Design optimization of offshore wind farms with multiple types of wind turbines

Ju Feng, Wen Zhong Shen⁎

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

HIGHLIGHTS

- Non-uniform wind farm’s design includes number, types and locations of turbines.
- The mixed-integer-discrete-continuous optimization is solved by random search.
- The extended random search outperforms the mixed-discrete PSO algorithm.
- Whether non-uniform designs better depends on the capital costs comparison.
- Better treat wind farms as non-uniform and consider multiple types of turbines.

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ABSTRACT

Most studies on offshore wind farm design assume a uniform wind farm, which consists of an identical type of wind turbines. In order to further reduce the cost of energy, we investigate the design of non-uniform offshore wind farms, i.e., wind farms with multiple types of wind turbines and hub-heights. Given a set of different types of wind turbines with a different default hub height for each type, we can specify the design of a wind farm by the types of turbines, number of turbines for each type, and turbine locations. We consider the optimization of such design to minimize the levelized cost of energy, which is calculated using a capital cost model that covers the turbine cost and the balance of plant cost. An empirical wind turbine design cost and scaling model is utilized to model the cost of turbines with different sizes. Constraints on wind farm boundary, wind turbine proximity and total capacity are also included. We solve the problem with a newly developed extended random search algorithm and tested it in a realistic design optimization problem based on the Horns Rev 1 offshore wind farm in Denmark. The optimized non-uniform designs are compared with their uniform counterparts. We find that a non-uniform design can achieve a lower levelized cost of energy than its uniform counterparts, when the capital cost per MW is slightly lower for the smaller size turbine. Comparison with the mixed-discrete particle swarm optimization algorithm is also carried out for a non-uniform wind farm design problem with a fixed number of turbines, which shows the effectiveness and superiority of the proposed algorithm. Finally, the advantages and possible disadvantages of non-uniform design are also identified and discussed.

1. Introduction

The world’s first offshore wind farm (WF), Vindeby offshore WF located in Denmark, was connected to the grid in 1991. After more than 25 years of service, its owner and operator, DONG Energy has recently decided to decommission it [1]. This event reminds us that offshore wind energy is still a young field with a short history. Nevertheless, offshore wind energy has achieved an astonishing development in the recent years. According to the latest statistics from the Global Wind Energy Council (GWEC), the global cumulative offshore wind capacity was increased from 4117 MW in 2011 to 14,384 MW in 2016, representing an average annual increase of 28.4% [2]. As the main form of utilizing offshore wind energy, offshore WFs proliferate in the world in the past two decades, especially in Europe. Consequently, the design and planning problem of offshore WFs has received a lot of attention [3].

1.1. Traditional offshore WF layout optimization

Among many problems in WF design and planning, layout optimization is one of central importance, which is to find the optimal positions of wind turbines (WTs) inside an WF with regards to a single/
multiple objective(s), while satisfying certain constraints and assumptions [4]. Since the seminal work of Mosetti et al. in 1994 [5], this problem has been investigated by a large amount of studies, with the majority focusing on onshore WFs [6].

Many recent studies have also investigated the specific problem of offshore WF layout optimization [7]. For example, Elkinton et al. [8] developed a tool for optimizing offshore WF layout to minimize the levelized production cost (LPC), considering simple cost models for different components and using genetic algorithm (GA) and greedy heuristic algorithm; Rivas et al. [9] applied simulated annealing to optimize an offshore WF layout, with annual energy production (AEP) as its objective function; González et al. [10] proposed to optimize offshore WF layout for maximizing its net present value (NPV), by means of an improved GA with tailored operators; Gao et al. [11,12] investigated the potential and feasibility of constructing offshore WFs in Hong Kong, by optimizing the offshore WF layout for minimal cost of energy (COE) with the multi-population GA; Salcedo-Sanz et al. [13] applied the Coral Reefs Optimization algorithm to maximize AEP of offshore WFs; Feng et al. [14] developed a new heuristic global search algorithm, Random Search (RS) algorithm, and applied it in the layout optimization of the Horns Rev 1 offshore WF in Denmark for maximizing AEP; Gao et al. [15] proposed a two-dimensional wake model, Jensen-Gaussian wake model, and applied it in WF layout optimization using multi-population GA; layout optimization with regards to the robustness of WF power production in the changing wind was also investigated in a recent study [16]; González et al. [17] studied the optimization problem of offshore WFs with grid-like layouts. While most of the published studies, including those mentioned above, applied various metaheuristic algorithms in the optimization problems, there are several efforts made recently to apply conventional mathematical optimization techniques, such as sequential convex programming [18], nonlinear mathematical programming [19,20] and mixed integer programming method [21].

Since most of the constructed offshore WFs are uniform, i.e., they are composed of one type of WTs with the same hub-height, the majority of the published studies focused on uniform offshore WFs. Usually a fixed type of WT was considered in these studies, while a few considered the problem of type selection, i.e., choosing a proper type from a group of available WT types. For instance, Mustakerov et al. [22] addressed the WT type and number choice optimization problem for minimizing the cost per unit energy. In their study, the cost model depends only on the number of WTs, and they assumed an array-like rectangular WF with the numbers of WTs per row and per column as design variables. They then solved the problem with the combinatorial optimization method for multiple types of WTs. Their results showed that using big size WTs is more profitable than using small size WTs. However, their study suffered from the simplified wind cases and a lack of proper wake effect modelling.

In another study, Chowdhury et al. [23] formulated three different scenarios for WF design: optimizing WF layout with a defined WT type; simultaneously optimizing the WF layout and selecting a single type of WTs; simultaneously optimizing the WF layout and the type of each WT. In the second scenario, they assumed that WF consists of a fixed number of identical WTs and solved it with a mixed-discrete particle swarm optimization (PSO) algorithm [24]. They tested the methodology for a 25 turbine WF in North Dakota, USA and improved the WF capacity factor by 6.4% when simultaneously optimizing the layout and the turbine type selection. Note that the capacity factor is defined by the average power generated by WF, divided by its total capacity.

Furthermore, it should be noted that the complete design of an offshore WF is more than the type selection and siting of WTs. Many other factors (such as the design of foundations, electrical systems) and requirements/considerations (e.g. visual impact [25] and underwater noise emission [26]) are also parts of the complete design and in principle should be taken into consideration. Several studies tried to solve the integrated optimization problem of the layout of WTs and other factors for uniform offshore WFs. For example, the WF layout and the internal cable network were optimized simultaneously, both as a multi-objective optimization problem in [27] and as a single-objective optimization problem in [28]. Guirguis et al. [20] proposed a gradient-based approach to solve the multi-objective WF design optimization problems considering land footprint, energy output, electrical infrastructure, and environmental impact. Studies of solving the design optimization problems with other factors were also done, usually by assuming the WF layout is given. For example, the optimization of offshore WF electrical system design was studied in [29] and many other studies as summarized in the review article [30].

1.2. Non-uniform offshore WF optimization

Constructing a uniform offshore WF with one type of WTs seems to be a good choice, as this kind of design naturally brings convenience for supply chain management, installation, operation and maintenance (O & M). Nevertheless, we should realize that there are no fundamental limits preventing us from using multiple types of WTs in offshore WFs. When limiting the offshore WF design to using only one type of WTs, we are essentially limiting ourselves in the feasible design space, leaving a large part of the design space unexplored. Thus, it is beneficial to at least consider the option of non-uniform offshore WF in the design and planning stage. Here we use the term ‘non-uniform offshore WF’ to represent an offshore WF that is composed of multiple types of WTs.

However, most of the published studies on WF design optimization assumed that one type of WTs are used, while few recent studies considered the possibility of non-uniform WFs. One example is the study done by Chowdhury et al. in 2012 [31]. Among the 3 different layout optimization cases in this study, the second one considered WF with non-identical WTs (multiple WT types). The optimization problem was formulated to find the locations and types for each WT that maximizes the WF’s capacity factor, with constraints on WF boundary, minimal clearance distance between WTs and maximal WF cost. The WF cost was calculated in considering each WT’s cost, which was in turn estimated based on a quadratic function of the WT’s rotor diameter. They solved the problem using a constrained PSO and found that an optimal combination of different types of WTs could appreciably improve the WF capacity factor. Although it is a seminal work that first considered non-uniform WF, this study [31] have several drawbacks: (i) the experimental WTs used in the study have quite different power curves from today’s mainstream MW sized WTs; (ii) the cost model used is quite simple and not included in the objective function; (iii) the wind condition considered (unidirectional and fixed wind speed) is too simplified to reflect the realistic situation in WF design; (iv) the rotor diameters of different types of WTs are treated as continuous variables; (v) the choice of the proper number of WTs is not taken into consideration. In the scenario 3 of a later study also done by Chowdhury et al. [23], which we briefly described before, the first four of these drawbacks were largely tackled. In this study, the design variables include x and y coordinates (continuous variables) and turbine type codes (discrete variables) for a given number of WTs.

The potential benefits of non-uniform WFs have also been investigated by Chamorro et al. [32] through wind tunnel experiments. They placed a non-uniform WF composed of 3 by 8 model WTs with 2 alternating sizes in a boundary layer flow over both smooth and rough surfaces and focused on investigating the dynamics involved in a non-uniform WF and the effect of surface roughness. Their results showed that reduced levels of turbulence and increased levels of kinetic energy flux to the WF can be achieved using variable-size WTs in a WF, suggesting the potential advantages of non-uniform WF design.

More recently, Abdulrahman et al. [33] investigated the WF design optimization considering WT type selection and hub height variation for three different objective functions: power, capacity factor and COE. They considered two cases in this study: the first one optimizes the locations, types and hub-heights of 6 WTs in a line; the second one
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