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A game equilibrium model of a retail electricity market with high penetration of small and mid-size renewable suppliers

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ABSTRACT

Game theory has provided a practical tool to model players' strategic behavior in electricity markets, particularly as the world moves towards a more competitive market. A game theoretic approach can be used to find the clearing electricity price in a retail electricity market with a high penetration of small and mid-size renewable suppliers.

1. Introduction

Traditionally regulated electric power markets have undergone massive changes due to environmental and economic incentives. Therefore, deployment of a market structure that favors more competitive and less regulated models, such as the retail competition model, has been a worldwide trend over the last few decades. Market models can be classified into centralized and decentralized versions (Barroso et al., 2005). Considering the wide range of varieties in electricity market structures, several methods have been introduced to analyze and optimize different aspects of deregulated electricity markets. These models vary significantly at the level of competition (Bompard et al., 2010) and can be ranged from the most uncompetitive situation, Stackelberg (Day et al., 2002) to the most competitive model, Bertrand Competition (Haraguchi and Matsumura, 2016; Ma et al., 2015; Younes and Ilic, 1999). There is a rich literature in modeling strategic interactions in electricity markets. Yang at al. (Peng et al., 2013) obtained the Nash equilibrium using backward induction to model the costs to utility companies arising from fluctuations in user demand. Song et al. (Song et al., 2002) employed the Nash equilibrium to analyze bidding strategies in a bilateral market. Market clearing prices within a hydrothermal power exchange market were found by developing a Nikaido-Isoda function to achieve the Nash-Cournot equilibrium in (Molina et al., 2011). In (Kiani and Annaswamy, 2010) authors analyzed the energy market in the presence of renewable energy resources and demand response. Chen et al. (Chen et al., 2010) developed a distributed demand response algorithms and achieved the equilibria in both a competitive and oligopolistic market. A non-cooperative game was employed by Sikdar et al. in (Sikdar and Rudie, 2014) to model a trade mechanism through the example of electricity trade at an electric vehicle charging facility to help create decentralized markets. Despite these scholarly efforts in finding the market equilibrium, the retail sector of the electricity market has not been extensively studied to the best of the author's knowledge. It is necessary to comprehend how the retail market responds to recent technological developments that allow the high integration of small renewable suppliers in a competitive context. In the proposed electricity market, the end users of electricity are actively engaged in the market either through generation or load management. This study covers the challenges at the intersection of the foreseeable future technologies, namely smart grids, and the concept of game theory from an economic point of view.

Introducing competition in a deregulated market structure gives rise to a high penetration of renewable resources, particularly wind and solar energy, and thus enables distributed generating units that are economically efficient (Negrete-Pincetic et al., 2015). Integration of these units at the residential level into the power grid can alleviate concerns regarding anticipated high load demand and sustainability issues. Small renewable suppliers, if employed at a large scale in the residential sector, can compensate for the high costs of operating reserve capacity in the utility grid. The resulting financial advantage will be shared among both consumers and the utility grid. Consumers will be financially incentivized by selling their generated electricity. The utility grid will benefit from both the reduced costs of the reserved capacity and increased ancillary services which are required by these small suppliers. Searching for possible market equilibria has been an objective for market participants (Pozo et al., 2011), since it is the most beneficial strategy for all the agents. It empowers all players to make an optimal decision, based on their competitors' choices. Due to the

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multitude of both suppliers and consumers in this market structure, this article employs a game theoretic method to clear hourly electricity market prices in a deregulated retail electricity market. The game modeling and the market framework in this study are unique and necessary for a better understanding of the future of the electricity markets.

The remainder of this article is organized as follows: Section 2 introduces the main features of the market model and formulates the problem based on a game theoretic approach. Section 3 describes the main features of game theory and Nash equilibrium and illustrates the modeling of the games in this problem. Section 4 presents the simulation results, including the optimized behavioral pattern of each of the market participants and the clearing electricity prices. Section 5 concludes this article's findings and discusses future directions. A detailed description of the mathematical formulation of the problem can be found in Appendix A.

2. Materials and methods

2.1. Market framework

In the past few years, environmental concerns, increasing penetration of electric vehicles and subsequent concerns regarding high load demand, smart metering and energy storage needs, as well as the urgent need for a more efficient and reliable electricity network, have necessitated a more complicated and intelligent construct within the electricity market. The smart grid, defined by the Smart Grids European Technology Platform as: "electricity networks that can intelligently integrate the behavior and actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic, and secure electricity supplies" (Smart Grids Advisory Counsel, 2010) has captured great interest as a reliable and secure grid. Smart grid technologies enable the integration of small renewable resources at the residential level. These small suppliers are equipped with various generation and storage units, such as wind turbines, solar panels, diesel generators, and distributed energy storage devices (DESD) and are able to communicate and exchange information with other agents. This communication not only results in maximizing profits but also improves market stability and reliability. As a result, substantial innovations and cost reductions in the future of the electricity market can be expected. Plug-and-play technology enables customers to connect to the utility grid at any time, in order to buy or sell electricity. It provides an interface for all agents to be easily recognized as soon as they connect to the grid and collects information regarding loads, storage, and generating units of that agent. This feature is facilitated by the bidirectional flow of electricity (Bae et al., 2014) in smart grids. In this system, electricity suppliers become independent of their conventional role (Su and Huang, 2014). While the main focus of literature in the last few years has been on the distribution power operations of utility companies, increasing consumers' active engagement in a deregulated competitive market calls for an urgent attention to further address the technical concerns regarding distributed energy generation and storage.

In a traditional electric market, electricity price is set by regulations. In a retail competitive model, however, consumers' active involvement in the market will eventually result in a market with controlled lower prices. In this article, we employed an inverse-demand function to obtain the hourly electricity prices. These prices are a function of the aggregate load demand. Thus, by managing their dispatchable load demand, consumers are constantly involved in setting the market prices. The electricity cost function is based on the well-known Cournot model, which is widely used to approximate competition in the electricity market (Kwang-Ho Lee and Baldick, 2003; Siriruk and Valenzuela, 2011). Since suppliers are infinitesimal, they have no effect on the market price (Novshek, 1980). In this market structure, the role of utility grid is considerably different than in traditional models. The utility grid no longer monopolizes the whole market. In fact, it appears as a complementary unit to compensate for the deficiency of power from small suppliers. It is responsible for implementing the necessary infrastructure to enable secure communication among market participants. It can make a profit not just by selling electricity but by providing ancillary services to various consumers including small or mid-size suppliers. This article excludes the role of the utility grid as an active player in the game. Its main focus is on the interactions among a large number of suppliers and consumers. Thus, the grid is not considered a separate player, though its role is conspicuous when suppliers prefer to buy electricity from the grid rather than switching on a diesel generator with a high cost function.

In every market, participants strive to achieve maximum profit. At the same time, they are very well aware of the fact that their competitors' decisions will influence their results. Game theory provides a tool to analyze the strategic interactions among market participants (Singh, 1999). Depending on market characteristics, various game approaches can be employed to find a market's equilibrium. Since the proposed model is highly reliant on the active participation of multitudes of small or mid-size renewable suppliers, the market structure would be complex and dynamic. In the first step, since consumers are separate entities, a non-cooperative game is employed to find the Nash Equilibrium among consumers. The interactions among suppliers are modeled by a cooperative game. From suppliers' perspective, collaboration is not only possible, but can result in a more stable market as various suppliers share information. This coalition is facilitated by the utility grid, which enables small suppliers to have access to the necessary information for this cooperation to take place. Finally, a non-cooperative game among consumers and suppliers is taken into consideration to find the Nash equilibrium. In a Nash equilibrium, all the market participants can achieve the highest possible outcome. By employing a design of experiment approach, the rational reaction set of market participants can be obtained. These rational reaction sets are used to model the interactions among the consumers and the suppliers to find the Nash equilibrium. It reveals the clearing price at each hour, as well as the optimum behavior of each of the participants. Several well-known equilibrium models have been introduced and applied to electricity markets in the last few decades. For the proposed model, the same assumptions and features as the Cournot model are taken into consideration (Allaz and Vila, 1993; Vives, 1984):

- All units produce a homogeneous product.
- The market price is influenced by the total supply and therefore is fixed for all units.
- Each firm's output decision affects the market price.
- The number of firms is fixed during the market clearing price.
- Firms compete in quantities and act simultaneously.
- Each player is considered to be rational.

2.2. Problem formulation

This section formulates the mathematical model and key concepts in a highly competitive retail electricity market. This model allows for a high penetration of distributed generators (DG) and distributed energy storage devices (DESD). Market participants can be categorized into three groups: small suppliers, consumers, and the utility grid. However, the utility grid is not an active player in the game modeling of the problem. The objective function and constraints for each entity is formulated in mathematical terms.

2.2.1. Objective functions

For suppliers, the objective function of the ith player is defined as the summation of differences between revenue and cost over 24 h in one-hour intervals. This set of players seeks to maximize their objective function. This goal can be achieved whether by minimizing costs or maximizing revenue at each hour.