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Risk management of wind farm micro-siting using an enhanced genetic algorithm with simulation optimization

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ABSTRACT

Wind farm micro-siting is the decision problem for determining the optimal placement of wind turbines in consideration of the wake effect. Existing micro-siting models seek to minimize the cost of energy (COE). However, little literature addresses the production risk under wind uncertainty. To this end, we develop several versions of the simulation optimization based risk management (SORM) model which embeds the Monte Carlo simulation component for obtaining a large number of samples from the wind probability density function. Our SORM model is flexible and allowing the decision makers to conduct various forms of what-if analysis trading profit, cost and risk according to their business value. Then we propose an enhanced genetic algorithm (EGA) which is customized to the properties of wind farm dimensions. The experimental results show that the EGA can obtain the SORM decision both effectively and efficiently as compared to other metaheuristic approaches. We demonstrate how the risk under wind uncertainty can be effectively handled with our SORM models. The simulations with what-if analyses are conducted to disclose important characteristics of the risky micro-siting problem.

1. Introduction

The reduction on the reliance of main fossil fuels (oil, coal and gas) has been included in the long-term energy policy by many countries. The reason is two-fold. *First*, the oil and gas was predicted to be exhausted by 2042 and the depletion time for coal is 2112 [1]. For the nation's safety and maintaining a stable economic growth, it is prudent to invest renewable energy as alternative sources. *Second*, the social awareness of environmental protection for restraining the emission of greenhouse gases has pushed the government toward the use of various sources of renewable energy. Among others, wind energy generation is fast growing in recent years. The leading Big Five countries, namely, China, United States, Germany, Spain and India have respectively installed from 114 to 22 GW wind power capacity as of the end of 2014 [2].

The investment for new wind farms involves three phases: the planning phase, the operation and maintenance phase, and the decommissioning phase. Several factors affecting the investment return may be uncertain such as the wind directions and speeds, turbine failure, personnel and material cost, and energy price. When there is uncertainty, there exists risk. Some researches [3–9] have addressed the risk issue for wind farm investment under the uncertainty of wind conditions. The focus of risk management for different phases of wind farm investment varies significantly. For the risk management in the planning phase, the focus is to seek the optimal configuration of micro-siting which determines the number and positions of wind turbines considering the varying wake effect under wind uncertainty. While in the operation and maintenance phase, as the layout of the wind farm micro-siting has been determined, the aim is to find the best control configuration for each individual wind turbine in order to stabilize the power generation against the wind variations. And for the decommissioning phase, apparently, there is no risk induced by wind uncertainty. Most of the existing works were devoted to technology improvement in the wind-farm operation and maintenance phase. To the best of our knowledge, only the following three works [7–9] have considered the risk management in the wind-farm planning phase. Messac et al. [7] has noted the ill formulation of generation prediction adopted by classic micro-siting methods which calculate the mean generation from the wind distribution, overlooking the risk that the generation could be greatly deviated from the mean with non-negligible probabilities. The expected return of investment is thus vulnerable by significant risk. Therefore, Messac et al. [7] proposed a sophisticated wind uncertainty model considering

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wind variations characterized by short-term and long-term factors, respectively. Both parametric and nonparametric models were formulated. A PSO is used for uncertainty minimization of the cost of energy (COE) while keeping the COE value within a satisfactory range. Serrano-González et al. [8] sought to find the optimal micro-siting configuration by modeling the wind uncertainly based on a set of input scenarios and its probability of occurrence. The expected value of the net present value (NPV) is calculated for trial micro-siting configurations. A GA is thus developed for searching for a near-optimal micro-siting to mitigate the profitability risk by maximizing the expected NPV. Both [7] and [8] identify risk as the variation of the production benefit and this paper follows the same line. Nevertheless, a different angle for identifying risk has been presented in Ref. [9] which proposed the power deficiency risk management (PDRM) model considering power deficiency risk under weekly electricity demand. A cyber swarm algorithm is developed to approximate the optimal micro-siting solution of the PDRM model.

The strategy employed in the planning phase may have greater impact on the effectiveness of risk management than that practiced in the operation and maintenance phase because the former is a one-time decision (the micro-siting is unchangeable once it was implemented) and it deals with the wind uncertainty with a longer time horizon. The turbulence range in power generation produced by implementing different micro-siting varies more significantly than by tuning individual turbine control settings. However, the importance of risk management in the wind-farm planning phase has been long neglected in the related research. Although [7] and [8] provided initial attempted solutions, these two works are not suitable for the decision makers who require a decision support system which is flexible enough to be able to provide what-if analyses through iterative interactions with different scenario settings. The inadequacy of [7] and [8] includes the following. *First*, the best strategy for risk management could vary for different decision makers. For instance, some decision makers may strive to risk minimization on generation variations with the COE upper-bound constraint, and some others would focus on generation maximization while constraining the risk within a tolerance level. *Secondly*, the risk can be gauged by various statistical measures such as mean, standard deviation, minimum, maximum, or percentile. The choice for the most suitable measure depends on the business value determining the attributes of the project investment. *Thirdly*, the quality of decision is really affected by the applied values for the model parameters. The decision makers prefer to see the analysis results obtained by a pool of alternative values for each parameter. However, none of [7] and [8] provided such flexible interfaces for conducting what-if analyses.

In this paper, we propose new micro-siting strategies to be employed in the wind farm planning phase under the risk of varying wind condition. To handle wind uncertainty, we develop several versions of the simulation optimization based risk management (SORM) model which embeds the Monte Carlo simulation component for obtaining a large number of samples from the wind probability density function. Our SORM mode is flexible and allowing the decision makers to conduct various forms of what-if analysis trading profit, cost and risk according to their business value. Most existing works for wind farm planning adopt some forms of evolutionary algorithm (EA) [10], revealing that EA is a reliable method for tackling the micro-siting problem. So we propose an enhanced genetic algorithm (EGA) which is customized to the properties of wind farm dimensions to obtain the planning result effectively and efficiently.

The remainder of this paper is organized as follows. Section 2 presents the literature review for micro-siting and risk management. Section 3 articulates the proposed SORM models and the EGA approach for obtaining the optimal micro-siting decision. We report in Section 4 the experimental results and comparative performances. Finally, Section 5 concludes this work.

2. Literature review

Wind farm micro-siting planning involves a number of factors including wind potentials, wake effect, wind energy extraction, cost analysis, optimization planning, etc. In this section, a generic micro-siting model which is broadly used in the literature is presented. Then, we review main existing approaches for obtaining optimal micro-siting. Finally, several important applications for risk management with the simulation optimization technique are presented.

2.1. Micro-siting problem

A generic model for wind farm micro-siting planning consists of several mandatory components including the representation and calculation for wind data (direction and speed of wind and the probability of occurrence), wake effect incurred by wind turbines in the implemented micro-siting, the cost and production of the established wind farm, and the applied optimization methods to obtain the micro-siting planning. Multiple methods exist in the literature for describing each of the noted components. The reader is referred to a most updated survey [10].

2.1.1. Generic model

For the wind data component, wind rose and Weibull distribution are two alternative representations for describing the proportion of occurrence for every instance of wind speed and direction. Wind rose model has been deployed by many existing works such as [11–16]. A wind rose (see Fig. 1) is a circular histogram having a number of bins, each of which indicates a particular range of wind-direction degrees. The occurrence proportion for

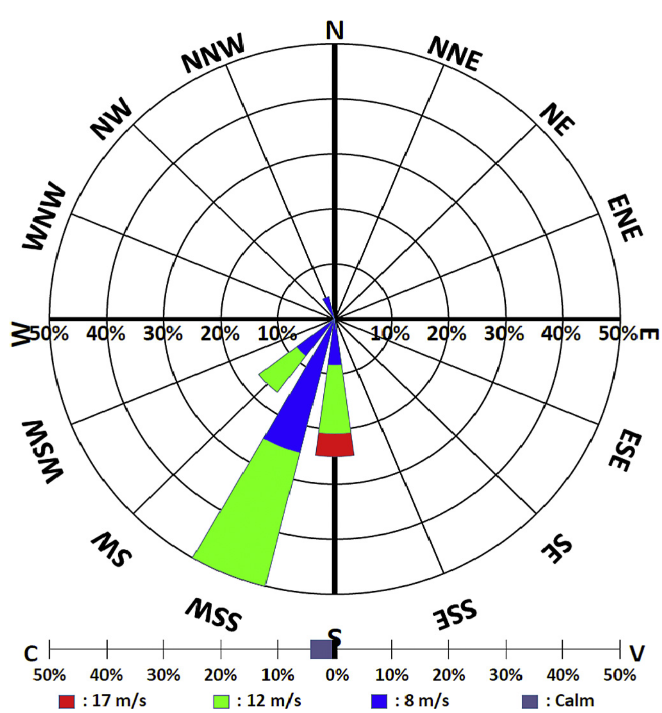

Fig. 1. The wind rose for indicating occurrence proportion for each wind speed in various wind-direction bins.