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Optimum layout design of onshore wind farms considering stochastic loading

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ABSTRACT

Renewable energy technologies are developing rapidly, while in the last decade great interest is encountered in the use of wind energy, especially due to the energy crisis and serious environmental problems appeared from the use of fossil fuels and therefore a large number of wind farms have been installed around the world. On the other hand the ability of nature inspired algorithms to efficiently handle combinatorial optimization problems was proved by their successful implementation in many fields of engineering sciences. In this study, a new problem formulation for the optimum layout design of onshore wind farms is presented, where the wind load is implemented using stochastic fields. For this purpose, a metaheuristic search algorithm based on a discrete variant of the harmony search method is used for solving the problem at hand. The farm layout problem is by nature a constrained optimization problem, and the contribution of the wake effects is significant; therefore, in two formulations presented in this study the influence of wind direction is also taken into account and compared with the scenario that the wake effect is ignored. The results of this study proved the applicability of the proposed formulations and the efficiency of combining metaheuristic optimization with stochastic wind loading for dealing with the problem of optimal layout design of wind farms.

1. Introduction

Wind power stands for the conversion of wind energy into a useful form of energy. In order to exploit this type of energy, wind turbines are used to produce electricity, windmills are used to produce mechanical power or wind pumps are used for water pumping. So far, several hundred wind turbines have been installed into large offshore or onshore wind farms which are connected to the electric power transmission network. In particular, the original *Alta-Oak Creek Mojave Project* plan consisted of up to 320 wind turbines occupying an area of 36 km^2 while producing 800 MW of power. Today, Alta Wind Energy Center located in Tehachapi Pass of the Tehachapi Mountains (in Kern County, California), is the largest wind farm in the world with a combined installed capacity of 1550 MW consisted of 600 wind towers [1]. Although, offshore wind farms can take advantage of more frequent and powerful winds than those available to land-based installations and they have less visual impact on the landscape, their construction cost is considerably higher. On the other hand, onshore wind facilities take advantage of the winds at higher altitudes, which are stronger and more consistent, through appropriate tower heights, while small wind farms can be used to provide electricity to isolated areas.

Recent advances in engineering optimization have enabled the transition from traditional trial-and-error design procedures to fully automated ones. This is mostly attributed to the rapid development of metaheuristic search algorithms that were found efficient and robust for dealing with real world problems. In the past many researchers have studied the problem of optimum layout design of wind farms. In particular, Mosetti et al. [2] presented an approach for the optimization of large windfarms aiming to extract the maximum energy for minimum installation cost. Grady et al. [3] applied a genetic algorithm approach in order to obtain optimal placement of wind turbines for maximum production capacity while limiting the number of turbines installed and the acreage of land occupied. Marmidis et al. [4] introduced a procedure based on the Monte Carlo simulation method for the

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optimal placement and arrangement of wind turbines into a wind farm. Sood et al. [5] determined via a Monte Carlo-like random search methodology the optimal positioning of multiple wind turbines into a small footprint wind farm under multiple wake effects. Rahmani et al. [6] used the particle swarm optimization (PSO) method in order to optimize placing of wind turbines in a wind farm. Ituarte-Villarreal and Espiritu [7] proposed a viral based optimization algorithm and was used in order to find the optimal wind turbine placement considering constant and unidirectional uniform wind velocity. Chowdhury et al. [8] used constrained PSO for dealing with a wind farm layout optimization problem that simultaneously determines the optimum farm layout and the appropriate selection of turbines that maximizes the net power generation, while in the work by Zhang et al. [9] used a wind farm power generation model to evaluate downtime energy losses during preventive maintenance for a given group of wind turbines in the entire array. Chen and MacDonald [10] adopted genetic algorithms to solve the nonlinear constrained optimization problem, minimizing cost and maximizing power output; while the optimization results showed that, given a projected participation rate, the most crucial plots prior to the negotiation process with landowners can be identified. DuPont et al. [11] and DuPont and Cagan [12] presented a multi-level extended pattern search algorithm aiming to optimize both the local positioning and geometry of wind turbines on a wind farm. The objective of the study by Wan et al. [13] was to maximize using Gaussian PSO algorithm the electrical power extracted from a wind farm while satisfying the required distance between turbines for operation safety. Eroĝlu and Seçkiner [14] used an ant colony algorithm for maximizing the expected energy output in a layout design wind farm problem taking into account wake losses and wind direction. On the other hand in two works by Chowdhury et al. [15] and Tong et al. [16] the applicability of metaheuristic search algorithm was explored to a large scale engineering design problem such as wind farm layout optimization. In the work by Khan and Rehman [17] the design issues and constraints involved in the layout design of a wind farm are briefly outlined while the computational complexity, along with single and multi-objective approaches of the problem, are also examined. Salcedo-Sanz et al. [18] presented the layout optimization problem of a real offshore wind farm in northern Europe; in this direction different strategies for the wind farm design were tested, like regular turbines layout or free turbines allocation with fixed number of turbines, while evolutionary computation techniques were used for solving the optimization problem. Eroĝlu and Seçkiner [19] used a particle filtering approach in order to define an optimized layout of a wind farm that has the minimum wake effects and maximum power generation. Karakostas and Economou [20] proposed the controlled non-dominated sorting genetic algorithm-II for treating multi-objective spatial optimization problems, aiming at deriving the optimal spatial allocation of wind farms on the Greek island of Lesvos. While, Salcedo-Sanz et al. [21] presented the Coral Reefs optimization algorithm, that is based on the simulation of reef formation and coral reproduction, for wind farm design and layout optimization of a real offshore wind farm in northern Europe. Furthermore, Chen and Macdonald [22] applied a levelized wind farm cost model, including landowner remittance fees, to determine optimal turbine placements under three landowner participation scenarios and two land-plot shapes. Turner et al. [23] developed a new mathematical programming approach for wind farm layout optimization resulting into layouts that tend to be more symmetric and that generate slightly more power. Kwong et al. [24] presented continuous-location models for layout optimization that take noise and energy as objective functions, in order to characterize the design and performance spaces of the wind farm layout optimization problem. While Dupont and Cagan [25] validated models used in wind farm optimization studies performed in the past. In addition, Prabhu et al. [26] proposed an improved harmony search algorithm approach for the optimal placement of offshore wind farms based on three scenarios; while in this work, the harmony search algorithm in conjunction with stochastic modeling of the wind load that is based on actual wind data is applied on an existing wind park located in Cyprus. Furthermore, apart from maximizing energy production, a formulation aiming to minimize the required number of wind turbines is also presented herein.

Various technical issues arise due to the close spacing of multiple wind turbines into a wind farm, particularly one with a severely limited spatial footprint. One of the most important factors under consideration is the wake effect. Since energy losses due to wakes can significantly decrease energy production and lead to fluctuations in the output power of a wind farm it is desired to determine optimized positions for installing multiple wind turbines. In this direction, a new optimum layout design framework for onshore wind farms where the wind load is considered stochastically is presented herein, while the well-known harmony search algorithm is used for solving the problem at hand. Specifically, the optimization problem is formulated by means of the maximum energy production and minimum cost installation criteria while for the test case considered the site is subdivided into 289 square cells that represent possible turbine locations and as a result optimized arrangements of the wind turbines in the wind farm are obtained. The location of each wind turbine could be freely adjusted within the predefined square cells in order to maximize the generated energy. The farm layout model used herein incorporates traditional restrictions imposed on the location of turbines based on a standard analytical wake model that has been used to account for the velocity deficits in the wakes created by individual turbines. Furthermore, the wind speed is considered stochastically over the landscape of the wind farm location, for this reason a number stochastic fields are generated, corresponding to the wind velocity for different wind directions. This representation denotes a step forward compared to the work of others where in addition to orography, shape of the wind farm, simulation of the wind speed and direction (for example the work by Saavedra-Moreno et al. [27]) a stochastic simulation of the wind load is presented herein. The farm layout problem is by nature a constrained optimization problem, in which the coupling of wake effects is strong and the number of position constraints between turbines is large while the wind direction is also taken into account. The reason for selecting the harmony search algorithm for solving the problem at hand is due to its ability to handle complex discrete optimization problems, as it was proved in two recent studies by the authors where HS was found very efficient in order to handle districting problems regardless the size of the problem [28,29], while a discrete variant of the harmony search method is used for solving the problem at hand.

2. Problem formulation

In this section the objective function and design variables of the optimization problem dealt with in this study, are described. In this study two problem formulations are presented, in the first one the objective is to maximize the profit obtained from the wind farm by defining optimized locations of N wind towers. Therefore, the objective function to be maximized is defined as follows:

$$\max \sum_{i=1}^{N} C_i \tag{1}$$

where C_i is the profit obtained from each wind tower.