



Original Research Article

Modeling the bids of wind power producers in the day-ahead market with stochastic market clearing

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ABSTRACT

This paper studies optimal bidding decision for a strategic wind power producer participating in a day-ahead market that employs stochastic market clearing and energy and reserve co-optimization. The proposed procedure to derive strategic offers relies on a stochastic bilevel model: the upper level problem represents the profit maximization of the strategic wind power producer, while the lower level one represents the market clearing and the corresponding price formulation aiming to co-optimize both energy and reserve. Using the Karush–Kuhn–Tucker optimality condition for the lower level problem, this stochastic bilevel model is reformulated as a stochastic mathematical program with equilibrium constraints and solved using a suitable relaxation scheme. The effectiveness of the proposed method is demonstrated by two illustrative case studies.

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Introduction

Motivation

In the modern world, wind power has become an essential technology in the developing modern electrical generation [1,2]. In some countries such as Denmark and Germany, wind power producers (WPPs) have taken dominant positions in the electricity pools. U.S. Department of Energy also set the goal of 20% of electricity energy consumed by wind power generation by 2030 [3]. Wind power will have increasing influence on the marginal cost in market clearing, where energy is scheduled [4]. In Denmark and Spain, such high wind power prompted Independent System Operators (ISOs)/Market Operators to allow wind power producers to bid in the day-ahead market as other traditional sources. Similarly, in ISOs/Transmission System Operator markets of North America that have high penetration of wind power, WPPs are increasingly authorized to bid in the day-ahead market [5]. Like PJM, ERCOT and MISO, these ISOs/Region System Operators with high wind power installed require that wind power producers must bid in the day-ahead market [6].

Integrating wind power into a short term electricity market brings many challenges for the current electricity market

operations, because the high penetration and inherent uncertainty of wind power significantly impact the security of system operation. A variety of relevant researches have gained in popularity in recent years [7]. To participate in the deregulated markets, WPPs bid the price and quantity of wind power in the day-ahead market, which operates once a day, one day ahead, and on an hourly basis [8,9]. However, the high risk of financial penalties from realized wind power production's deviation from day-ahead schedule in the real-time market is hindering WPPs' participation in markets like other independent power producers. To mitigate the financial risk of failing to meet day-ahead schedule due to variable wind power production, the Federal Energy Regulatory Commission is discussing and working on changing the market rules of day-ahead and capacity [10]. Generally the transaction in the day-ahead market and the balancing market is settled based on pool prices or locational marginal prices (LMPs) depending on the particular market rules. For ISOs in the east coast of U.S., the hourly LMPs in the day-ahead market are derived through a security-constrained unit commitment and economic dispatch market clearing algorithm which simultaneously optimizes energy and reserve [11], in contrast to European markets' sequential schedule of energy and reserve. All current market clearing practices are based on deterministic methods where scheduling reserve is based on a worst-case scenario. However, current deterministic market clearing cannot fully integrate the uncertainty of wind power [12]. In regard to market redesign for distributed energy, [13] discussed

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the necessity of stochastic procedures to guarantee efficient and fair market clearing. Additionally, [14,15] proposed a two-stage stochastic programming with network-constrained market clearing model to deal with the uncertainty of wind power. Reference [12] formulates a short-term stochastic market clearing model for operation planning and demonstrates economical benefit of the stochastic method comparing with a deterministic worst-case scenario method. Reference [16] which models the effect of a WPP as a price-maker based on deterministic market clearing recommends further work of the effect of stochastic optimization to be done. Therefore, it is necessary and urgent to study the effect of stochastic procure in market clearing on bidding of renewable energy. In this paper, our main purpose is to study the strategic behavior of a WPP who participates in the day-ahead market with stochastic security-constrained market clearing as a price-maker and analyze the effect of simultaneous scheduling energy and reserve on WPPs' bidding.

Literature

There has been many approaches proposed to solve wind power trading problems [17–20]. Reference [17] models optimal wind power bids for a short-term market to minimize the imbalance cost considering uncertain imbalance prices and wind power predictions. In [18], a two-stage stochastic programming method is used to obtain the optimal offering strategy of WPPs. The paper [19] formulates a general methodology for deriving optimal bidding strategies based on probabilistic wind power forecasting and the sensitivity of a WPP to regulation costs. Reference [20] derives the optimal contract offerings in a perfectly competitive two-settlement market. Recently, the bilevel model has become attractive in modeling wind power markets [21–25], as bilevel programming works well in modeling the strategic bidding problems. Reference [21] proposes an optimal offering strategy for a strategic WPP that participates in the day-ahead market as a price maker and in the balancing market as a deviator. Reference [22] studies the equilibria of wind power producers in an oligopolistic market. Reference [23] considers the problem of a wind power producer that is a price taker in the day-ahead market, but a price-maker in the balancing market. The reference [24] develops the wind power producer offering model, where the maximum profit of wind power producer is the objective in the upper level problem, and the lower level problem represents a sequential market clearing process from the day-ahead market to the real-time market. To help wind power producers profitably recover investment cost and reduce the risk of offering, Reference [25] proposes a multi-stage risk constrained method to help wind power producer derive offer strategy. A bilevel program can be reformulated as a mathematical program with equilibrium constraints (MPEC) under suitable convexity conditions and constraint qualifications in the lower level problem. MPECs are known to be a highly difficult class of NP hard problems, due to the fact that usual constraint qualifications are violated at any feasible point (see [26, Proposition 1.1]). Hence, the classical Karush–Kuhn–Tucker (KKT) condition is not always a necessary optimality condition for an MPEC. Most literature on this topic, including [21–25], transform the complementarity constraints into mixed integer linear constraints by using Fortuny–Amat transformations [27] and solve the resulting mixed integer linear program. Alternatively, Reference [28] approximates an MPEC using a relaxed family of better-behaved nonlinear programs (NLPs), solves the sequence of the NLPs and drives the relaxation parameter to zero. In all related literatures, generators' true quadratic cost functions are linearized. Although the linearization simplifies the computation and make the problem tractable, it introduces many more new constraints and variables [29]. Moreover the linearization sections are hard to choose [29].

Contribution

This paper proposes a new stochastic bilevel model where the upper level problem represents the decision of variable wind sources and the lower level problem adopts the two-stage stochastic security-constrained market clearing model. Within the above framework, the contributions of this paper are fourfold:

- (1) To provide a new stochastic bilevel model for a strategic WPP with two-stage stochastic market clearing. The model that we propose integrates the day-ahead market stage and the balancing market stage to co-optimize energy and reserve. The balancing market is “stochastically” cleared with all plausible realizations of the wind power production, resulting in the “balancing price” introduced into the objective function of 80 the WPP as a variable. Since the balancing price is chosen to maximize the strategic WPPs profit, in the proposed market settlement which co-optimizes day-ahead and real-time dispatches in a single shot, the strategic WPP can exercise more market power so as to gain steady income. This approach is different from [21] where balancing price is selected from historical data or [24] where energy schedule is solved in the day-ahead market, and the solution of which is fed to the real-time market to obtain reserve dispatch. To the best of our knowledge, there are no papers or references which focus on strategic bidding behavior of a WPP in the stochastic security-constrained market clearing.
- (2) To reformulate the stochastic bilevel program into a stochastic MPEC and solve it numerically using a relaxation scheme. This method is also suitable to use generators' true quadratic cost function, without the need to linearizing it.
- (3) To take two illustrative examples as case studies, where optimal bidding strategies are discussed in details. The comparison between strategic and non-strategic WPPs and the comparison between reserve and non-reserve are presented.

This paper is organized as follows. Section “Problem description” gives a detailed problem description. Section “Mathematical formulation” presents the mathematical formulation of the bi-level model, derives the stochastic MPEC reformulation of the bilevel program and proposes the relaxation scheme for solving the stochastic MPEC. Two case studies based on a three-bus system and the IEEE 30-bus Test System (TS) are given in Section “Case study”. Finally, Section “Conclusion” concludes the paper.

Problem description

Stochastic market-clearing model

The day-ahead market clearing is a two-stage procedure in most markets, which is composed of security-constrained unit commitment and security-constrained economic dispatch. In the day-ahead market energy and reserve clearing methods differ from different market rules of regions. European markets like Iberian Peninsula market sequentially clear energy and reserve, while most ISOs in the east coast of U.S., such as PJM, New York ISO and New England ISO, simultaneously co-optimize reserve and energy. Detailed advantages of the simultaneous method are described in [30]. In PJM, LMPs of the day-ahead market are calculated according to generation offer and demand bidding of each hour with network constraints. In this paper unit commitment constraints (e.g. ramping rates, startup costs/times, minimum down-times) are not considered. However, the proposed single period market clearing model can be extended to multi-period.

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