curve, the brand and model, the hub height) in the farm so that the farm is homogenous.
4. For a given location, height, and direction, wind speed v follows a Weibull distribution $p_v(v,k,c) = k/c(v/v)^{k-1}e^{-(v/c)^k}$ where k is the shape parameter, c is the scale parameter, and $p_v(.)$ is the probability density function. This assumption is hold for many windy sites in long-term [12].
5. Wind speed is given as a parameter of the Weibull distribution function and it is continuous function of the wind direction $\theta(k = k(\theta),\ c = c(\theta)$ and $0^\circ \leq \theta \leq 360^\circ)$. In a wind farm, wind speeds at different locations with the same directions have the same Weibull parameters. Wind direction is one of the important variables for the WFLOP and illustration of the wind directions for our model is shown in Fig. 1 where is stand for 0° East and 90° is stand for North.
6. There must be a sufficient space between any two turbines to reduce some hazardous loads on the turbine such as wind turbulence. Since this can be a complex constraint, any two turbines are separated from each other by at least 4 rotor diameters in this study. If the rotor diameter of turbine is R, any two turbines are located at $(x_i,\ y_i)$ and $(x_j,\ y_j)$ then this has to satisfy the inequality $(x_i,\ y_i)^2 + (x_j,\ y_j)^2 \geq R^2 * 64$.
7. Because this problem is a layout optimization problem, the shape of the layout – boundary of the farm has to be described and so, we selected a circular wind farm shape as a boundary in the model (Fig. 1).
8. Turbines must be in the farm and this is geometrically represented by the equation of $x_i^2 + y_i^2 \leq r^2$ where r is the radius of the circular farm and it is 500 m and (x_i, y_i) is the coordinates of the ith turbine. (The center of the farm is represented by (0,0) on the coordinate system.)
9. Search space of the problem has continuous coordinate variables and it is restricted with the wind farm shape.
10. The mathematical model of the problem is constructed in two parts. First part of the model is wake effect that may cause lower power generation of the downstream turbines and the second is power output model.
11. The objective is to maximize power output so that the wake effect model can be minimized with respect to assumptions of sixth and eighth.

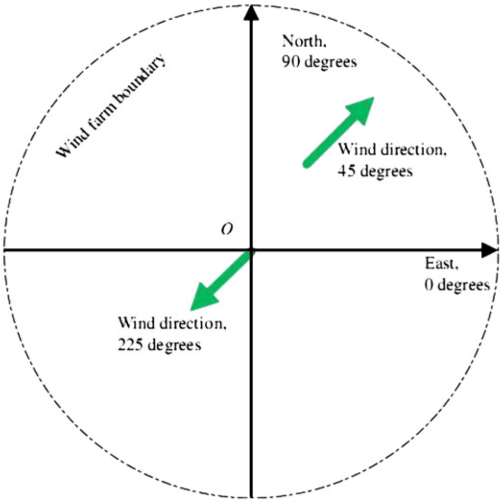

Fig. 1. Wind farm boundary and the wind speed directions (Ref. Kusiak and Song 2010).

2.1. The wake effect model

Wind farms are developed to get more power in a single windy site but this may cause lower power generation of the downstream turbines if they are located behind one or more turbines. This is known as the wake effect [12] and it is an important factor in considering wind farm layout design [13]. The wake effect model developed by Jensen [14,15] is used to compute velocity deficits of the wind turbines by the following equation,

$$\text{Velocitiy deficit}_{ij} = 1 - v_{\text{down}}/v_{\text{up}} = \frac{1-\sqrt{1-C_t}}{(1+\kappa d/R)^2} \tag{1}$$

where Velocity deficit$_{ij}$ refers to velocity deficit at turbine i in the wake of turbine j, v_{up} refers to original wind speed and v_{down} refers to wind speed after wake, C_t refers to thrust coefficient of the turbine, κ refers to wake decay constant, d is the distance between turbine i and j projected on the wind direction θ, and R refers to radius of the turbine.

If a turbine is effected more than one turbines wake, the total wake effect on the turbine i is computed by the following equation,

$$\text{Velocity deficit}_i = \sqrt{\sum_{j=1, j\neq i}^{\text{Nt}} \text{Velocity deficit}_{ij}^2} \tag{2}$$

As it can be seen from Eq. (1) and Eq. (2), the wind speed is reduced by the wake effect projected on the wind direction θ and it can be said that the velocity deficit is a function of θ and turbine locations (x, y). As the wind speed is given as a parameter of the Weibull distribution function, only the scale parameter c will be affected of the wake effect as it is given by the following Eq. (3)

$$c_i(\theta)^*(1 - \text{Velocity deficit}_i),\quad i = 1, 2, \ldots, \text{Nt} \tag{3}$$

2.2. The power model

Based on Kusiak and Song's energy output model [2], the expected energy generation of a single turbine located at (x, y) and wind direction θ is computed as follows (Eq. (4));

$$\begin{aligned} E(P,\theta) &= \int_0^\infty f(v) p_v(v, k(\theta), c(\theta)) \mathrm{d}v \\ &= \int_0^\infty f(v) \frac{k(\theta)}{c(\theta)} \left(\frac{v}{c(\theta)}\right)^{k(\theta)-1} e^{-(v/c(\theta))^{k(\theta)}} \mathrm{d}v \end{aligned} \tag{4}$$

The objective is to maximize power output of the wind farm with respect to assumptions sixth and eighth and this is represented by the mathematical model (Eq. (5))

$$\begin{aligned} &\text{Objective} \\ &\max \sum_{i=1}^{\text{Nt}} E(P)_i \\ &\text{s.t.} \\ &(x_i - x_j)^2 + \left(y_i - y_j\right)^2 \geq 64R^2, i, j = 1, 2, \ldots, \text{Nt}, i \neq j \\ &x_i^2 + y_i^2 \leq r^2 \end{aligned} \tag{5}$$

where $E(P)_i$ is the power output of the ith turbine. The power equation (Eq. (4)) seems more complex and it could be written in a linear shape [3] as follows (Eq. (6))