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Development of a virtual power market model to investigate strategic and collusive behavior of market players

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HIGHLIGHTS

- A virtual power market model is proposed using a heuristic dynamic game theory.
- The proposed model can simulate the behavior of market players in a certain period.
- This model can evaluate the oligopoly, collusive and strategic behavior of players.
- The price uncertainty and security constraint are considered.
- Neglecting strategic behavior of players can cause adverse consequences.

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ABSTRACT

In this paper, a virtual power market model is proposed to investigate the behavior of power market players from regulator's point of view. In this approach, strategic players are modeled in a multi-agent environment. These agents which are virtual representative of actual players forecast the prices and participate in the markets, exactly the same as real world situation. In addition, the role of ISO is encountered by using security constraint unit commitment (SCUC) and security constraint economic dispatch (SCED) solutions. Moreover, the interaction between market players is modeled using a heuristic dynamic game theory algorithm based on the supply function equilibria (SFE). In addition to the collusive behavior, using the proposed model, the short-term strategic behavior of players, which their effects will appear in long-term, can be simulated.

The proposed model enables the market regulators to make decision before implementing new market rules with the confidence of their results. To represent the effectiveness of the proposed method, a case study including wind power plants is considered and the impact of various market rules on players' behavior is simulated and discussed. Numerical studies indicate that simulating the strategic and collusive behavior prior to any change in the market rules is necessary.

1. Introduction

The important targets of the regulatory body in the power market are providing a safe and clear competition environment. Since the experience of one market cannot be directly applied to another one, if a tool is available that can evaluate the effect of changes in the market rules before their implementation, the risks of the market failure can be greatly mitigated. In this basis, a market simulator can be used by regulatory bodies to predict the behavior of market players, especially in oligopoly environments.

Several methods have been utilized to model the oligopoly power market. David and Wen (2001) have developed a stochastic optimization to study the offering strategies. Gutiérrez-Alcaraz and Sheblé (2006) have studied the decisions of a two-player oligopolistic market in a dynamic sequential framework using a discrete control theory. Li and Shahidehpour (2005) have implemented a method based on incomplete information to analyze the suppliers' competition. Menniti et al. (2008) have used an evolutionary game based on Genetic Algorithm (GA) to simulate the electricity market in the presence of more than two producers. Nanduri and Das (2007) have presented a nonzero sum stochastic game theoretic model based on reinforcement learning to assess the market power. In addition, numerous models based on the game-theoretic concept have been proposed to simulate the oligopoly behavior of the competitors (Singh, 1999; Park et al., 2001; Neuhoff et al., 2005; Lise et al., 2006).

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However, the nonlinear and non-convex nature of the ac power flow is incompatible with the optimization formulations of oligopolistic market models. For this reason, several oligopoly models have used a linearized dc representation of load flow (Hobbs, 2001; Metzler et al., 2003). Moreover, network constraints complicate the market clearing mechanism and cause the income functions to be non-differentiable and non-concave (Lee and Baldick, 2003).

To overcome these problems, in this paper, a dynamic game theory is used to model the power market virtually. Since the market participants might be able to reach equilibrium through the “trial and error” learning process, a dynamic game approach can be used to achieve converged solutions. Therefore, an agent-based modeling technique can maintain certain features of the power markets ignored by static models and therefore it will be helpful in analysis of new market rules. In this paper, the learning model is based on the assumption that a supplier agent could observe some statistics related to previous actions of the others.

In addition, different models for strategic offer of generating companies have been presented such as Bertrand, Cournot, Stackelberg and supply function equilibria (SFE). Among these models, only SFE enables a firm to link its offering price with the offering quantity of its product and only this model is the closest to the actual behavior of players. Green and Newbery (1992) have been adopted the SFE as a model to offer in a competitive power market. They generalized the linear demand and linear marginal cost asymmetric two firm models including capacity constraints. Green (1996) utilized a linearized version of this model and acquired a significant theoretical breakthrough by studying SFE in a non-symmetrical case. In the case of deconcentration, when the number of thermal units increases and potentially goes to infinity, Newbery (1998) showed that the equilibrium conditions of the system converge to a solution in which prices tend to marginal costs, when there are sufficient spare capacity and no contracts. Most of the previous works have simplified the SFE model to a problem with one degree of freedom (Hobbs et al., 2000; Li and Shahidehpour, 2005; Bompard et al., 2010). In this paper, we suppose that the GenCos use SFE model with two degrees of freedom in order to be able to choose both prices and quantities to prepare their strategic offers.

In the mentioned models, considering the practical issues in electricity market, such as non-convexity and discontinuity of cost function, and obtaining the closed solutions are generally difficult (Baldick, 2002; Ventosa et al., 2005). Nevertheless, regulatory bodies should have the ability to simulate the behavior of participants and to detect the agents that have the potential of market power and collusion. The collusion of some participants increases their potential to exercise the market power. It can provide an important limitation on the ability of consumers to benefit from restructuring of electricity generation markets. On the other hand, experience has shown that strategic behavior of market players, such as limit-pricing, might affect the market performance (Wolfram, 1998). Therefore, there is need for a new method to analyze the power market in more realistic and complicated conditions including collusive and strategic behavior.

For this purpose, in this study, a virtual power market model has been presented to cover the above issues. In the model, a hybrid method based on multi-agents and dynamic game theory is proposed. Despite the previous works that simulate the equilibrium of the market in 1 hour, in this model the power market is simulated in a period. Therefore, the proposed model allows analyzing the self-scheduling problem of players and to consider the start-up and shut-down costs, minimum up/down times, prohibited operating zones (POZs) and ramp rates of generation units. In addition, since transmission constraints may create opportunities for the market players, especially those who can withhold the capacity and induce congestion to create an uncompetitive market, considering the network constraints in market simulation is very important. In spite of most of the previous works, where the transmission system had been modeled as linearized dc power flow (Hobbs et al., 2000; Day and Hobbs, 2002), in the proposed virtual power market model, an ac power flow is used. Moreover, the security constraints should also be considered, because in an actual market the clearing price is obtained with respect to these constraints. In this paper, security constraint unit commitment (SCUC) and security constraint economic dispatch (SCED) make the core of the proposed market simulator in the day-ahead and real-time markets, respectively and model the role of ISO in the mentioned markets.

Furthermore, in this model, two types of collusion have been considered, tacit and explicit. The tacit collusion is the spontaneous cooperation resulted from strongly perceived interdependence. This type of collusion, that is usually entitled as oligopoly behavior, sets the market price above the system marginal cost. The explicit collusion, which has been rarely studied in previous works, is an agreement among two or more players to change the price of the market to increase their joint profit. Since this action in the most markets is illegal, it may be done in a secret meeting. If the regulatory body cannot prevent the formation of the explicit conspiracy, in order to prove the collusion, it will need to look for an agreement among coalition members (on paper or tape), which is a very difficult work.

The rest of the paper is organized as follows. Section 2 provides the virtual power market model. The proposed algorithms to model the explicit collusion and strategic behavior are presented in Section 3. Theoretical discussions are validated by numerical studies in Section 4 and the paper is concluded in Section 5.

2. Development of virtual power market model

In this paper, an agent-based virtual environment is developed in order to simulate the power market from regulator's point of view. On this basis, each market player has been independently modeled using an agent that its objective is maximizing the player's profit. Based on this, each GenCo agent forecasts the nodal prices of the reserve and energy markets upon which, it determines the offering strategy to participate in the said markets while considering uncertainties of these forecasted prices. On the other hand, the role of the ISO in clearing the day-ahead and real-time electricity markets to determine the auction winners is respectively defined using a detailed model of SCUC and SCED with the aim of minimizing the system costs and considering security constraints of power system. Fig. 1 shows the proposed approach for simulating the virtual power market from regulator's point of view.

Details of each step of the proposed model are described as following.

2.1. Price forecasting

Similar to the real players, the agents forecast the prices using only the history of locational prices because they do not have detailed data such as the failure rate of system components and maintenance scheduling of generation units. Accordingly, in this paper, a forecasting method (Wavelet-ARIMA-RBFN) is used for price forecasting which is based on historical prices (Shafie-khah et al., 2011b). This forecast method is applied to predict the market prices for next iteration of the game by using the previous ones. Details of the forecasting method have been presented in Shafie-khah et al. (2011b).