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Wind farm layout using biogeography based optimization

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ABSTRACT

Wind energy is one of the most promising option for the renewable energy. Finding optimum set of locations for wind turbines in a wind farm so that the total energy output of the farm is maximum, is usually referred as the wind farm layout optimization problem (WFLOP). This article presents the solution of WFLOP using a recent unconventional optimization algorithm, Biogeography Based Optimization (BBO). In this article, for a given wind farm not only the optimum locations of the wind turbines are obtained but also the maximum number of turbines is recommended. Experiments have been carried out for wind farms of various sizes. BBO has shown to outperform as compare to earlier methodologies of solving WFLOP.

1. Introduction

Wind energy is the most precious gift of nature to the world. The advance technology is trying to find out alternative of nonrenewable energy resources using wind energy. Now advance technology is developed to generate electricity from wind energy. Now a days, conventional windmills have been substituted by specially designed wind turbines for increasing the production of electricity. Wind turbine converts the wind energy into electricity.

Wind farm layout optimization (WFLO) is the pattern of wind turbines scheme subject to the constraints related to the position of the turbines, rotor radius and farm radius. In the wind farm layout optimization problem (WFLOP) model, the objective function is the maximization of expected power. The solution of this problem is to find the optimal placement of wind turbines so that the expected energy output of the whole wind farm is maximum. The complexity of WFLOP model depends on the constraints type.

The wake model depends on the thrust and the turbulence level at the turbine. The wake from one turbine will be detrimental on the wind speed and turbulence at down wind turbines. The effects of the wake spread out downwind and decay with distance according to generalized wake models. The effect of the wake is measured in the specific range. If the turbines are located within the range of four rotor diameter, they get affected by wake.

Significant development has been taken place in the machinery of wind energy production. The percentage of wind energy production is increasing rapidly. In near future also the wind energy production is expected to increase. The inherent challenge with wind energy is its product cost. This challenge can be controlled by the optimal wind farm layout design. Wind farm layout optimization problem is being solved from many years. Researchers are continuously developing the new approaches of designing and solving WFLOP. Lackner et al. [1] provided an analytical framework for offshore wind farm layout optimization. Here the annual energy production of the wind farm is fully dependent on the turbines position. Castro et al. [2] presented a genetic algorithm for the optimal design of the wind farms. In Ref. [3], Elkinton et al. presented offshore wind farm layout using several optimization algorithms. There are limited efforts done by optimization community to solving WFLOP. Mosetti et al. [4] and Grady et al. [5] demonstrated the placement of wind turbines using binary coded GA (genetic algorithm) for maximizing energy production. Haung et al. [6] applied the distributed GA to finding more effective optimal solution of WFLOP. Emami et al. [7] introduced a new approach on optimal placement of wind turbines using GA with additional property, the controlling capability of wind farm construction cost in objective function. Şişbot et al. [8] used a multi-objective GA to solving WFLOP. M. Samorani [9] demonstrated WFLOP consisting of

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two conflicting problem as maximization of expected power production with minimization of wake effect within several turbines. Ozturk et al. [10] developed greedy heuristic methodology for wind energy conversion system positioning. Bilbao et al. [11] applied simulated annealing (SA) to compute the optimal placement of wind turbines in a wind farm to produce maximum power. Rivas et al. [12] also applied the simulated annealing algorithm to solve wind turbine positioning problem. Kusiak et al. [13] presented a generic model for wind farm layout optimization based on wind distribution. In Ref. [13], evolutionary strategy is considered for optimizing layout up to 6 number of turbines in the circular wind farm. Wagner et al. [14] presented a better evolution strategy, named as covariance matrix adaptation based evolutionary strategy (CMA-ES) for maximum power production. Yeng yin et al. [15] developed a combined algorithm named as greedy randomized adaptive search procedures algorithm with variable neighborhood search algorithm (GRASP-VNS) for optimal placement of wind turbines. In Refs. [16,17], Eroğlu et al. developed ant colony optimization (ACO) and particle filtering (PF) approach to solve WFLOP, respectively. These intensive uses of metaheuristic algorithms to solve WFLOP inspire researchers to explore other recent metaheuristics also for the same.

This article presents relatively a recent approach Biogeography-based optimization algorithm (BBO) to solving WFLOP. The main objective of this article is to investigate the applicability of the BBO algorithm in solving WFLOP. In this article, we try to find out the optimal locations of wind turbines and maximum possible number of wind turbines in the wind farms with radii 500 (m), 750 (m) and 1000 (m).

Rest of the article is organized as follows. The problem modeling and statement are described in section 2. Section 3 details of BBO algorithm. In section 4, BBO algorithm is applied to solve WFLOP model. In section 5, various numerical experiments, comparison of results and discussions are given. The article concluded in section 6.

2. Problem modeling and statement

Some basic definitions are required to constructing the wind farm and to finding the optimal placement of turbines. It is important to make some assumptions to solving the WFLOP.

1. The number of turbines N is fixed before the planning of the wind farm construction because investment in the wind farm project depends on the number of turbines. For example, a 30 MW wind farm project, requires 20 number of wind turbines of capacity 1.5 MW each.
2. Location of each turbine in the farm is represented in the form of two-dimensional co-ordinates (x, y) and length of the location vector of each turbine is given by $\sqrt{x^2+y^2}$. Here only slight changes in surface roughness and the optimal solution of WFLOP is represented by the N positions (x_i, y_i), $i = 1, \ldots\ldots, N$ for N number of turbines.
3. All turbines in the wind farm are considered to be uniform with respect to both external quality (design, brand, model, hub height) and internal quality (power curve, theoretical power, capacity).
4. For a given location, height and direction, wind speed v follows a Weibull distribution $p_v(v,k,c)=\frac{k}{c}\left(\frac{v}{c}\right)^{(k-1)}e^{-\left(\frac{v}{c}\right)^{k}}$, where k is the shape parameter, c is the scale parameter and $p_v(.)$ is the probability density function. This assumption is very common for many windy sites [18].

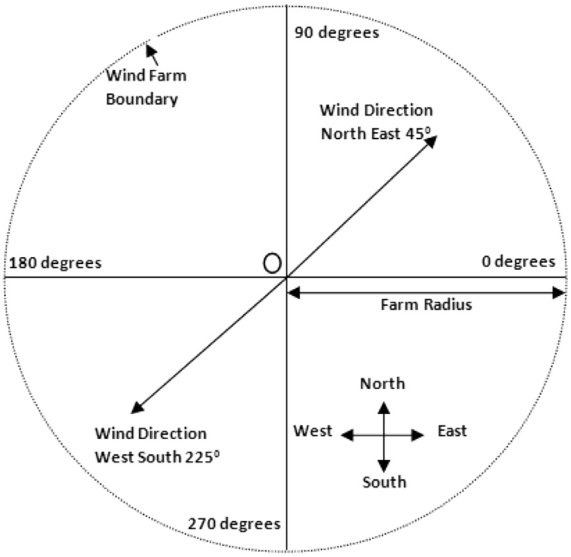

Fig. 1. A typical circular wind farm with wind directions [13].

5. One of the parameter of Weibull distribution function is wind speed v which is a function of wind direction θ then $v = v(\theta)$, i.e. $k = k(\theta)$, $c = c(\theta)$, $0^\circ \le \theta \le 360^\circ$. Thus, the wind direction θ is a significant parameter of WFLOP. Fig. 1 gives the pictorial description of wind direction for proposed work, where $\theta = 0^\circ, 90^\circ, 180^\circ$ and 270^0 represents east, north, west and south, respectively.
6. There must be a proper space between two turbines. Proper spacing between turbines reduces some dangerous loads on turbines, e.g. wind turbulence. If $T_i(x_i, y_i)$ and $T_j(x_j, y_j)$ be two turbines then they should satisfy the inequality $(x_i - x_j)^2 + (y_i - y_j)^2 \ge 64R^2$, where R is the given rotor radius.
7. WFLOP is a layout optimization problem. Thus the primary task of this study is to consider the wind farm layout boundary. We can take elliptical, circular or any other shape of the wind farm. We have selected circular shape of the wind farm as a boundary for this study.
8. All the turbines must be situated within the farm. Thus any turbine T_i with Cartesian coordinate (x_i, y_i) must satisfy the constraint $x_i^2 + y_i^2 \le r^2$, where r is the radius of the wind farm. In this study, wind farms of radii 500 (m), 750 (m) and 1000 (m) are considered.
9. Search space of the problem is bounded by the wind farm shape and has continuous coordinate variables. Therefore, to locate a wind turbine, the grid system is not required.
10. Mathematical model of the problem consists of two parts: wake effect and power output model. Wake effect causes lower power generation of downstream turbines. The Jensen's wake model [19,20] is used and adopted the continuous search space of WFLOP. Power output model is considered from Kusiak et al. [13].
11. The objective of this study is to maximize power output in such a way that wake effect model can be minimized with two constraints obtained from assumptions 6 and 8, i.e., the spacing between any two turbines is at least four rotor diameters and all turbines must be situated within the farm.