Electrical Power and Energy Systems 42 (2012) 350–358

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Pay-as-bid versus marginal pricing: The role of suppliers strategic behavior

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ARTICLE INFO

Article history:
Received 7 February 2007
Received in revised form 29 March 2012
Accepted 8 April 2012
Available online 16 May 2012

Keywords:
Bidding strategy
Marginal pricing
Pay-as-bid pricing
Nash equilibrium
Risk profile
Strategic interaction

ABSTRACT

This paper illustrates how a generator profit may be affected by the pricing method of an oligopoly market model. Through utilizing a bilevel optimization technique and game theory concepts, Supply Function Equilibria (SFE) of pay-as-bid pricing (PABP) and marginal pricing (MP) mechanisms are derived. Theoretically, it is demonstrated that in the presence of strategic interaction, the generator optimal bidding strategy and the market clearing price are higher under PABP as compared with MP. In addition, the probability distribution patterns of expected loss and profit of each generator are constructed by simulating a multiperiod market under PABP and MP rules. It is shown that a generator has a higher expected loss or profit under PABP in unconstrained networks. However, the generator may gain less expected loss or profit if its physical location or transmission limitations are considered.

1. Introduction

The most common approaches for auctioning electricity markets are sealed-bid mechanisms. Suppliers offer supply schedules and the market supply curve, showing the bid price as a function of the cumulative bid quantity, is formed. The market clearing price is then determined at the price where supply is equal to demand. All the bids submitted at a price lower than or equal to the market clearing price are accepted and paid according to either pay-as-bid pricing (PABP) or marginal pricing (MP) method. Under the PABP mechanism, the suppliers (generators/generating firms) are paid their own bids they have offered; whereas under the MP scheme, accepted suppliers are paid the market marginal price (either the last accepted price-offer, LAO, or the first rejected price-offer, FRO). The PABP scheme may force generators to bid higher than their true marginal costs in order to make profit, while under MP, non-price setting generators gain profits even if they bid their marginal costs.

The choice between MP and PABP mechanisms for electricity markets and the arguments for and against them have been the subject of market studies [1–5]. Although revenue equivalence result [1] suggests that the expected payment in a uniform pricing scheme will be identical to that in a PABP mechanism, some papers argue in favor of MP (see e.g., [4,5]) because of other considerations such as fairness and efficiency. MP is recognized an efficient pricing method since, bidders have an incentive to reveal their true costs and therefore the dispatch will be efficient [2]. MP is known to be fair as well, because all the winners receive (or pay) the same price and nonwinners fail to win, as they refuse to offer at or less than the market clearing price [3]. A potential problem with MP is that whenever a supplier can influence the price, the MP mechanism gives the supplier an opportunity to exercise market power by bidding above its marginal cost. PABP is recommended as a way to prevent the exercise of market power. In contrast to MP, under PABP, there is no incentive to increase the offer curve above marginal cost in an effort to increase the price received on all quantity offered below the market clearing price [3]. Reduced price volatility is one of the arguments used in support of PABP because it is based on an average price rather than a marginal price which is volatile to gaming [4]. Another advantage with the PABP is that the risk for tacit collusion is lower in this mechanism compared to the MP [7]. A drawback of pay-as-bid pricing is that the market price does not reflect a surplus or deficit of generation capacity and in the long-run, the potential investors are deprived of the correct economic signals [8].

A number of studies have concentrated on the bidding behavior in the electricity markets and compared the market performances under PABP and MP schemes. These references are briefly reviewed here. Wolfram [4] illustrated a simple electricity auction to examine the differences between discriminatory and uniform pricing auctions [4]. It is shown that for a typical case there is equal revenue between the discriminatory and the uniform pricing cases.

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0142-0615/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijepes.2012.04.001

Federico and Rahman [6] compared uniform price and discriminatory auctions for perfect competition and monopoly. They demonstrated that the expected output decreases and the expected consumer surplus increases after a switch to PABP. Analysis in [7] focuses on developing a Nash equilibrium (NE) for a duopoly model with constant marginal costs. It is shown that if the demand is inelastic and certainly known, average prices will be lower under PABP than those under MP. Ren and Galiana compare the quantitative behavior of a perfectly competitive market under PABP and MP structures [8,9]. Assuming an uncertain demand, they demonstrate that although MP and PABP yield the same expected generator profits and consumer payments, the risk of not meeting these expected values is greater under MP. Game theory and auction theory are employed in [10] to analyze the strategic behavior of a two-player auction game, under discriminatory and uniform pricing mechanisms. It is shown that the revenue equivalence theorem does not hold in a simple multiunit auction model in the presence of market power. Ref. [11] develops an SFE (Supply Function Equilibrium) for a discriminatory auction and proves that SFE always exists if the system demand follows an inverse polynomial probability distribution. Assuming this probability distribution and compared to the uniform price auction, the demand-weighted average price is shown to be equal or lower in the discriminatory auction. The Q-learning (QL) method and the model-based (MB) approach in optimizing supplier's bidding strategy in a PAB auction is compared in [12]. It is shown that the Q-learning algorithm can enable suppliers to find the optimal bidding strategy in the PoolCo market. Ref. [13] proposed a method for finding the SFEs in the constrained electricity market assuming the slope of the supply function as the decision variable. Through simulations it is shown that producers can benefit more from bidding slope as compared to the model whose decision variable is the intercept. A global optimization method is developed in [14] for predicting the bidding strategy of gencos in the electricity market. The PAB payment rule and the SFE model are assumed in the solution approach. A realistic PAB electricity market (namely, Iran's electricity market) is considered in [15,16] and the market performance is assessed. Authors in [15] analyze the efficiency and the competition intensity of the market using structural market power indices such as HHI and entropy coefficient. The effectiveness of countermeasures implemented for mitigation of market power is also discussed in [15]. Statistical analysis based on the experimental load and price data of the market is carried out in [16] to reveal the predictability and stationarity characteristics of the market data. Li et al. present a comprehensive literature review on the recent research of modeling methods for bidding strategy analysis in the electricity markets [17].

In this paper, we deal with the effects of the PABP and MP mechanisms on a generator/generating firm profit under imperfect competition. An oligopolistic market model is considered, which consists of a number of strategic generators with gaming ability. The SFE approach is adopted to model the strategic behavior of each generator, assuming that it offers an affine nondecreasing supply function to the market. By adjusting the intercept of the linear supply function as the decision variable of a generator, we develop the SFE of a noncoopration perfect information game. A bilevel optimization technique and a mathematical program with equilibrium constraints (MPECs) approach is used in formulating the game problem under the PABP and MP mechanisms. Analytic expressions for the optimal bidding strategies and the maximum profits are then derived under both pricing mechanisms, assuming a common loading condition. Theoretically, it is demonstrated that for a certain and inelastic demand, the optimal bidding strategies and the market clearing price are higher under PABP mechanism. It is also shown that the maximum profits of generators under PABP and MP are not the same. To confirm the theoretical results and to establish a quantitative comparison between PABP and MP schemes, we simulate a multiperiod market over a specified time horizon. Considering the generator random outages, we calculate the expected loss and profit of each generator and construct the cumulative probability distribution curve (referred as risk profile). The resulting risk profiles, exhibiting the probability of the expected loss and profit, are then compared under PABP and MP.

The remainder of this paper is organized as follows. The notation is introduced in Section 2. Section 3 provides the mathematical formulation of the problem including the ISO and the power producer problem. The game solution technique and a methodology for constructing the generator risk profile are also discussed in Section 3. Section 4 is devoted to the simulation results of a number of case studies. Concluding remarks are presented in Section 5.

2. Notation

The notations used in this paper are introduced as follows. For a generic variable x, the notation x_i (for $i = 1\ldots n$) is used to refer to each element of vector x. The upper bound on the value of x_i is represented by $\bar{x}_i$. The notation q is used for quantity and p for price. The subscripts e and d stand for energy and demand, respectively. The notation "$diag(w)$" indicates a diagonal matrix whose entries are the components of the vector w. Also, the notation $u \perp v$ is used for expressing the complimentary conditions, means that the two vectors are perpendicular.

The electrical network composed of n nodes, indexed by i. A demand at node i is represented by $q_{d,i}$. Generators are denoted by $G_{i,f}$ where i is a node index and f (or h) is a generator index. The total number of generators is denoted by N_G. The set of arcs is denoted by A and, if $ij \in A$ there is an arc between i and j. The power flow between nodes i and j is represented by F_{ij} and notation $\overline{F}_{ij}$ is used for capacity limit of the line between nodes i and j. L is the set of Kirchhoff loops in the network indexed by m such that L_m is the ordered set of arcs associated with kirchhoff loop m. z_{ij} is the reactance on arc $ij \in L$ and $s_{ijm} = \pm 1$, depending on the orientation of arc ij in loop m. To indicate the time dependency of a generic variable x notation x^t is used. The ramp up rate and the ramp down rate limits are represented by ru and rd, respectively. δ^t is defined as $\delta^t = 0$ for $t = T$ and $\delta^t = 1$ for $t < T$.

The marginal cost function of a single generator is assumed affine in the form $p(q^t_{e,i,f}) = a_{e,i,f} + b_{e,i,f} q^t_{e,i,f}$, where $a_{e,i,f}$ and $b_{e,i,f}$ are positive coefficients. For each generator (player) in the game, $\alpha^t_{e,i,f}$ (or, for simplicity $\alpha^t_{i,f}$) represents the bidding strategy of generator f at node i, and $\alpha^t_{i,-f}$ indicates the bidding strategies of generators other than generator f. Also, $\Pi_{i,f}(\alpha^t_{i,f}, \alpha^t_{i,-f})$ represents the payoff function of generator f. To model the strategic behavior, $\alpha^t_{e,i,f}$ replaces the true intercept $a_{e,i,f}$ in the marginal cost function. The failure probability of $G_{i,f}$ is denoted by $fp_{i,f}$. $E(x)$ denotes the expected value of x. Symbol "$*$" represents value in the equilibrium state.

3. Mathematical modeling

3.1. Market assumptions

In this paper, we assume the bid function of each generator in the form of an affine nondecreasing supply function because it allows representing more realistically the bidding procedure through the strategic variation of the supply bid. As found in some references a preferable choice for bidding (e.g., see [18,28,29]), we assumed that with a one-degree-of-freedom parametrization, the decision variable for each generator is the intercept of its supply function (namely, $\alpha^t_{i,f}$). Similar approaches for supply function parameterization can be found in literature, as in [19], which takes