Electricity market equilibrium model with resource constraint and transmission congestion

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ABSTRACT

Electricity market equilibrium model not only helps Independent System Operator/Regulator analyze market performance and market power, but also provides Market Participants the ability to build optimal bidding strategies based on Microeconomics analysis. Supply Function Equilibrium (SFE) is attractive compared to traditional models and many efforts have been made on it before. However, most past research focused on a single-period, single-market model and did not address the fact that GENCOs hold a portfolio of assets in both electricity and fuel markets. This paper first identifies a proper SFE model, which can be applied to a multiple-period situation. Then the paper develops the equilibrium condition using discrete time optimal control considering fuel resource constraints. Finally, the paper discusses the issues of multiple equilibria caused by transmission network and shows that a transmission constrained equilibrium may exist, however the shadow price may not be zero. Additionally, an advantage from the proposed model for merchant transmission planning is discussed.

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1. Introduction

In US, pre-deregulation the wholesale electricity price is set and regulated by FERC or State Public Utility Commission (SPUC). A vertical integrated electric utility only operates based on cost minimization in a short-run, and keeps a rate of return supervised by FERC or SPUC in a long run.

Current industry structure generally requires separating the functions associated with selling and buying electric energy, the generation and distribution (or consumption), from transmission. Market participants have to face the volatility of price and make sure profitable in a long run. Instead of discussing all of players, this paper will mainly focus on the short-run operation strategies of GENCOs. The traditional economic dispatch (EDC) and unit commitment (UC) programs used by electric utilities for many years are only helpful to GENCOs who own multiple generation facilities when they make one offer to the market and then need to dispatch their units in the most economic fashion to deliver this offer. A profit based bidding decision support system is critical for GENCOs to operate in the new environment.

The previous research on bidding strategies is methodologically classified into the following three groups.

1.1. Pure optimization model

The first group of research pays attention to a specific player, the one under study. The idea is to simplify "the rest of the world" as a set of exogenous variables (stochastic or deterministic). The group of study has developed many mathematical programming models to find an optimal bidding strategy (*e.g.* Dynamic Programming, Fuzzy Linear Programming, and Stochastic Dynamic Programming, etc.). A bidding strategy using Markov Decision Process (MDP) is proposed in [1]. The authors discussed the impacts of production limit and market share on optimal bidding strategies. The number of states is reduced by classifying peak/off-peak load, peak/off-peak price. A decision aid for scheduling and hedging (DASH) model is proposed in [35] for power portfolio optimization. The inputs of the model, electricity demand, electricity forward price, gas forward price, and electricity spot price are captured by several stochastic processes. A multiple time scale decision-making problem is solved considering both long-term financial and short-term operational constraints. The group of models is usually easier to generalize and analyze because of well-established mathematical foundation. The disadvantage is that the methods do not model the behavior aspect of players.

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1.2. Game theory model

The second group discussed the bidding strategies from a perspective of players' interactions. It is also called equilibrium model, for the whole purpose of the group is to analyze economic equilibria of the system. The mutual interaction is represented by Game Theory. Game Theory can be classified into two areas—Cooperative and Non-cooperative [2]. Cooperative games can be applied to investigate the effects of firms' collusion. In a model named Stackelberg game, a firm as a leader (first-mover) with largest market power is assumed to be able to manipulate prices subject to the accurately predicted reactions of naive followers who have small market shares and believe they cannot affect prices [3]. The Stackelberg game is also modeled as a mathematical programming with equilibrium constraints (MPEC) problem [4].

In more competitive models, Cournot and Bertrand are assumed to represent the type of interaction [5–9]. However, assumptions of the two models are naive for ISO-type auctions, in which GENCOs bid a whole set of price/quantity pairs for each generator. In this case, decision variables become parameters of a function that determines a relationship between price and quantity that GENCO is willing to produce. The type of competition is termed as Supply Function Equilibrium. Section 3 will review Supply Function Equilibrium model in detail. Game with incomplete information is discussed in [10]. A contribution of this group is that this research provides analytical rationale and explanation regarding how market power can be exercised by strategic bidding behavior [11]. The actual market prices can be simulated rather well through a SFE model [24] given some certain assumptions. However, game theory itself is based on the rationality of all players. This assumption does not generally hold in practice. The issue of multiple equilibria frustrates a lot of game theorists. This type of game model is logically limited lack of dynamic theory, too.

1.3. Agent and heuristic model

The last group of past research efforts fully utilizes computer science methods to mimic human beings and simulate optimal bidding strategies [11]. Sheble and co-workers [12] proposed a genetic algorithm based framework to evolve utility bidding strategies in a double side auction marketplace and developed a market simulator by Pascal language. An evolutionary programming bidding strategy is discussed in [13]. Gao and Sheble [14] analyzed and compared the pros and cons of genetic algorithm, evolutionary programming, and particle swarm to simulate GENCOs' bidding. Wu and co-workers [15] have discussed those issues on modeling electricity market as Multi-Agent System (MAS), both theoretical and practical aspects. Reinforcement-learning algorithms are considered to "teach" an agent to learn the optimal bidding strategy gradually. A particular reinforcement-learning algorithm—Roth/Erv algorithm is implemented in [16,17]. Others joined MDP model in Group 1 with some reinforcement-learning algorithms. They proposed to use Q-learning or Actor/Critic learning algorithms to solve optimal policy for a MDP with incomplete information [18–20]. The basic intuition underlying reinforcement learning is that the tendency to implement an action should be strengthened if it produces favorable results and weakened if it produces unfavorable results [21]. The group of models is more flexible, robust, and easily implemented compared with analytical approach (Groups 1 and 2). However, the drawback is that the underlying mathematical foundation is not well developed.

2. Contributions of this paper

Based on literature [27], this paper further discusses why the SFE model with slope parameterization (called k-parameterization

[37]) is properly applied to single-, not multiple-period situation. The model of intercept parameterization (called l-parameterization [37]) can handle different biddings during multiple periods and is computational efficient. The existence, uniqueness, and stability of equilibrium are easy to show compared to slope parameterization [29].

Then, this paper analytically derives a multiple-period optimal bid strategy based on manipulating intercept parameters. Discrete time optimal control technique is utilized. GENCO's decisions in both fuel and electricity markets are modeled together. A special structure, which results in a nice decoupling of the optimal bids with respect to time, is recognized.

Regarding to transmission constraints, the paper discusses a different type of constrained equilibrium from literatures and shows that a transmission constrained equilibrium may exist, however the shadow price may not be zero. An illustrative example is given on the existence of pure SFEs with transmission constraints. The paper also discusses that the pure transmission constrained "equilibria" found in [37] may not be a true Nash Equilibrium.

The last contribution of the paper is for merchant transmission planning. In the current market environment, transmission planning needs to consider market players' strategic behaviors besides reliability and economics issues. The proposed model can give a quantitative measurement to support transmission planning.

3. Supply function equilibrium model

3.1. Literature review

The general supply function equilibrium (SFE) model was introduced by Klemperer and Meyer [22] and applied by Green and Newbery [23] to the electricity industry reform in England and Wales (E&W).

Recently, some empirical analysis on SFE model has been done for ERCOT real time balancing market. ERCOT is undergoing a transition process from zonal to nodal structure. The new nodal market will be launched in early 2009. Niu [24] applied a linear SFE model to evaluate the previous market performance of ERCOT BES from 2002 to 2003. She found that the balancing up energy market is relative efficient, however balancing down market is rather inefficient. Sioshansi and Oren [25] studied bidding strategy of market participants in ERCOT within the same period and showed that several major participants with largest market share behave close to what a SFE predicts given certain assumptions. These examples prove that SFE model is a valuable tool to simulate current electricity market.

In SFE model, functional forms must be specified for demand, cost, and supply. A particularly simple form is to assume a linear demand function, a quadratic convex cost function, and a linear supply function. The great advantage of the SFE with linear functional forms over the more general form is the analytical solvability.

Assume that for GENCO i, the true cost function is given by a quadratic convex function

$$\text{Cost}_i(q_{it}) = \alpha_i q_{it} + 0.5\beta_i q_{it}^2, \quad \beta_i > 0 \tag{1}$$

Also assume that the rules require GENCO i to bid a linear increasing supply function with two strategic parameters: intercept l_{it} and slope k_{it}. GENCO i's bid function at time t is given:

$$P_t = l_{it} + k_{it}q_{it}, \quad (k_{it} > 0) \tag{2}$$

The system integrated demand curve is assumed to be

$$P_t = h_t - g_t Q_t, \quad (g_t > 0) \tag{3}$$