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Assessing impact of subjective demand beliefs on a dynamic duopoly electricity market game

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ABSTRACT

In the context of liberalized markets, market outcomes generally result from the strategic interactions of all market players. Generation company (Genco), as the distributed players, build their subjective demand evaluations (SDFs) about market for optimal bidding purpose. Due to the differences in terms of data availability and modeling techniques, subjective demand models held by various Gencos are heterogeneous and normally deviate from the real market model as well. The picture of a real electricity market game in Genco's eye is 'playing is believing'. Therefore, a question naturally comes to the table: how those SDFs with the heterogeneous manner impact individual player's decision and game results. To answer this question, this paper relaxes a conventional assumption, commonly used in the classical oligopolistic equilibrium model, that one correct and uniform demand knowledge is shared by all Gencos. The results suggest that the system equilibriums would be influenced by the Gencos' knowledge about market demand. The economic value of demand information is assessed regarding the system performances.

1. Introduction

In oligopoly Cournot electricity market games, market players, e.g. generation companies (Gencos) in this paper, simultaneously adjust their strategy (i.e. outputs) to increase their profits. The behaviors of Gencos are normally interpreted as a kind of equilibrium-oriented bidding evolution process. The notion of market equilibrium, e.g. Nash equilibrium, is commonly referred to a system state when dynamic interactions approach stable. Modeling market equilibrium is not only useful for system operator to monitor market power and assess market rules [1–3] but also could facilitate Gencos to identify their market power so as to bid in a reasonable way [1,3].

Many approaches have been proposed with the intention to model market players' behaviors and capture the resulting market equilibrium.

Taking its advantage of simple and flexible modeling, agent-based automatic learning, as one approach category, is used to simulate players' strategy decision making [4–8]. The reinforcement learning or its varieties are employed by all agents in the repeated market environment to weight predefined discrete actions via a long-term beneficial function. The system is said to converge if all players converge to the certain actions with which an optimal long-term beneficiary is assumed to be obtained.

Market equilibrium model, as another promising approach, also attracts much research interest. In equilibrium model, the rivals' behaviors are taken into account when on Genco develop its optimal strategies. When the interactions among Gencos approach stable it is said system reach the Nash equilibrium. Ref. [9] proposes a binary expansion scheme to find the Nash equilibrium in the short-term electricity markets. Ref. [10] proposes a compact formulation to find all pure Nash equilibriums in a pool-based electricity market with stochastic demands. Ref. [11] firstly employs the mathematical program with equilibrium constraints (MPEC) to model a single producer's behavior and then achieves the equilibrium by solving all MPEC simultaneously in a pool-based network-constrained electricity market.

However, all those approaches assume that there is one uniform and accurate market demand function available and shared by all Gencos. In the realistic electricity market, many stochastic factors, e.g. weather, demand side features, influence the real market demand functions. It is hard to have a commonly agreed function available for all Gencos. Each Genco has to construct its own market demand function, namely subjective demand function or belief

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in this paper, for bidding with all available data: history public data and its private information. Compared to real market model, in most cases Gencos more or less have evaluation errors or bias towards real market demand model, saying subjective demand error in this paper. Thus, it is important to study how the game will be changed with those demand errors, in term of, e.g. game equilibrium, steady state and system performance. The research questions in this paper are derived from the concerns of practical electricity market systems.

To our best knowledge, there has been relatively little prior work in this topic within electricity market system literature. Ref. [12] analyzes the impact of demand knowledge diversities on players' conjecture variation based bidding strategies and proposed a linear data filter method to alleviate system oscillations which are caused by such demand evaluation noises in a dynamic bidding process. Ref. [13] studies the impact of a mis-specified demand function on the steady state and the related attraction basins of a symmetric duopoly system. However, it did not consider the asymmetric system with heterogeneous players' behavior, which conform more to the reality.

In this paper, a duopoly game based on the subjective demand beliefs is set up. Our main result is that the system equilibriums are indeed influenced by the Gencos' knowledge about market. These influences are reflected by the two facts: first the SDFs could determine if the system equilibriums are local stable; and second if in the case of stable state the SDFs could change the positions of system equilibriums. Considering the possible knowledge deviations in the real electricity markets, the learning strategy by Gencos such as the adjustment length α in this paper should be cautiously chosen. By doing so, the unstable state of economic system and the resulting instabilities of the physical electricity network can be prevented.

The rest of this paper is organized as follows: Section 2 introduces the equilibrium model based on the subjective demand functions. Section 3 analyzes the stability conditions of the equilibriums in the proposed system. In Section 4, the system dynamics induced by demand errors are analyzed. The final section concludes the paper.

2. Genco's models with subjective demand functions

In this section, we introduce the game models which contain demand belief errors. For the models without belief errors, one can refer to the literature such as the work in [14–16]. Note that in this paper Gencos develop their strategic bidding responses based on a uniform price market clearing model.

2.1. Subjective demand beliefs

We assumes that there are a set of Gencos, denoted as I and a set of loads, denoted as J, dispersed among geographical locations. The node number is denoted as N. The demand evaluations by Genco i for the load j at the node n, denoted as f^e_{ijn}, is represented by the product of the reference demand of the load j located at the node n and an error coefficient ε_{ijn} $(0 < \varepsilon_{ijn} \leqslant 2)$. Then the subjective belief of the linear demand function by Genco i is described as follows:

$$f^e_{ijn} : p^e_{ijn} = \varepsilon_{ijn} \cdot (a^r_{jn} - b^r_{jn} \cdot D_{jn}) = \varepsilon_{ijn} \cdot (a^r_{jn} - b^r_{jn} \cdot (Q_{ijn} + Q_{\text{-}ijn})) \quad (1)$$

where a^r_{jn} and b^r_{jn} are the coefficients of the reference demand function; p^e_{ijn} is the evaluation price about the load j located at the node n by Genco i; D_{jn} is the demand consumption of the load j at the node n; Q_{ijn} and $Q_{\text{-}ijn}$ are, respectively, the supplies by Genco i and its competitors to the load j at the node n.

Since electricity market demands are dispersed among geographical locations, a vector to denote all subjective demand beliefs for Genco i at all nodes in system is defined as:

$$F^e_i = [f^e_{i11}, \cdots f^e_{ijn}, \cdots f^e_{IJN}]$$

where I, J and N are the total number of Gencos, loads and nodes.

In this paper, we assume that transmission capacities on all transmission lines are large enough so that the demand functions at different nodes can be integrated as one. Thus the node number is 1. Then the subscript of n and N in (1) can be omitted. Then for Genco i, its subjective demand function is transferred as:

$$p^e_i = \varepsilon_i \cdot (a^r - b^r \cdot (Q_i + Q_{-i})) \quad (2)$$

Fig. 1 shows an example about the relation between a reference demand function and the subjective demand functions held by different Gencos. In the figure, the value of the error coefficient, ε_i, represents the belief deviation of Genco towards the real demand function. Being smaller or larger than 1 indicates the cases of demand underestimation or overestimation respectively; the correct evaluation is the value 1. In this paper, we only discuss the cases that the error coefficients are static ones. The stochastic case is left for the future work.

2.2. Genco's behavior model with subjective demand beliefs

When Genco i outputs quantity Q_i, the production marginal cost takes the form as follows:

$$MC_i = \gamma_i \cdot Q_i + \beta_i$$

where $\gamma_i(\geqslant 0)$ and $\beta_i(\geqslant 0)$ are the coefficient of the cost curve for Genco i.

At time t, the profit maximization for a Genco is represented by the following optimization formula with the quantity $Q_{i,t}$ as the decision variable:

$$\begin{aligned} &\max \ P_{i,t} = p^e_{i,t} \cdot Q_{i,t} - \left(\tfrac{1}{2}\gamma_i \cdot Q^2_{i,t} + \beta_i \cdot Q_{i,t}\right) \\ &s.t. \ Q^{\min}_i \leqslant Q_{i,t} \leqslant Q^{\max}_i \end{aligned} \quad (3)$$

where $P_{i,t}$ is the expected profit of Genco i at time t. $p^e_{i,t}$ is the expected market price by Genco i at time t, which is an exogenous value for all Gencos. $Q^{\min}_i$ and $Q^{\max}_i$ are the upper and lower generation capacity limits for Genco i.

With the subjective demand functions defined in (2), the expected marginal profit of the Genco i for time $t + 1$ is the derivative of profit calculated by (3) associated to the quantity $Q_{i,t+1}$:

$$\frac{\partial P_{i,t+1}(\varepsilon_i)}{\partial Q_{i,t+1}} = \varepsilon_i \cdot a^r - \beta_i - \gamma_i \cdot Q_{i,t+1} - 2 \cdot \varepsilon_i \cdot b^r \cdot Q_{i,t+1} - \varepsilon_i \cdot Q^e_{i,-i,t+1} \quad (4)$$

According to the first-order optimality condition, when letting the formula (4) equals to zero, the obtained quantity $Q_{i,t+1}$ is the

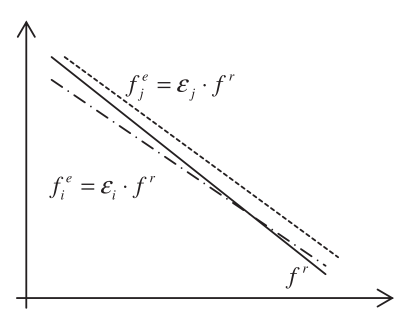

Fig. 1. An example of subjective demand beliefs.