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Optimization of offshore wind farm layout in restricted zones

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ABSTRACT

In this research, an optimization method for offshore wind farm layout design is proposed. With the purpose of maximizing the energy production of the wind farm, the wind turbine (WT) positions are optimized. Due to the limitations of seabed conditions, marine traffic limitations or shipwrecks, etc., the WTs are expected to be placed outside specific areas. Based on this fact, a restriction zone concept is proposed in this paper and implemented with the penalty function method. In order to find a feasible solution, a recent proposed stochastic algorithm, particle swarm optimization algorithm with multiple adaptive methods (PSO-MAM) is adopted. The simulation results indicate that the proposed method can find a layout which outperforms a baseline layout of a reference wind farm (RWF) by increasing the energy yield by 3.84%.

1. Introduction

An offshore wind farm (OWF) shows more benefits at higher wind speeds, less turbulence and less impact on residents compared with an onshore wind farm; however, the construction and maintenance cost is high. In order to get a cost-effective wind farm, the layout of the wind farm should be optimized.

The wake effect will cause a wind speed deficit at the downstream wind turbines (WTs). As a result, the energy production of the wind farm will be reduced. Hence, it is necessary to optimize a wind farm layout design which can minimize the wake losses so that the rate of return on investment can be increased. In Ref. [1], Mosetti et al. used a genetic algorithm (GA) to optimize the OWF layout, this is the initial work of OWF layout design. The construction area is partitioned into 100 squares and the WTs can be placed at the center of each square. Later, the authors of [2] improved this method which can get a layout with more power production considering the possibility of installing more WTs in the same area. Many researchers have worked on the wind farm layout optimization problem (WFLOP) and the results have been compared with the above two layouts [3–6]. Reference [3] demonstrated that the Monte Carlo algorithm was outperformed by the GA in finding a higher value of the objective function under the assumption that the wind direction is constant, while [4] showed the advantages of using an Intelligently Tuned Harmony Search algorithm for WFLOP. In Ref. [5], a binary particle swarm optimization method with time-varying acceleration coefficients (BPSO-TVAC) is proposed and the obtained results are compared with other 5 meta-heuristic algorithms. In Ref. [6], another wake and energy production model was considered to conduct the work and the obtained result was compared with that of the commercial software WindFarmer. Different from previous work, [7] proposed a sequential optimization method which shows better performance in finding a near optimal solution in calculation precision. In Ref. [8], an evolutionary computational approach to optimize the layout for a real offshore wind farm in northern Europe was proposed. Though the final wind farm was irregularly shaped, the WTs inside the wind farm were still placed with an array layout. One year later, the authors in Ref. [9] introduced another heuristic method, coral reefs optimization algorithm, to solve the WFLOP, the simulation results showed that the proposed method outperformed evolutionary approaches, differential evolution and harmony search algorithms in finding a better layout with more power generation. It can be seen that the works mentioned above are focused on solving the WFLOP using meta-heuristic algorithm based on grid partition methods. Since the problem is pre-simplified by partitioning the whole area into grids, some possible solutions have already been neglected.

In order to conquer this drawback, the works [10–18] optimize the WT locations using Cartesian coordinate form which permits the WTs to move within a predefined region freely. This increases

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Nomenclature

V_0 [m/s]	input wind speed at the WT
V_x [m/s]	wind speed in the wake at a distance x downstream of the upstream WT
R_0 [m]	radius of the WT's rotor
R_x [m]	generated wake radius at x distance along the wind direction
$S_{overlap}$ [m^2]	affected wake region
C_t	thrust coefficient
k_d	decay constant
ρ [kg/m^3]	air density,
$C_{p,i}$	power coefficient of WT i
$P_{m,i}$ [W]	mechanical power generated by WT i
v_i [m/s]	wind speed at WT i
N	total number of WTs in a wind farm
$P_{tol,t}$ [W]	total power production during interval t
T_E [day]	duration interval for energy yields calculation
T_t [h]	duration when the wind farm generating power of $P_{tol,t}$
$E_{tol,av}$ [Wh]	mean energy yields in one year
t [h]	energy yields calculation time
L	vector of WT positions
F	construction area of wind farm
$E_{tol,av}(L)$ [Wh]	mean energy yields in one year when the wind farm layout is L
x_i, y_i	coordinate of WT i
x_k, y_k	coordinate of WT k
$d_{\min}$	minimal distance between any pair of WT
R	index of constraint function
N	total number of WTs
C	total number of penalty functions that should be used in the problem for unrestricted sea area
C_1	total number of penalty function that should be used in the problem for restricted sea area
R	restriction zone in F
C_FR	complementary set of restriction zone, R, in predefined sea area, F.
$\varphi(L_i)$	penalty function for WT i
W	inertia weight
l_1, l_2	learning factors
r_1, r_2	stochastic numbers which can generate some random numbers within [0, 1]
q_i^k, q_i^{k+1} [m]	position of i^{th} particle at iteration k and k+1 respectively, in other words, the i^{th} solution generated randomly at iteration k and k+1 respectively
v_i^k, v_i^{k+1} [m]	speed of i^{th} particle at iteration k and k+1 respectively, in other words, the updating step length for the i^{th} solution at iteration k and k+1 respectively
Q_i^k [m]	best position found by the i^{th} particle before iteration k, in other words, the best solution obtained in position i^{th} till iteration k which is also called as personal best solution till iteration k
Q_g^k[m]	best position found by all particles (the swarm) before iteration k, in other words, the best solution obtained till iteration k which is also called as global best solution till iteration k
Q_i	best position found so far by the i^{th} particle
Q_g	best position found so far by all the particles
I	swarm size
O	maximum iteration

the freedom of the search space and gives more chances for the meta-heuristic method to find a near optimal solution. In Ref. [10], the wind farm is assumed to have a circular shape. Several wind turbines are placed optimally within this area which is an initial attempt to solve WFLOP based on a coordinate system. Similarly, [11] used colony optimization algorithm to optimize the WT positions, which was demonstrated to be outperformed by Ref. [10] in increasing the wind farm power production which was the objective function in this paper. Furthermore, a particle filtering approach is proposed to solve WFLOP in Ref. [12]. From the comparison, it can be seen that it is an alternative way of optimizing the WFLO compared with evolutionary strategy algorithm [10] and ant colony optimization method [11]. In Ref. [13], the wind farm layout was optimized by seeding an evolutionary algorithm heuristically considering the wind farm orography, while PSO was adopted in Refs. [14, 15] to design the wind farm. In Ref. [14], the WFLOP was solved considering three aspects: the location of each WT, the number of WT as well as the type selection of WT using mixed-discrete PSO while [15] adopted Gaussian PSO with local search strategy to optimize the WT positions. Besides, there were also some attempts to use mathematical programming to solve WFLOP as specified in Refs. [16–18]. In Ref. [16], a random search (RS) algorithm which showed better performance than the heuristic algorithm in computational time is proposed, the RS algorithm was demonstrated by using the Horns Rev I wind farm as the case study. Also, Horns Rev I wind farm layout was selected as the benchmark and compared with the optimized layout obtained by sequential convex programming in Ref. [17]. Since the WFLOP is non-convex, a global optimal solution cannot be guaranteed. In order to get a near optimal solution, a mathematical programming method was adopted in Ref. [18] that used heuristic methods to set an initial layout then used nonlinear mathematical programming techniques to get a local optimal solution. However, due to the offshore topology limitation, some predefined zone may not be available to install WTs or could be costly for installation in practice. In Ref. [19], the Dogger Bank Reference Wind Farm layout (DRW) was designed by avoiding installing WTs within the highest foundation cost region which resulted a blank area in the wind farm. In Ref. [20], three types of offshore wind farm configurations in Hong Kong (aligned, staggered, scattered) were investigated using GA. The simulation results showed that the scattered layout was the best choice in terms of levelised cost of energy (LCOE). The works mentioned above are concentrated on the WFLOP within a predefined area without considering the impact of the restriction area to the design of the WFLO. Though the WTs were placed away from the higher cost foundation zone in Ref. [19], the wind turbine locations are chosen manually. Thus, it is still possible to increase the energy yields of the wind farm layout in Ref. [19] by adopting optimization methods.

The LCOE is the most interesting parameter in many cases, while in this paper we try to address the problem of layout optimization for harvesting total energy production under the assumption that the size and number of turbines are given. The contributions of this paper are twofold: 1) WFLOP is solved by taking the offshore restricted area into consideration. 2) PSO with multiple adaptive methods (PSO-MAM), is arranged to solve the WFLOP. The