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A review of offshore wind farm layout optimization and electrical system design methods

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Abstract There is more wind with less turbulence offshore compared with an onshore case, which drives the development of the offshore wind farm worldwide. Since a huge amount of money is required for constructing an offshore wind farm, many types of research have been done on the optimization of the offshore wind farm with the purpose of either minimizing the cost of energy or maximizing the total energy production. There are several factors that have an impact on the performance of the wind farm, mainly energy production of wind farm which is highly decided by the wind condition of construction area and micro-siting of wind turbines (WTs), as well as initial investment which is influenced by both the placement of WTs and the electrical system design, especially the scheme of cable connection layout. In this paper, a review of the state-of-art researches related to the wind farm layout optimization as well as electrical system design including cable connection scheme optimization is presented. The most significant factors that should be considered in the offshore wind farm optimization work is highlighted after reviewing the latest works, and the future needs have been specified.

Keywords Energy production, Wake modelling, Wind farm layout optimization, Cable connection scheme optimization, Offshore wind farm

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1 Introduction

Due to the increasing demand for clean energy, the utilization of prolific renewable energy such as wind energy becomes more and more popular. The wind energy can be offshore or onshore. Though much more investment is required for an offshore wind farm, it still attracts more interests of researchers and engineers all over the world due to the public preference and high wind speed with low wake turbulence. Based on the study in [1], the total investment for array cables can be up to 9%. With the decreasing cost of wind turbine (WT) and installation, it is expected that this percentage will increase. In addition, the overall investment for the offshore wind farm is huge which means that even a small improvement in the WT placement or electrical system topology design would save a large sum of money. Hence, many works targeted at maximizing the energy production of a whole wind farm or minimizing the cost of energy to get a lower levelized cost of energy (LCOE) of the wind farm.

The wind speed deficit calculation is a complex process which is related to the micro-siting of WTs, the wind condition as well as the control strategy of WTs. The analytical model of wind in the wake involves a mass of constraints that make the wind farm layout optimization problem (WFLOP) as an NP-hard (nondeterministic polynomial time) optimization problem [2]. For solving such a problem, the classic optimization algorithm would flop because of excessive computation time. Hence, the heuristic optimization algorithm becomes popular in solving the large-scale WFLOP [3]. Compared with WFLOP, the electrical system design concerns about the investment on electrical components and the power losses associated with them. In [4–9], an optimized strategy of electrical components including voltage level selection was proposed, while [10–33] focused on the internal cable connection layout optimization. To decide the quantity and location of offshore substation (OS), several works [8, 14, 18, 20, 25] presented different optimization methodologies. The above three parts composed the main content of the electrical system optimization of the offshore wind farm. Within these, the cable connection layout are mainly optimized by deterministic method as minimum spanning tree algorithm [34], travelling salesman problem [35] algorithm and open vehicle routing problem (OVRP) [36], which are the classic algorithms in graphic theory [37] or hybrid method using genetic algorithm (GA) or particle swarm optimization (PSO) combined with deterministic algorithm [22–37]. The decision variables for electrical system optimization are both discrete and continuous which is hard to guarantee the optimality. Without considering the OS locating, the optimal cable connection layout could be achieved if there are only tens of wind turbines. With the increasing number of WTs in the large-scale offshore wind farm, the computational time for getting the optimal layout is increasing exponentially which challenges the application of such methodologies, since the modern offshore wind farms are developing towards large capacity with hundreds of WTs.

In this paper, the most promising and effective methods for offshore wind farm optimization have been reviewed and highlighted by their strengths and weaknesses. The paper is organized as follows. Section 2 gives the general framework of offshore wind farm design. Section 3 provides the review of the research works for WTs micro-siting. The algorithms for electrical system optimization of the offshore wind farm are specified in Section 4 while the co-optimization problem of an offshore wind farm is also presented at the end of Section 4. Section 5 summarizes the main conclusions.

2 Optimization framework of offshore wind farm

The optimization works regarding the above two aspects can be illustrated in Fig. 1.

To launch an offshore wind farm project, the wind farm construction area should be defined at first, which is called the wind farm macro-siting. In this phase, the political and regulatory issues are the main concerns, which takes the distance to shore, restriction area such as military forbidden area, fishing farm, natural reserve area, main channel, and wind resource distribution into account. Then, based on the measured wind speed, the wind turbines will be located in an optimized way. In this phase, the wake effect [38] which incurs the wind speed deficit on the downstream WTs and thereby the total power production reduction of the whole wind farm is the main concern. Considering the wake losses, the energy production model of the whole wind farm is extremely non-convex. Since the estimation of wake losses is the critical part of the micro-siting optimization of WTs, in another term, WFLOP [39], it becomes quite challenging to ensure the optimality of the solution. The fundamental elements of WFLOP can be summarized as follows [40]:

1) Variables: the positions of each WT which can be modelled via grid model (partition the whole area into grids and the center of each grid represents the potential location of wind turbine) or coordinate model (WTs are given in x and y coordinates).
2) Objective function: the objective function is either minimizing the LCOE which accounts for the capital cost, operational and maintenance (O&M) cost and annual energy production or maximizing the energy production considering wake losses.
3) Constraints: some offshore restriction areas might be defined. In order to ensure a longer lifetime of WTs, the minimum distance between each pair of WTs should be considered.

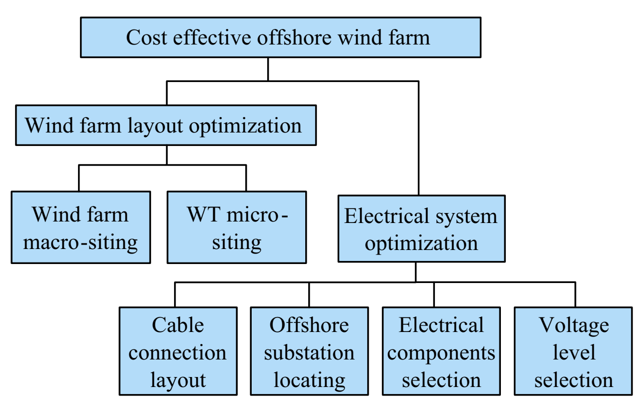


Fig. 1 Dominant factors related to the offshore wind farm layout and electrical system optimization

4) Methodology: heuristic optimization method is widely applied, whereas the recent works start to use mathematical programming method to solve the problem via wake model linearization.

3 Micro-siting of WTs

The wake losses can take up to 10%–15% [41] of annual energy production (AEP) which will make the wind farm owner lose a large sum of money. Hence, it is critical to estimate the energy yield of an offshore wind farm considering wake losses accurately so that a solid background and basis can be provided to the wind farm optimization research.

3.1 Energy production estimation of wind farm

The wind speed at the downstream WT will be reduced when the wind bypasses the upstream WT which incurs the reduction of the energy yields of a wind farm. This is the simple description of the wake effect [42, 43]. To estimate the wake losses, the wind resource distribution of the construction area will be measured via years of sampled onsite wind speed at first. The uncertainty of wind power levels off when it is considered for a long time span in wind farm planning and design phase. Then, the measured wind speed will be represented statically via Weibull distribution [4] and used as the input for the wake model for energy production calculation. Currently, the works of wake modelling can be categorized into two sorts: one is using computational fluid dynamic (CFD) technology which can obtain the dynamic wind flow characteristic accurately by discretizing the continuous field, however, the computational time is quite long [44]; the other is using an analytical model instead of differential equations to estimate the wind speed deficit [45–50]. The long calculation time keeps the CFD technology away from involving into wake loss estimation for the whole offshore wind farm while analytical wake models are widely used as Jensen model, Ainslie model and G. C. Larsen model [45]. In the Jensen model, the generated wakes are assumed to have a characteristic of linear expanding along wind flowing direction while vertical to wind direction, while the wind speed within the wake is considered to be identical. A parabolic eddy viscosity model was proposed by Ainslie in which the two-dimensional wake model was assumed to be axially symmetric. Though the calculation process has already been simplified by solving an axisymmetric form of Navier Stokes equations, it is still quite slow for the optimization work. Similarly, Larsen provided a semi-analytic wake model which was recommended for solving wake loading problem [46]. Recently, a binary matrix calculation method is proposed for wake loss calculation based on the Jensen model [47] which is applicable for WFLO. Based on the existing wake models, some commercial software has already come out, such as Wind Atlas Analysis and Application software [48] which is the most popular one [39], WindSim [49] and Meteodyn [50]. The above-mentioned works provided vital information for wind resource assessment. However, the Jensen model is most frequently used for solving the WFLOP due to its simplicity and accuracy [39]. The analytical equations are specified in the following.

3.1.1 Common wake models

The Jensen wake model is the most popular model in this research area due to its high simplicity and practicality. The wind speed deficit due to upstream WT is calculated by identifying the effective wake influence area which is illustrated in Fig. 2.

In Fig. 2, O_i, O_j, and O_j' represent the position of upstream WT, the position of downstream WT and the centroid of the generated wake at distance x along the wind blowing direction, respectively. Due to the wake effect, the wind speed decays when it bypasses the WT rotor (as indicated by the black filled object in Fig. 2a). As can be seen in Fig. 2a, the red lines indicate the shape of the wake expansion while the blue area in Fig. 2b shows the effective wake area, which means that only the blue area of the downstream WT is actually taken into account in the wind

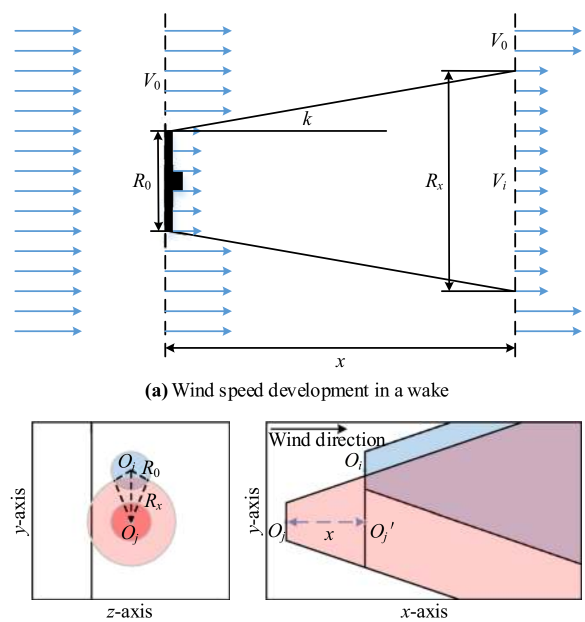


Fig. 2 Schematic representation of wind speed deficit

speed deficit calculation process [51]. The mathematical formulations are as follows [43]:

$$V_i = V_0 - V_0\left(1 - \sqrt{1 - C_t}\right)\left(\frac{R_0}{R_{\mathrm{i}}}\right)^2\left(\frac{S_{overlap}}{S_0}\right) \tag{1}$$

$$R_x = R_0 + kx \tag{2}$$

where V_0 and V_i are the incoming wind speed and wind speed at distance x along wind flowing direction in the wake; C_t is the thrust coefficient of the WT; S_0 is the rotor swept area; $S_{overlap}$ is the wake swept area; R_0 and R_x are the rotor radius and the generated wake radius at distance x along wind flowing direction; and k is the wake decay constant. The recommended value of k is 0.04 for the offshore environment [52].

Another popular wake model is the Larsen model which defines the boundary conditions using the results of the full-scale experiment. The mathematical formulations are calculated as follows:

$$V_i = -\frac{V_0}{9}K^2\left(\pi R_0^2 C_t x - 2\right)^{\frac{1}{3}} \tag{3}$$

$$K = R_0^{\frac{2}{3}}\left(3c_1^2 C_t \pi R_0^2 x\right)^{-\frac{1}{2}} - \left(\frac{35}{2\pi}\right)^{\frac{3}{10}}\left(3c_1^2\right)^{-\frac{1}{5}} \tag{4}$$

The wake swept area is expressed as:

$$S_{overlap} = \pi\left(\frac{35}{2\pi}\right)^{\frac{2}{5}}\left(3c_1^2\right)^{\frac{2}{5}}\left(C_t \pi R_0^2 x\right)^{\frac{2}{3}} \tag{5}$$

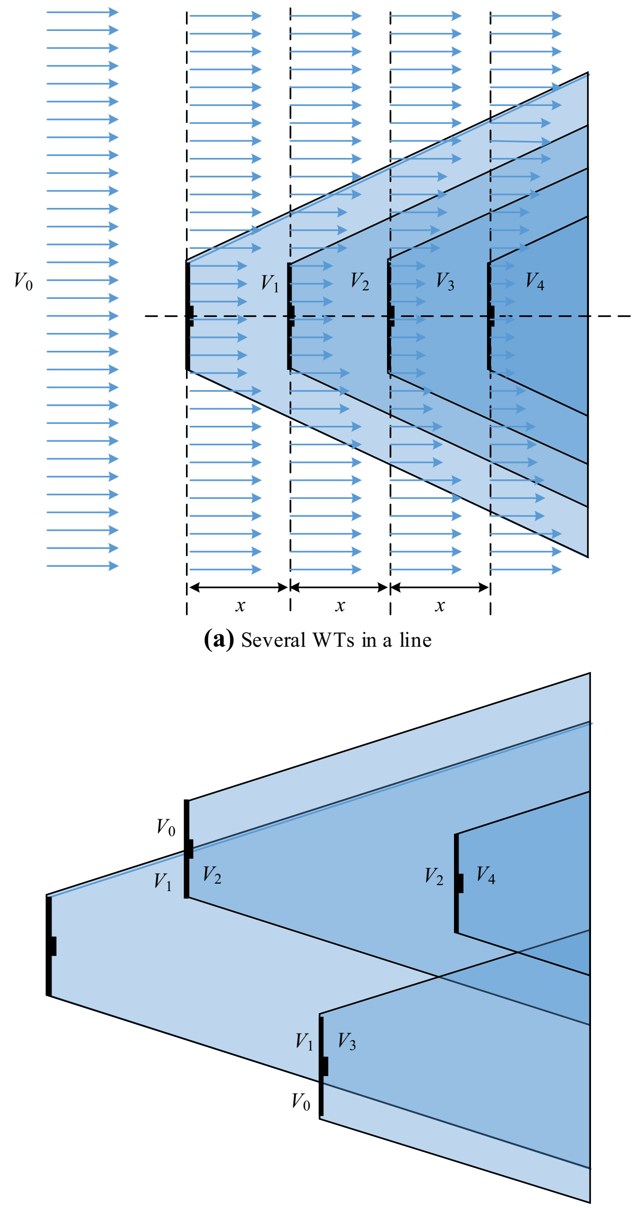
where c_1 is a constant that is defined empirically; K is an intermediate variable. Additionally, the multiple wake effects are superposed using the linear sum for Larsen model. There are other four widely used wake models developed by Technical University of Denmark: Dynamic Wake Meandering, Fuga, Ellipsys3D LES and RANS.

3.1.2 Wake combination

The wake speed deficit can incur the energy loss within the wind farm, and this effect will be more severe in a large wind farm with large numbers of WTs. Figure 3 shows two examples of multiple wake effect [53]. If the WTs are aligned as Fig. 3a, the calculation will be simpler compared to Fig. 3b, since in Fig. 3b, the effective wake area should be identified one by one.

Normally, the multiple wakes are calculated by using the following four approaches [54]. Then the wind speed deficit corresponding to multiple wakes can be formulated as:

1) Geometric sum:



(a) Several WTs in a line

(b) Scattered WT placement

Fig. 3 Schematic multiple wake model

$$\frac{v_{n+1}}{V_0} = \prod_{i=1}^{n}\frac{v_{i+1}}{v_i} \tag{6}$$

2) Linear sum:

$$1 - \frac{v_{n+1}}{V_0} = \sum_{i=1}^{n}\left(1 - \frac{v_{i+1}}{v_i}\right) \tag{7}$$

3) Energy balance:

$$V_0^2 - v_{n+1}^2 = \sum_{i=1}^{n}\left(v_i^2 - v_{i+1}^2\right) \tag{8}$$

4) Quadratic sum:

$$\left(1-\frac{v_{n+1}}{V_0}\right)^2=\sum_{i=1}^{n}\left(1-\frac{v_{i+1}}{v_i}\right)^2 \tag{9}$$

where n is upstream turbines number; v_{n+1} is the wind speed at the calculated WT; v_i and v_{i+1} are the wake velocities of wind turbine i and i+1, respectively. Reference [55] emphasizes the importance of wake combination methods which are compared in four different offshore wind farms. The result shows that the linear and quadratic wake combination methods have the best results.

3.2 Wind farm control strategy

In general, the power of a single WT is calculated by its power curve and the frequency distribution of the wind speed at the hub height. The effect of other factors on the wind farm power production, such as the wake effect, is estimated by the approximation formula [56]. The advantage of this method is that it is easy to calculate, but the impact of the turbine control and wind farm control strategy on power production is ignored.

It should be noticed that not all the energy from the wind can be converted into electricity and transferred to the main grid, and that this quantity is in part decided by the control strategy. If the WT is controlled to generate the maximum power at any wind speed, in other words, the WT is controlled to catch its maximum power point, this control strategy is called maximum power point tracking (MPPT) strategy [57], which is widely used for WT control. Based on this strategy, the power generated by each WT can be calculated as [58]:

$$P=0.5\rho C_{p,opt}(\beta,\lambda_{opt})\pi R_0^2 v^3 \tag{10}$$

where ρ is air density; R_0 is the rotor radius; and v is the wind speed in hub position. The generated power P is obtained by following the maximum power coefficient $C_{p,opt}$, which is dominated by two factors: pitch angle β and optimal tip speed ratio λ_{opt}. The MPPT can ensure the maximum power to be obtained for each WT. However, taking wake effect into consideration, the MPPT might not be the optimal control strategy for the whole wind farm.

In recent years, many researches focus on maximizing the power production of wind farm. The basic idea is to reduce the impact of the wake by derating the upwind turbines so as to maximize the total power production of wind farm. This concept is named as active wake control (AWC) in [59]. There are basically two methods: one is pitch-based AWC; the other is yaw-based AWC. Pitch-based AWC reduces the wake effect by adjusting the pitch angle or decreasing the active power reference. Yaw-based AWC controls the upwind turbine operating with rotor yaw misalignment to divert its wake away from the downwind turbine [60]. Most of the research belongs to the former method. Because an inappropriate yaw-based AWC will lead to the increase of the loads. Reference [61] tried to get a higher total power production compared with MPPT by tuning the pitch angle of each WT. GA was adopted to find the optimized pitch angels which contributed to a higher power production. The methods were validated through a simple array layout wind farm and the power production estimation was accomplished by blade element momentum (BEM) theory and eddy viscosity model (EVM). In the meantime, a simultaneous optimization method of tip speed ratio and blade pitch angle was specified in [62] and validated using Horns Rev I wind farm layout. Similarly, the pitch angle optimization for maximizing the overall power production of the wind farm was done in [63] with a simplified wake model. Recently, an optimized power dispatch strategy for a scatter wind farm layout was proposed with the purpose of minimizing the levelized production cost [64]. Compared with [61–64] where meta-heuristic optimization method was adopted to benefit the objective function, a gradient-based optimization has been reported in [65] to improve the power production of the offshore wind farm.

3.3 Optimization of wind farm layout

As mentioned in the previous text, the estimation of energy production of an offshore wind farm highly depends on the wake model and control strategy. Though many works [61–65] have presented the possibility of increasing the energy yields of whole wind farm using new control strategy, there is no evidence for its application in real farms. Hence, the WFLOP is always done based on assuming a MPPT control strategy. From (1) to (5), it can be seen that the wake model is highly related to the relative positions of WTs and the input wind speed. That explains why the wind farm is selected to be constructed in a good wind resource distribution zone, and why the wind farm layout requires to be optimized.

At the beginning, the WTs within the wind farm are designed to be distributionally well-regulated. Thus, the dominant wind direction of the local area becomes an important factor for WT placement [66]. It can be imagined that the distance between WTs along prevailing wind direction should be longer than the weak wind direction so that the wake loss can be reduced. As stated in [67], the proper distance between WTs in dominant wind direction is 8 times rotor diameter (8D) to 12D, while in the direction perpendicular to dominant wind direction, the distance should be 3D to 5D [67]. In the initial stage, the placements of WTs are based on this empirical conclusion. In practice, the wind farm layout is usually designed manually. The wind resource engineer will initialize some blueprints according to individual experience, and compare the energy production of them using commercial software before making the final decision. However, the positions of WTs are actually not in the optimization procedure. A mathematical derivation between WT positions and the objective function (annual energy production or cost of energy) should be specified so that a clear rule for wind farm layout design can be further determined.

3.3.1 Grid model

In 1994, reference [68] proposed a method to minimize the cost of energy for offshore wind farm using GA which is the beginning of offshore WFLO. After that, several works have been published using the optimized layout in [68] as a benchmark [69–72]. By tuning the parameters of GA, a better layout has been obtained in [69] and further improved by Monte Carlo method [69]. Similarly, a binary particle swarm optimization with time-varying acceleration coefficients (BPSO-TVAC) algorithm to solve the WFLO was presented and compared with five other heuristic algorithms [71]. Also, using GA to solve the WFLOP was presented in [72]. However, it adopted another wake model instead of Jensen model to estimate wake losses, and the final result was compared with commercial software WindFarmer instead of benchmark [68]. A layout design for a real offshore wind farm was addressed in [73] using evolutionary computational approach. It should be noticed that the final design is still with an array layout, though many types of research have been done on making a scattered WT placement. Hence, the same authors have adopted coral reefs optimization method to make a better design, which can generate more power production compared with the layouts obtained by the evolutionary approach, differential evolution and harmony search algorithm [74]. A comparative study between GA and PSO in solving WFLOP was done in [75] considering the irregular boundary wind farms.

In addition to heuristic algorithms, mathematical programming (quadratic integer program (QIP) and mix-integer linear program (MILP) in [76] while sequential optimization in [77]) was also adopted to solve WFLOP. The LP was adopted in [78] to optimize the positions of WTs for the onshore case. The combined wake losses are calculated by linear superposition of wind velocity deficit incurred by each WT. This method was further developed in [79] to solve the WFLOP for offshore case by using MILP based heuristic algorithm. To increase the accuracy of wake loss estimation, a CFD wake model was adopted in [80] and used as the input of mixed input programming (MIP) to solve the WFLOP. In [76–80], the wake model was either linearized or modified to formulate a convex optimization problem. However, the wake model itself is non-convex, while the modified model would give out a larger error on energy production estimation. Thus, reference [81] suggested to combined the heuristic method with the mathematical programming to solve the WFLOP. In [81], the initial solutions were generated by the heuristic method, and a nonlinear solver was implemented for searching the local optimum. It was proved that the final solution holds the Karush-Kuhn-Tucker optimality conditions.

3.3.2 Coordinate model

In the above papers, the micro-siting of the offshore wind farm was done by separating the construction area into a number of grids, which simplified the problem and thus reduced the computational cost. The number of possible solutions of wind farm layout can be expressed as follows [82]:

$$N_s = \frac{N_{cell}!}{N_{WT}!(N_{cell}! - N_{WT}!)} \tag{11}$$

where N_s indicates the overall possible solutions; N_{WT} and N_{cell} are the totally number of WTs to be installed and total number of areas that the studied area has been divided into, respectively. By using the grid model, the complexity of WFLO can be simplified. However, some potential solutions will certainly be neglected. In order to get a more cost-effective wind farm layout, some works solve the WFLOP using the coordinate form to represent the position of WT [83–93], which is the so-called coordinate model. The two models are commonly used for wind turbine micro-siting optimization. Under the constraint that the distance between each pair of WTs should be larger than 4D, an evolutionary algorithm was used in [83] to find the coordinate of WTs within a circular boundary profile wind farm. Compared with [83], the ant colony algorithm was proved to be more outstanding by getting a layout which can produce more power in [84]. Two advanced PSO techniques (Gaussian PSO algorithm in [85] and mixed-discrete particle swarm optimization (MDPSO) algorithm in [86]) were also implemented to solve the WFLOP. GA was again used to get an optimized layout in [87, 88]. However, the proposed optimization model considered more practical aspects as load-bearing capacity, WT hub height, seabed condition and restricted area on sea were in [87], while a scattered layout was proved to be with the best performance in terms of LCOE within three common layouts: aligned, staggered, scattered in [88], where an offshore wind farm in Hong Kong was selected as the study case. Based on the Jensen model, a continuous wake model was proposed in [89] to formulate the wind farm power function and calibrated using CFD simulation data. Moreover, the optimized layout was found by sequential convex programming, which was demonstrated to be efficient enough to tackle the large offshore wind farm optimization problem with a large number of WTs. Using Horns Rev I as the benchmark which was the same as [89], reference [90] used a random search (RS) algorithm to get the optimized layout. Due to the non-convex characteristic of WFLO, no evidence shows that the existing work can ensure the optimality. Hence, researchers took efforts in improving the optimization algorithm to get a near optimal solution which can benefit the wind farm owner more. In [81], a combined optimization method was introduced using the heuristic method to set an initial layout, and the local optimal solution under each initial layout was obtained using nonlinear mathematical programming techniques. A comparative study in terms of layout model (grid model and coordinate model) and cost model (model in [68] and Chen's model in [92]) was done in [91] using GA. Recently, a WFLO has been done in [93] considering the forbidden area offshore due to the gas pipe, oil well, etc.

4 Optimization of electrical system for offshore wind farm

For offshore wind farms, many expensive components should be used, which reduce the proportion of WT investment, while the array cable cost is enhanced up to 9% [1]. Due to the development of offshore wind energy technology, the offshore WTs become bigger and bigger, which requires a larger sea area for minimizing the wake effect. On the other side, the offshore wind farm is moving further to the sea. Both factors indicate that a large number of submarine cables and electrical components would be needed so that the power extracted from the wind can be effectively transferred to the grid. The present optimization work for the offshore wind farm electrical system can be categorized into three parts: the algorithm development and application for cable connection scheme design, the combinatory optimization of offshore wind farm electrical system, as well as the determination of OS in terms of quantity and location.

4.1 Electrical system optimization with given WT positions

Reference [4] on a comparative study of the wind farm electrical system is the initial work related to wind farm electrical system design. Similar comparisons have also been done in [5, 22]. Some typical AC and DC wind farm topologies were compared and investigated in terms of power losses, cost as well as reliability in [5], while different collection system designs for the offshore wind farm were analyzed and compared in [22]. The above works concerned about the best electrical system design for offshore wind farm within a limited selection, and no optimization method was applied, whereas there are many factors that can have an impact on the performance of offshore wind farm as voltage level, electrical equipment type, cable connection layout, etc. If the input database is so big that the traditional ergodic method will make the computer out of memory, then some optimization method should be considered to reduce the computational cost and increase the computational efficiency. By thinking of solving the problem efficiently, references [6, 7] presented a heuristic optimization method which can help get an optimized offshore wind farm electrical system with lower cost and higher reliability [23]. However, the optimization is actually done based on the selection of electrical equipment regarding voltage level and type, and the cable connection scheme is decided based on several typical schemes (string clustering, star clustering, with or without redundancy). It should be noticed that the cable connection layout in [4–7, 20–23] is selected from a variety of empirically designed layouts. If the cable connection layout can be designed using some specific and suitable algorithm, the cost of the whole electrical system can be expected to be further reduced.

From the practical point of view, the cable connection scheme should concern two aspects: no crossed layout should be permitted, and the current in each cable under full load condition should not exceed the current carrying capability of responding cable. Some classical mathematical problem has been introduced to solve the cable connection layout optimization problem (CCLOP), such as minimum spanning tree (MST) problem [34], travelling salesman problem (TSP) [35], and open vehicle routing problem (OVRP) [36]. The cable connection layout was optimized based on the concept of MST in [8, 10, 15, 19, 24, 25]. Reference [8] presented an overall work on the topic of offshore wind farm electrical system optimization, which took voltage level and electrical equipment type selection, OS determination regarding locations and quantity, as well as collection system cable connection layout design into consideration. The fuzzy *c*-means (FCM) clustering algorithm was adopted to decide the number of WT groups and in each group the OS will be centrally located. The cable connection layout was derived by using the concept of MST and the large wind farm was partitioned via FCM method [9]. A capacitated MST was introduced in [25] to help find the cable connection layout using mixed integer linear programming method, while MST was applied in [8] to connect WTs in each WT group which was decided by *k*-clustering algorithm with the radial angle criterion. Moreover, local search method was used to find some alternative layouts by which a better layout with lower cost was also found. Considering the seabed condition, some sea area will not be suitable or costly to lay cables. This problem was described and solved by a convex hull based bypassing algorithm combined with the MST algorithm in [24], while MST was modified by introducing external splice locations in [10]. The same authors [10] also proposed a quality threshold clustering algorithm to solve the same problem [13]. The CCLOP was formulated as a well-known OVRP with unit demands in [20] and solved by Clarke and Wright savings heuristic algorithm. However, only one cable is permitted to connect a turbine, a condition that is not imposed in the real-world cases. Similarly, the cable connection layout can also be optimized by TSP [11, 12]. In [11], the GA was adopted to optimize the layout considering the cable capital cost and power losses. The simulation results showed that the branched layout was superior to their radial counterpart. It should be noticed that the CCLOP is non-convex, which means the deterministic method can help find a better layout compared with manual design. Hence, some authors tried to use the heuristic algorithm as GA or PSO [10, 12, 15, 16] to make a better design. The cable connection layout of a 4-substation offshore wind farm was optimized with GA in [17] and was treated as the benchmark to be compared within [12]. Though some improvements for reducing cost were obtained by the layout proposed in [12], some crossed cables which contribute to a higher cost are not taken into account. PSO was firstly introduced to solve CCLOP in [16] where the proposed heuristic method was proved to be outperformed by a deterministic algorithm (MST) by finding a layout with a lower cost.

The OS is usually located near the shore or in the center of the offshore wind farm. The impact of the OS location was not introduced until the presentation of [14]. In [14], the benefit of centrally located OS was analyzed from a practical point of view. Later, the real OS location optimization was done by making the best decision from a series of given positions in [18]. Reference [15] specified the significant impact of OS location on the cost of offshore wind farm cable connection layout optimization, which permitted more free areas for OS. In addition to the heuristic algorithm, deterministic optimization method, such as linear programming [18], was also adopted to solve CCLOP. In [25], the OS location was optimized using *k*-means++ clustering method. The CCLOP was solved using an MILP formulation. However, the OS location and the cable connection layout were optimized separately and only one type of cable was considered. In [19], FCM method was adopted to cluster the wind turbines into groups. The cable connection layout, voltage level, electrical equipment type, and OS location were all taken into account. However, the power losses were within the objective function. Compared to [25], different cable types, voltage constraints, and power losses were considered in [26–28]. The priority of [28] over [26, 27] is that the OS location was optimized using PSO-FCM, while the CCLOP was formulated as a mixed integer non-linear programming (MINLP) problem and transformed into MILP problem through Bender's decomposition algorithm. In [29–31], the same author presented a new MILP formulation model which solved the CCLOP by considering technical constraints, OS location, cable types and obstacles within the wind farm. It should be noticed that a new transformer module was considered in [31] as an alternative solution to collect wind power instead of OS, and optimized together with the cable connection layout. Besides, some recent works [32, 33] considered CCLOP using ring structure to reduce the losses due to expected energy not supply (EENS) during the lifetime [32] as well as the failure rate and mean time to repair (MTTR) of cables [33].

4.2 Co-optimization for offshore wind farm

The works introduced in Section 3 show more interests in harvesting the offshore wind farm without considering the investment on the electrical system, while the CCLOP was solved by the methods proposed in Section 3 with a predefined wind farm layout. It could be imagined that if two aspects of optimization work can be combined and solved simultaneously, a better wind farm design could be decided. The overall optimization in terms of WT positions as well as the cable connection layout was conducted in [94] to make reach the target of a cost-effective wind farm. However, the highlighted innovation was not well demonstrated through the case study. The wind farm layout was optimized using a grid model, while the optimized cable connection layout was obviously crossed. Recently, a combined optimization for the offshore wind farm was presented in [95] which made some progress in optimizing the WT position using coordinate-based model, and the uncrossed cable connection layout was also considered. From the simulation results [95], it can be seen that the simultaneous optimization for the offshore wind farm outperforms the traditional way (which optimizes the WT position first and design the cable connection layout based on this layout) of finding a lower LCOE.

5 Conclusion

The offshore wind farm increasingly attracts worldwide attention due to its contributions in reducing carbon emission as well as the potential value of higher energy production efficiency. In this paper, a review work has been done based on earlier works related to the WT micro-siting and electrical system optimization of the offshore wind farm. Generally, most of the recently published works for WT micro-siting have been done based on a coordinate model, which has been demonstrated to be a better model than the grid model. The reason is that a coordinate model allows the WTs to move within a continuous domain which provides more potential solutions. As mentioned previously, the wind farm layout design is an NP-hard optimization problem. Thus, most of the works were presented by implementing a heuristic algorithm as GA, PSO, etc., while a new trend of adopting gradient-based or hybrid optimization technology for wind farm layout design appears. On the other hand, the method of solving CCLOP has been updated from merely deterministic algorithms or heuristic algorithms to hybrid methods, ending up with a better layout with lower cost.

Based on a literature study, some potential future research fields can be concluded as follows:

1) Most of the papers present the works considering optimizing the electrical system topology solo, while these two factors are actually co-related which should be considered at the same time in wind farm planning phase so that an overall cost-effective wind farm could be found. However, the wind turbine micro-siting and electrical system design usually belong to the different sections or teams in the same company. Great efforts should be put on the data exchange, and a new management system may be needed to ensure the good collaboration between different sections.
2) Fatigue load is the change observed in a material under the influence of stress generated during cyclic loading. It causes the reduction of wind farm lifetime due to the wake turbulence. If closer spacing is arranged between a pair of WTs, the fatigue load will increase. In contrary to that, the larger distance will result in a smaller fatigue load. This problem is never addressed in any existing WFLO paper. Analytical models are needed to estimate the fatigue load of the whole wind farm, and it would be interesting to consider its impact on the economic performance of the final layout which could contribute to the further reduction of LCOE.
3) Reliability is an important factor for the performance of offshore wind farm. Since the O&M is very expensive and time-consuming for an offshore wind farm, it would be nice to have a safe electrical system. However, more reliability always responds to more investment. Hence, the electrical system design should concern about both aspects and find the trade-off according to the practical requirements. From the engineering point of view, the electrical engineers expect more than one feeder to collect the energy generated by the WTs. However, according to the real operation experience, the faults usually come from the electronic devices and control system while the cable is relatively reliable for the offshore case. Though some works have addressed reliability problem in wind farm design [4, 7], the quantitative relations between reliability and economy of cable connection layout has not been well addressed. Based on the historical O&M data, it would be interesting to include the reliability issue in the large-scale offshore wind farm optimization so that a better design can be proposed which contributes to the reduction of LCOE.
4) Heuristic algorithm and mathematical programming method are both applicable in solving the CCLOP. For wind farm with a limited number of WTs, mathematical programming method has its unique advantages as fast convergence and robustness. However, the development of offshore wind farm is towards large capacity with more than 100 WTs. In such a case, the heuristic algorithm will show its advantage since it can get a new optimal solution faster, and high-performance computing technology can be easily adopted to further increase the computational speed. It could be a breakthrough if a hybrid method can be proposed for solving the CCLOP of the future offshore wind farm.

The literature study is focusing on the optimization work of an offshore wind farm. It can be imagined that there is a great similarity between the offshore and onshore wind farm optimization. The present algorithm and methodologies can be applied to onshore wind farm optimization if the following problems can be resolved.

1) The terrain condition for the onshore case is much more complex. The onshore wind turbines can be installed in plain, mountainous region or forest, which makes the present wake model inapplicable. More accurate models are required to estimate the wake losses accurately.
2) For an onshore wind farm, the overhead line is widely used. For the sake of the possibility of overhead line T connection, there will be more solutions for the onshore wind farm electrical system layout optimization. In addition, the design of construction road and forbidden area for installation should also be considered, along with the overhead line routine optimization work which is another challenge for using the present optimization method. The well-known minimum Steiner tree problem can be introduced to help optimize the layout. However, new models and algorithm should be applied to tackle this problem and help find an optimal solution.

References

[1] Wind energy Denmark (2017) http://www.windenergydenmark.dk/program/presentations/day-1.aspx. Accessed 1 November 2017
[2] Eric W (2018) NP-problem. http://mathworld.wolfram.com/NP-Problem.html. Accessed 20 April 2018
[3] Rosalind A, Gary N, Stuart D et al (2011) Wind turbine interference in a wind farm layout optimization mixed integer linear programming model. Wind Eng 35(2):165–175
[4] Stefan L (2003) Configuration study of larger wind park. Dissertation, Chalmers University of Technology
[5] Himanshu JB, Bruce AM, Hans KH (2012) Comparison of wind farm topologies for offshore applications. In: Proceedings of 2012 IEEE PES general meeting, San Diego, USA, 22-26 July 2012, pp 1–8
[6] Zhao M, Chen Z, Blaabjerg F (2008) Application of genetic algorithm in electrical system optimization for offshore wind farms. In: Proceedings of the 3rd international conference on electric utility deregulation and restructuring and power technologies (DRPT), Nanjing, China, 6–9 April 2008, pp 1–7
[7] Zhao M, Chen Z, Blaabjerg F (2009) Optimization of electrical system for offshore wind farms via genetic algorithm. IET Renew Power Gener 2(3):205–216
[8] Chen N (2011) Large-scale offshore wind farm electrical collection systems optimization. Dissertation, Shanghai University of Electric Power
[9] Huang LL, Chen N, Zhang HY et al (2012) Optimization of large-scale offshore wind farm electrical collection systems based on improved FCM. In: Proceedings of the international conference on sustainable power generation and supply (SUPERGEN 2012), Hangzhou, China, 8–9 September 2012, pp 1–6
[10] Sudipta D, Thomas JO (2012) Optimal wind farm collector system topology design considering total trenching length. IEEE Trans Sustain Energy 3(3):339–348
[11] Jenkins AM, Scutariu M, Smith KS (2013) Offshore wind farm inter-array cable layout. In: Proceedings of 2013 IEEE Grenoble conference, Grenoble, France, 16–20 June 2013, pp 1–6
[12] Gonzalez-Longatt FM, Wall P, Regulski P et al (2012) Optimal electric network design for a large offshore wind farm based on a modified genetic algorithm approach. IEEE Syst J 6(1):164–172
[13] Dutta S, Overbye TJ (2011) A clustering based wind farm collector system cable layout design. In: Proceedings of the 2011 IEEE power and energy conference (PECI), Illinois, USA, 25–26 February 2011, pp 1–6
[14] Hopewell PD, Castro-Sayas FD, Bailey I (2006) Optimising the design of offshore wind farm collection networks. In: Proceedings of the 41st international universities power engineering conference (UPEC), Newcastle-upon-Tyne, UK, 6–8 September 2006, pp 84–88
[15] Hou P, Hu W, Chen Z (2015) Offshore substation locating in wind farms based on prim algorithm. In: Proceedings of the IEEE PES general meeting, Denver, USA, 26–30 July 2015, pp 1–5
[16] Hou P, Hu W, Chen Z (2016) Optimization for offshore wind farm cable connection layout using adaptive particle swarm optimization minimum spanning tree method. IET Renew Power Gener 10(5):694–702
[17] Li DD, He C, Fu Y (2008) Optimization of electric distribution system of large offshore wind farm with improved genetic algorithm. In: Proceedings of the IEEE PES general meeting, 20–24 July 2008, pp 1–6
[18] Lumbreras S, Ramos A (2013) Optimal design of the electrical layout of an offshore wind farm applying decomposition strategies. IEEE Trans Power Syst 28(2):1434–1441
[19] Hou P, Hu W, Chen C et al (2016) Overall optimization for offshore wind farm electrical system. Wind Energy 20:1017–1032
[20] Lundberg S (2003) Performance comparison of wind park configurations. Dissertation, Chalmers University of Technology
[21] Bauer J, Lysgaard J (2015) The offshore wind farm array cable layout problem-a planar open vehicle routing problem. J Oper Res Soc 3(66):360–368
[22] Quinonez-Varela G, Ault GW, Anaya-Lara O et al (2007) Electrical collector system options for large offshore wind farms. IET Renew Gener 1(2):107–114
[23] Zhao M, Chen Z, Blaabjerg F (2007) Generation ratio availability assessment of electrical systems for offshore wind farms. IEEE Trans Energy Convers 22(3):755–763
[24] Dutta S, Overbye TJ (2013) A graph-theoretic approach for addressing trenching constraints in wind farm collector system design. In: Proceedings of the IEEE power and energy conference (PECI), Illinois, USA, 22–23 February 2013, pp 48–52
[25] Pillai AC, Chick J, Johanning L et al (2015) Offshore wind farm electrical cable layout optimization. Eng Optim 47(12):1689–1708
[26] Cerveira A, Sousa AD, Pires EJS et al (2016) Optimal cable design of wind farms: the infrastructure and losses cost minimization case. IEEE Trans Power Syst 6(31):4319–4329
[27] Wedzik A, Siewierski T, Szypowski M (2016) A new method for simultaneous optimizing of wind farm's network layout and cable cross-sections by MILP optimization. Appl Energy 182(15):525–538
[28] Chen YY, Dong ZY, Meng K et al (2016) Collector system layout optimization framework for large-scale offshore wind farms. IEEE Trans Sustain Energy 7(4):1398–1407
[29] Fischetti M, Leth J, Borchersen AB (2015) A mixed integer linear programming approach to wind farm layout and inter-array cable routing. In: Proceedings of the American control conference, Palmer House Hilton, Chicago, USA, 1–3 July 2015, pp 5907–5912
[30] Fischetti M, Pisinger D (2016) Inter-array cable routing optimization for big wind parks with obstacles. In: Proceedings of the European control conference (ECC), Aalborg, Denmark, 29 June–1 July 2016, pp 617–622
[31] Fischetti M, Pisinger D (2017) Optimal wind farm cable routing: modeling branches and offshore transformer module. Networks 72(1):42–59
[32] Dahmani O, Bourguet S, Machmoum M et al (2017) Optimization and reliability evaluation of an offshore wind farm architecture. IEEE Trans Sustain Energy 8(2):542–550
[33] Gong X, Kuenzel S, Pal BC (2017) Optimal wind farm cabling. IEEE Trans Sustain Energy 9(3):1126–1136
[34] Devore RA, Temlyakov VN (1996) Some remarks on greedy algorithm. Adv Comput Math 5(1):173–187
[35] Bektas T (2006) The multiple traveling salesman problem: an overview of formulations and solution procedures. Omega 34(3):209–219

[36] Li F, Golden B, Wasil E (2007) The open vehicle routing problem: algorithms, large-scale test problems, and computational results. Comput Oper Res 34(10):2918–2930
[37] Bondy JA, Murty USR (1976) Graph theory with applications. North-Holland, Elsevier Science Ltd
[38] Ma Y, Yang H, Zhou X et al (2009) The dynamic modeling of wind farms considering wake effects and its optimal distribution. In: Proceedings of 2009 world non-grid-connected wind power energy conference (WNWEC'09), Nanjing, China, 24–26 September 2009, pp 1–4
[39] Shakoor R, Hassan MY, Raheem A et al (2016) Wake effect modeling: a review of wind farm layout optimization using Jensen's model. Renew Sustain Energy Rev 58:1048–1059
[40] Lackner MA, Elkinton CN (2007) An analytical framework for offshore wind farm layout optimization. Wind Eng 31:17–31
[41] Barthelmie RJ, Larsen GC, Frandsen ST (2006) Comparison of wake model simulations with offshore wind turbine wake profiles measured by sodar. J Atmos Ocean Technol 23:888–901
[42] Ainslie JF (1988) Calculating the flow field in the wake of wind turbines. J Wind Eng Ind Aerodyn 27(1–3):213–224
[43] Jensen NO (1983) A note on wind generator interaction. Risø National Laboratory, Roskilde
[44] Andersen SJ, Sørensen JN, Ivanell S et al (2014) Comparison of engineering wake models with CFD simulations. J Phys Conf Ser 524:1–11
[45] Thørgersen M, Sørensen T, Nielsen P (2005) WindPRO/PARK: introduction wind turbine wake modelling and wake generated turbulence. EMD International A/S, Aalborg
[46] Larsen GC, Højstrup J, Madsen HA (1996) Wind fields in wakes. In: Proceedings of the 1996 European wind energy conference and exhibition, Gothenburg, 20–24 May 1996, pp 764–768
[47] Hou P, Hu W, Soltani M et al (2015) A novel energy yields calculation method for irregular wind farm layout. In: Proceedings of the 41st annual conference of the IEEE industrial electronics society (IECON 2015), Yokohama, Japan, 9–12 November 2015, pp 380–385
[48] WAsP—the wind Atlas analysis and application program. http://www.wasp.dk/. Accessed 4 November 2016
[49] WindSim technical brochure. http://www.windsim.com/documentation/windsim_brochure_WEB.pdf. Accessed 12 December 2013
[50] Meteodyn meteorology and dynamics (2013) http://www.meteodyn.com/en/windenergy.html. Accessed 11 December 2013
[51] Hou P, Hu W, Soltani M et al (2015) Optimized placement of wind turbines in large scale offshore wind farm using particle swarm optimization algorithm. IEEE Trans Sustain Energy 4(6):1272–1282
[52] Brower M, Robinson N, Alonge C et al (2012) Overview of six commercial and research wake models for large offshore wind farms. In: Proceedings of the Europe's premier wind energy event, Copenhagen, Denmark, 16–19 April 2012, pp 95–99
[53] Hou P, Hu W, Soltani M et al (2017) Offshore wind farm layout optimization considering optimized power dispatch strategy. IEEE Trans Sustain Energy 2(8):638–647
[54] Katić I, Højstrup J, Jensen NO (1986) A simple model for cluster efficiency. In: Proceedings of the European wind energy association conference and exhibition, Rome, Italy, 7–9 October 1986, pp 407–410
[55] Habenicht G (2011) Offshore wake modelling. In: Proceedings of the renewable UK offshore wind conference and exhibition, Liverpool, UK, 29–30 June 2011, pp 1–8
[56] Schallenberg-Rodriguez J (2013) A methodological review to estimate techno-economical wind energy production. Renew Sustain Energy Rev 21:272–287
[57] Errami Y, Benchagra M, Hilal M et al (2012) Control strategy for PMSG wind farm based on MPPT and direct power control. In: Proceedings of the multimedia computing and systems, Tangier, Morocco, 10–12 May 2012, pp 1125–1130
[58] Gonzáleza JS, Payana MB, Santos JR (2010) Optimum wind turbines operation for minimizing wake effect losses in offshore wind farms. Renew Energy 8(35):1671–1681
[59] Kanev SK, Savenije FJ (2015) Active wake control: loads trends. Energy Research Center of Nethelands, Petten
[60] Gebraad PMO, Teeuwisse FW, van Wingerden JW et al (2014) A data-driven model for wind plant power optimization by yaw control. In: Proceedings of the American control conference, Portland, USA, 4–6 June 2014, pp 3128–3134
[61] Lee J, Son E, Hwang B et al (2013) Blade pitch angle control for aerodynamic performance optimization of a wind farm. Renew Energy 54:124–130
[62] González JS, Payán MB, Santos JR et al (2015) Maximizing the overall production of wind farms by setting the individual operating point of wind turbines. Renew Energy 80:219–229
[63] Behnood A, Gharavi H, Vahidi B et al (2014) Optimal output power of not properly designed wind farms considering wake effects. Int J Electr Power Energy Syst 63:44–50
[64] Hou P, Hu W, Zhang B et al (2016) Optimised power dispatch strategy for offshore wind farms. IET Renew Power Gener 3(10):399–409
[65] Gebraad PMO, Wingerden JW (2014) Maximum power point tracking control for wind farms. Wind Energy 18(3):429–447
[66] Porté-Agel F, Wu YT, Chen CH (2013) A numerical study of the effects of wind direction on turbine wakes and power losses in a large wind farm. Energies 6(10):5297–5313
[67] Patel MR (1999) Wind and solar power systems. CRC Press, New York
[68] Mosetti G, Poloni C, Diviacco B (1994) Optimization of wind turbine positioning in large wind farms by means of a genetic algorithm. J Wind Eng Ind Aerodyn 1(51):105–116
[69] Grady S, Hussaini M, Abdullah M (2005) Placement of wind turbines using genetic algorithms. Renew Energy 30(2):259–270
[70] Marmidis G, Lazarou S, Pyrgioti E (2008) Optimal placement of wind turbines in a wind park using Monte Carlo simulation. Renew Energy 33(7):1455–1460
[71] Pookpunt S, Ongsakul W (2013) Optimal placement of wind turbines within wind farm using binary particle swarm optimization with time-varying acceleration coefficients. Renew Energy 55:266–276
[72] do Couto TG, Farias B, Carlos A et al (2013) Optimization of wind farm layout using genetic algorithm. In: Proceedings of 10th world congress on structural and multidisciplinary optimization, Orlando, USA, 19–24 May 2013, pp 1–7
[73] Salcedo-Sanz S, Gallo-Marazuela D, Pastor-Sánchez A et al (2013) Evolutionary computation approaches for real offshore wind farm layout: a case study in northern Europe. Expert Syst Appl 40(16):6292–6297
[74] Salcedo-Sanz S, Gallo-Marazuela D, Pastor-Sánchez A et al (2014) Offshore wind farm design with the coral reefs optimization algorithm. Renew Energy 63:109–115
[75] Gonzalez JS, Garcia ALT, Payan MB et al (2017) Optimal wind-turbine micro-siting of offshore wind farms: a grid-like layout approach. Appl Energy 200:28–38
[76] Turner SDO, Romero DA, Zhang PY et al (2014) A new mathematical programming approach to optimize wind farm layouts. Renew Energy 63:674–680
[77] Gonzalez J, Burgos Payan M, Riquelme Santos J (2013) A new and efficient method for optimal design of large offshore wind power plants. IEEE Trans Power Syst 28(3):3075–3084

[78] Fagerfjäll P (2010) Optimizing wind farm layout-more bang for the buck using mixed integer linear programming. Dissertation, Chalmers University of technology & Gothenburg University

[79] Fischetti M (2014) Mixed integer programming models and algorithms for wind farm layout and cable routing. Dissertation, Aalborg University

[80] Kuo JYJ, Romero DA, Beck JC et al (2016) Wind farm layout optimization on complex terrains-integrating a CFD wake model with mixed integer programming. Appl Energy 178:404–414

[81] Pérez B, Mínguez R, Guanche R (2013) Offshore wind farm layout optimization using mathematical programming techniques. Renew Energy 53:389–399

[82] Gonzalez JS, Payan MB, Santos JR (2013) A new and efficient method for optimal design of large offshore wind power plants'. IEEE Trans Power Syst 28(3):3075–3084

[83] Kusiak A, Song Z (2010) Design of wind farm layout for maximum wind energy capture. Renew Energy 35(3):685–694

[84] Eroğlu Y, Seçkiner SU (2012) Design of wind farm layout using ant colony algorithm. Renew Energy 44:53–62

[85] Wan C, Wang J, Yang G et al (2012) Wind farm micro-siting by Gaussian particle swarm optimization with local search strategy. Renew Energy 48:276–286

[86] Chowdhury S, Zhang J, Messa A et al (2013) Optimizing the arrangement and the selection of turbines for wind farms subject to varying wind conditions. Renew Energy 52:273–282

[87] Rahbari O, Vafaeipour M, Fazelpour F (2014) Towards realistic designs of wind farm layouts: application of a novel placement selector approach. Energy Convers Manag 81:242–254

[88] Gao X, Yang H, Lu L (2014) Investigation into the optimal wind turbine layout patterns for a Hong Kong offshore wind farm. Energy 73:430–442

[89] Park J, Law K (2015) Layout optimization for maximizing wind farm power production using sequential convex programming. Appl Energy 151:320–334

[90] Feng J, Shen WZ (2015) Solving the wind farm layout optimization problem using random search algorithm. Renew Energy 78:182–192

[91] Wang L, Tan ACC, Gu Y (2015) Comparative study on optimizing the wind farm layout using different design methods and cost models. J Wind Eng Ind Aerodyn 146:1–10

[92] Chen Y (2013) Commercial wind farm layout design and optimization. Dissertation, Texas A&M University-Kingsville

[93] Hou P, Hu W, Chen C et al (2016) Optimization of offshore wind farm layout in restricted zones. Energy 113:487–496

[94] Wu YK, Kee CY, Chen CR et al (2014) Optimization of the Wind Turbine layout and transmission system planning for a large-scale offshore wind farm by AI technology. In: Proceedings of 2012 IEEE industry applications society annual meeting, Las Vegas, USA, 6 December 2012, pp 1–9

[95] Hou P, Hu W, Soltani M et al (2017) Combined optimization for offshore wind farm planning. Appl Energy 189:271–282

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