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A new constraint handling method for wind farm layout optimization with lands owned by different owners

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ABSTRACT

For wind farm optimizations with lands belonging to different owners, the traditional penalty method is highly dependent on the type of wind farm land division. The application of the traditional method can be cumbersome if the divisions are complex. To overcome this disadvantage, a new method is proposed in this paper for the first time. Unlike the penalty method which requires the addition of penalizing term when evaluating the fitness function, it is achieved through repairing the infeasible solutions before fitness evaluation. To assess the effectiveness of the proposed method on the optimization of wind farm, the optimizing results of different methods are compared for three different types of wind farm division. Different wind scenarios are also incorporated during optimization which includes (i) constant wind speed and wind direction; (ii) various wind speed and wind direction; and (iii) the more realistic Weibull distribution. Results show that the performance of the new method varies for different land plots in the tested cases. Nevertheless, it is found that optimum or at least close to optimum results can be obtained with sequential land plot study using the new method for all cases. It is concluded that satisfactory results can be achieved using the proposed method. In addition, it has the advantage of flexibility in managing the wind farm design, which not only frees users to define the penalty parameter but without limitations on the wind farm division.

1. Introduction

Due to the limited reserves of traditional fuel resources and the adverse environmental effects it causes, scientists have tried to find alternative sources of energy for a long time. Alternative sources of energy such as renewable energy, have been regarded as a promising substitute with the advantage of sustainability and environmentally friendly property. Among them, the wind power transforming technology lies at the forefront of the renewable energy studies for its unlimited capacity and the worldwide distribution. As the wind energy exploitation is getting more and more popular, a lot of researchers have focused on the study of the wind turbine(s) performance to improve the costs-over benefits ratio of transforming wind energy to electrical power. To achieve this, normally a large number of wind turbines are positioned together which is called wind farm. However, the wind farm with a cluster of wind turbines brings the problem of wake effects, which not only jeopardize the operation of rotors and affect the life expectancy of turbines, but decreases the turbine output power production. Hence, designing the wind farm by positioning a reasonable number of wind turbines with the best placement is extremely crucial for extracting the wind energy.

Before implementing a wind farm project, there are a few challenges that the developers have to meet to determine the number of wind turbines and their distributions, such as the wind scenario, the land geography and zoning [1,2]. Most of literatures discuss the wind farm design with predefined area as in Refs. [3–6]. Let us consider the situation where the whole land is owned by different owners. In such scenario, the developers can only approach the whole wind farm design when access is given by different landowners [7]. While it is not always the case in real situation where all the landowners are willing to participate in the wind farm project, the developers can try to persuade them by promoting the offer of negotiation which is known as land compensation or land leasing [8–10]. To have a rational decision on the expenses, the information containing factors, such as the status of different lands for developing the project, must be acquired before negotiation with the owners can take place. Therefore the

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focus of this paper is to identify which among the divided land plots is most insignificant compared with others according to the specific wind scenario. With this information, the developers will be aware that which of trivial lands should be compensated with least costs or can be abandoned otherwise [11].

To optimize the wind farm with different landowners, extra constraints must be added to the optimization process as discussed in Section 2. For most of optimizing problems in the real world, there are constraints to be satisfied. A particular difficulty in handling constrained optimization is that the solutions cannot be guaranteed to be feasible for all results during the searching process [12,13]. Hence evolutionary algorithms like Genetic Algorithm (GA) are incapable of optimizing the constrained problem directly, and some techniques must be introduced to the optimization under constraints [14,15]. Next the state of the art of constraint handling techniques is presented in more detail. When selecting the techniques applied for a specific constrained optimization problem, several features deserve to be taken into consideration. Firstly, the constraint handling approach should work with any kind of the problems or constraints, and the modifications should be minor even if it requires. Secondly, it should minimize the requirement of parameter tuning or should not even need it at all. Thirdly, it should not require a high evaluation cost so that optimization efficiency can be greatly improved [16]. To the authors' best knowledge, several basic methods have been reported in the literature to handle constraints, such as prevent infeasible solutions; discard infeasible solutions; repair infeasible solutions and penalize infeasible solutions [17]. As the name implies, the method of preventing infeasible solutions is to keep all the solutions of the optimization process feasible through the unique operators, and thus the feasible optimization results can be guaranteed. However, this method is highly unreliable since it is extremely problematic which requires customized operations. Hence it lacks the generality and requires fine tunings. The method of discarding infeasible solutions is to eliminate the infeasible solutions before evaluation and hence the search space can be effectively reduced. Although this method is the simplest one, it is also the most inefficient in handling the constraints. For this method, the current population will not be evaluated until the individuals are all feasible, thus it frequently fails in coping with the practical problems, being stuck into the initial population generating stage for a long time. So it is not only computationally costly but very inefficient. The method of repairing infeasible solutions is to transform the infeasible solutions into the feasible through replacing genes that cause infeasibility. Even though the method is also dependent on the specific problem, it can be easily implemented through a set of carefully designed procedures to bring infeasible solutions into the feasible region in an efficient way. And it is found to be able to surpass all other approaches in both speed and performance when applied for certain problems [16]. The penalty method, which is also the most popular approach in handling the optimization constraints, is to add a penalty term to the objective function so that any infeasible solution is not better than the worst feasible solutions in the population. Hence all the infeasible solutions will be artificially made to be inferior and end up being eliminated. However, since the penalty method is generic and applicable to any type of constraints, their performance always varies and most importantly, the appropriate penalty parameter is hard to determine. The detailed descriptions of the four methods can be referred in Refs. [17,18]. The repair and penalty methods which are applied in this paper will be discussed in detail in Section 3.

All the existing studies on wind farm design with different landowners utilize the penalty method which has a great limitation on wind farm divisions [7,19,20], and it may not be applicable when the land division is complex. Therefore, a generic repair infeasible solution method in handling the wind farm constraints is proposed in this paper to solve the problem. In order to validate the effectiveness of the proposed method, its result is compared with traditional penalty methods including the user-defined penalty method and the adaptive penalty method. The rest of the paper is organized as follows. Section 2 formulates the problem including the objective function, constraints and correlating the wind turbine to the land index. Section 3 details the different methods applied in this paper. Note that to analyze the effectiveness of the new method qualitatively, the penalty method is applied as a comparison. Section 4 shows the optimizing results and discussion. Finally, conclusions are given in Section 5.

2. Problem formulation

2.1. Objective function representation

Since the main scope of this paper is to discuss the effectiveness of the new constraints handling approach, only the wind farm design with the least important land plot is studied. Given the consistency and comparability of the current study with the study by other researchers, only identical wind turbine with the same power characteristic as discussed in Refs. [21,22] are used as the turbine model. The velocity magnitudes of cut-in, rated and cut-out are 2.3 m/s, 12.8 m/s and 18 m/s, respectively. Power P_i of wind turbine i in kW is given as following equations:

$$\begin{cases} P_i = 0 & \text{if } \ v_i < 2.3\ \text{m/s or } v_i > 18\ \text{m/s} \\ P_i = 0.3v_i^3 & \text{if } 2.3\ \text{m/s} < v_i < 12.8\ \text{m/s} \\ P_i = 630 & \text{if } 12.8\ \text{m/s} < v_i < 18\ \text{m/s} \end{cases} \tag{1}$$

the power is constant zero when the velocity is less than cut-in speed or more than cut-out speed; it is proportional to the cubic of velocity magnitude between cut-in and rated speed; and it keeps constant rated power between rated speed and cut-out speed.

The objective function is to minimize the wind farm cost and to maximize the total output energy production. The optimization function is the cost of energy (CoE) and it is defined as [19].

$$\text{CoE} = N \cdot \left(\frac{2}{3} + \frac{1}{3}e^{-0.00174N^2}\right) \Bigg/ \sum_{i=1}^{N} P_i \tag{2}$$

In which, N is the number of wind turbines in a wind farm and P_i is the individual wind turbine power.

2.2. Constraints representation

For the wind farm optimization when considering the factor of land availability, the function is optimized subject to:

$$\begin{aligned} h_c(X) &= \phi(X, c) = 0 \\ h_{c^*}(X) &= L(X) - n_{yes} = 0 \end{aligned} \tag{3}$$

In which, the first equation indicates all wind turbines should be placed at the feasible grids; X refers to the individual as a potential solution for the optimized function, as shown in Eq. (4); c represents the binary number denoting whether or not certain wind turbine exists in the specific square grid, and it belongs to the first 100 digits of X. The second equation indicates the number of land plots that are available for the placement of wind turbines should be fixed. c^* refers to the binary digits denoting the divided