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Multi-agent based experimental analysis on bidding mechanism in electricity auction markets

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ABSTRACT

Determining the best market pricing rule is a controversial issue in the design of electricity auction markets. Pay-as-bid (PAB) has been proposed to replace the market-clearing price (MCP) in deregulated electricity markets, with the expectation that it would lower market prices and reduce price volatility. A multi-agent based experiment was constructed to compare and analyze the balanced process of the two auction mechanisms. Each adaptive agent represents a generator who develops a bid price and quantity based on a reinforcement learning algorithm. In the simulation experiments, the experimental results are not as expected. Before the market reaches equilibrium, the market price with the PAB mechanism is lower than it is with the MCP mechanism. However, the market price in the PAB mechanism is higher than it is with the MCP when the market achieves a state of equilibrium. With the PAB mechanism, the volatility of volume and price of each generator is less than it is with the MCP system, as expected. The experimental results also show that unconscious collusion behaviors by generators during the game process are a key reason for producing generator market power in the two auction mechanisms.

1. Introductions

With the progress of the market-oriented reform of the electricity market, how to construct a good trading rule and auction mechanism has become a key issue. There are numerous constraints in the electricity market, such as the non-storability of electricity, limited resources and social necessity and the need to ensure real-time balance of supply and demand. With these constraints it is very difficult to design an effective bidding mechanism for the deregulated electricity auction markets. Margin clearing price (MCP) and pay as bid (PAB), are two kinds of bidding mechanism; but, which mechanism is better for improving market efficiency and decreasing the market-power of the generators?

The current studies on bidding mechanisms for electricity markets can be divided into two categories. One category applies the method of economic theory to analyze market mechanisms. Zou [32] comprehensively analyzed and compared two kinds of auction mechanism, considering the trading volume, market efficiency and consumer surplus based on economic theories. Papers [26,27] applied economic game theory to design the mechanism of an electricity market, and analyzed the efficiency of different auction mechanisms by auction theory. The other category analyzes the market mechanism by using experimental economics and economical simulation method. The game result is uncertain because the decision-making process of each participator is not controllable [5]. The game process can be observed by experimental economics or economical simulation. Hence, we can analyze the uncertainty of the game process better [17].

In recent years, complex adaptive system (CAS) theory and the Swarm simulation method have been applied in various fields. In 1994, Holland proposed CAS at the meeting for the 10th anniversary of the establishment of the Santa Fe Institute [14]. The Santa Fe Institute has developed the multi-agent SFI software tool, Swarm, based on CAS theory. The definitions of the various agents are independent because in Swarm there are no binding constraints on the model or on the interactions among the model elements. Swarm provides a general framework in which the researcher can focus on a particular system and interest, and need not be concerned with problems of software engineering and programming, such as data processing and user interface. In Swarm, the interaction between the agents is independent, the software is simple and easy to use, and the source code is open, so that computer non-professionals can easily use this tool to study complex adaptive system problems. Swarm will soon be expanded and can be widely applied to various fields in future.

At present, Swarm is mainly used to study problems in ecology, biology, economics, sociology, physics, chemistry and other fields [17], such as literature. For example, papers [34,30,15] applied Swarm simulation to study economic growth, ecological balance and social evolution, respectively. Studies simulating and analyz-

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ing the mechanisms of the electricity market with Swarm are emerging [16,1,6]. For example, [13,25,1] carried out simulations of the electricity market, including bidding price mechanisms, the formation process of the equilibrium price, regulatory policy and other issues in the electricity market.

Electricity markets are complex adaptive systems composed of many agents [16,3]. In an electricity market, each generator has its own rules of conduct and information, and continuously modifies these rules by self-learning when it receives information from other subjects. Therefore, it is difficult to use a single and fully dynamic model to describe a power market with its many features of a complex adaptive system. Considering the complexity of multi-agent games, the paper used Swarm simulation methods based on CAS theory to compare and analyze the bidding processes of generators in the spot electricity market, and to give the results of quantitative analysis.

Compared with other studies, the method in the present paper can show and analyze (1) the bidding process, (2) each participator's bidding behavior and (3) the balanced processes and game result of the two mechanisms. Through simulation experience, it can be found that before the market equilibrium, the clearing price of the PAB mechanism is lower that of the MCP mechanism. When the market equilibrium is achieved, the clearing price with the MCP mechanism is lower than it is with the PAB mechanism. In the PAB system, the volatility of transaction volume and price of each generator is less than it is with the MCP system. These results suggest that neither the PAB nor the MCP mechanism is absolutely good or bad for reducing the market power of the generators; each should be selected at a different stage of the electricity market-oriented reform.

2. The comparative and analysis of MCP and PAB mechanism

The MCP was adopted at the beginning of electricity market. Some problems of the MCP were discovered in the actual operations. In order to reducing the market-power of the generators. The Federal Energy Regulatory Commission requirements California PX and ISO study an alternative schema because the price mechanism of California electricity market cause serious electricity market accident [4]. UK Power Market agencies believe, compare to MCP mechanism, it is different for the generator to implement market-power with strategic behavior in PAB. Therefore, PAB had been adopted in Britain Electricity Market in 2001. In April 1 2002, the bidding mechanism of Power market in Shanghai had been changed to PAB.

Is PAB able to solve some problems existed in the power market? More and more researchers began to study the efficiency of the two bidding mechanism.

2.1. The view to support PAB

The researchers who support PAB mechanisms believe that, the market price will be dropped in PAB because the gains of each generator is according to its offer price base on the marginal cost [7]. They believe that in MCP mechanism, the trade price of the non-marginal generator is higher than its offer prices, so they will win more excess profits. If the MCP mechanism was replaced with the PAB mechanism removed, then the cost of purchasing electricity will be saved. Karandikar et al. [18] drawn that PAB is superior to MCP mechanism after two auction mechanisms was compared with fully competitive market model. Karandikar think although it is difficult to compare the economic efficiency and market prices of two mechanisms, but the fluctuations arising from the load forecast errors will be smaller and the market accident phenomenon with the price spike will be reduced because the supply curve in PAB mechanism will have a greater elasticity. Federico and Rahman [10] compared the output, market prices and social welfare of two bidding mechanism in the perfect competition and monopoly market structure, and proved that the PAB mechanism is better than MCP mechanism. These analysis conclusions provide a lot of support for the MCP mechanism was converted to PAB in the UK electricity market. Son et al. [33] pointed out that the auction revenue equivalence theorem in electricity market does not hold. They analyzed the bidding mechanism with two companies in the electricity market, assuming a generator owns most of the generating capacity, and another is a small generator. By comparing the strategic bidding behavior of generation companies and short-term market power in MCP and PAB, they derived the cost of purchasing electricity in MCP is high than it in PAB. The UK wholesale electricity prices fell by 19% when the PAB was implemented from March 2001 to February 2002. Ofgem [24] think the British electricity prices fall should entirely be attributed to PAB mechanism. Evans and Green [9] provided further evidence. He analyzed the generator's bidding strategy in PAB and MCP, and believed that the PAB auction mechanism may undermine the tacit collusion among generators.

2.2. The view to support MCP

Many researchers have proposed the opposite view. Wolfram publicly supported that the MCP mechanism should be implemented in the electricity market [31]. He believes that although the trade price was rising by the generator's strategic behavior in MCP mechanism, but these problems cannot be solved in the PAB. The generator's offer is not accordance with its marginal cost, but the market clear price in PAB mechanism. So the power market efficiency will be reduced, and the risk of the generator will be further increased, thus PAB will prevent the entry of small generators and increase market access barriers.

Kahn et al. [11] in-depth compared the advantages and disadvantages between MCP and PAB. They think that there is a fatal error in this view, "the market price could be decreased in the PAB mechanism", that is one key assumption is implicit that the generator will offer the same as before when the market rules was changed. But in fact this assumption is not valid. When the PAB mechanism was adopted, the rational generator will immediately change its bidding strategy, they will submit their price according to market price what they predicted. Nanduri and Das [12] further pointed out that the PAB mechanism will not only reduce the market efficiency, and not conducive to small generator, the market forces will not be eliminated. As the largest generator with more market information will be in a more favorable position in the electricity market. To formatting a competitive market will be affected in the long run.

Vazquez et al. [29] detailed analyzed the two mechanisms, and criticized some views to support PAB. Vazquez think that this view "the non-marginal generators will win excess profits in MCP, and PAB will reduce the purchasing cost," is wrong. Vazquez think that the non-marginal generators excess profits is reasonable. Because the trading price in a competitive market is according to the market price, rather than the manufacturers' cost.

Vazquez et al. [29] analyzed and compared between MCP and PAB, and think the latter is inefficient in the highly competitive market environment and will lead to the emergence of costly middlemen. Because generators have to bear the higher market risk in the PAB mechanism, it is difficult to predict which generator will successes in bidding mechanism. The generator would experienced more risk in the allocation process, so the cost would be higher and would be reflected in the price of them.

Emmanuel (2000) [8] also supports the view of [28] show that although the PAB could reduce the price fluctuations through empirical data, but the average price in electricity market will be higher.

Liu et al. [2] and Newbery [23] in-depth analyzed the reasons why the price of British electricity market was decreased, and shows that the conclusion is opposite with Ofgem. They think that the price decreasing are mainly caused by the British adopted a series measures to reduce market concentration (such as to decompose electricity assets, to increase capacity investment), not due to the implementation of the new bidding mechanism.

2.3. Others view

For this argument, individual researchers have some different views. [20] proposed their insights based on this issue. They think that the debate on the two auction mechanisms limit our understanding of the auction model, which makes the regulator more likely to PAB mechanism, but there is not enough evidence to show that the PAB certainly better than the MCP mechanism. The two mechanisms often used in financial markets and other production markets. PAB is superior to MCP mechanism could not be proved with any theoretical and practical method. The two mechanisms were compared according to the equilibrium results of a multi-part auction model created by [21]. Through analysis, they think the social welfare of the two mechanisms is ambiguous; if only considered consumer surplus maximization, then the PAB is better than MCP mechanism, but there is not enough evidence to support the view of the market efficiency will be increased if PAB was replaced by MCP. Fabra [19] think that the trade price in MCP is higher than it in PAB when the demand is certain, but the market efficiency of the two mechanisms is relevant to market structure.

Fabra [22] shows that the tacit collusion phenomenon among generators is more emergences in the MCP mechanism, and the motive of generator to deviation from collusion is are very small, and the collusion state is stable state.

3. Simulation model of the two mechanisms based on Swarm

The modeling concept of Swarm is that a series of standalone agents interact through independent interaction events. It is a contribution to the study of the behavior of complex adaptive systems composed of many agents. The modeling principle of Swarm is to achieve the interactive behavior through signal transduction between the various subjects. Economic entities calculate their earnings according to the information received, and thus adjust their strategies. In Swarm, the initial values of external variables are not critical because these variables will be adjusted in the self-adaptive process.

3.1. Game process of generators in two mechanisms

As shown in Fig. 1, the electricity market is characterized by the demand being rigid in a certain price range. To facilitate understanding the description, the demand curve above the bending

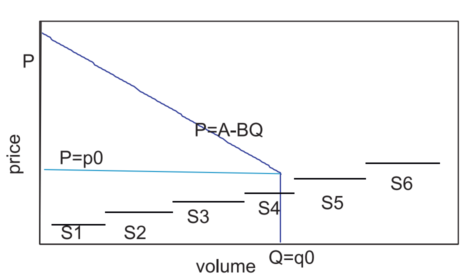

Fig. 1. Market demand and supply curve.

point is still known as the demand curve; the demand curve under bending point is called the split-line. When the price is on the split-line, the market demand does not change with the price because power is a necessity for life and production. When the price approaches a bending point, power consumption begins to be reduced, and the market demand starts to decline. In fact, we mainly study the behavior of generators which do not stay to the right side of the split-line. The offer of a generator to the right of the split-line is too high, so they cannot participate in market competition. The generators who do not stay on the right of the split-line can exercise market power by adjusting their volume and price.

In the PAB mechanism, the offers and transaction prices of the generators who do not stay on the right of the split-line are equal. The generators on the right of split-line cannot sell anything because their offer is higher than the market equilibrium price. In the MCP mechanism, the offer of generators on the split-line is the transaction price, also called the market-clearing price. The transaction prices of generators who do not stay on the right of the split-line are also the market-clearing price. The generators who stay on the right of the split-line have no transaction prices.

In the actual gaming process, the generators adjust their price and volume to stay on the split line, thereby affecting the market clearing price. The gaming processes of the market participators can be described as follows:

(1) At $t = 0$, the initial values are assigned to the variables of each generator and the electricity trading center.
(2) The generators submit their offers and corresponding volumes to the electricity trading center.
(3) The electricity trading center matches the generators, based on the offers and corresponding volumes of the generators, the market demand function and the auction mechanism.
(4) Based on the match method, the trading center calculates the transaction price and volume of the various generators in the PAB/MCP mechanism, and then the information is sent to each generator.
(5) Generators calculate their profits according to their transaction price and volume. The profit gained in the current period is compared with the profit in the previous period. Then they determine their strategies to adjust offer and volume in the $t + i$th period. A specific adjustments strategy can be described by the following: if the profit after adjustment is higher, then the same price adjustment strategy as in the previous period will be adopted. Otherwise, ① the generator adopts the opposite price adjusting strategy, and ② the generator adjusts its generating volume. The adjustment range is [0, maximum effective capacity]. Return to (2), start a new round of the game.

3.2. Game rules of the generators

In the simulation system, each generator is an independent player with the independent decision-making ability and self-adaptive learning ability. The generators can adjust their output and pricing on the principle of maximizing their benefits.

Assume that there are n generators in an electricity market. The initial offer and supply volume of the ith generator are $p_{i,0}$ and $q_{i,0}$, respectively. The profit of the ith generator in the tth game can be calculated by the following equation:

$$\pi_{i,t} = q_{i,t} \times (p_t - c_i) \tag{1}$$

where the volume of the ith generator in the tth game is $q_{i,t}$. The transaction price in the tth game is p_t. The unit cost of the ith generator is c_i.

The adjustment goal of the ith generator is Eq. (2), where $q_{i,\max}$ is the largest capacity of the ith generator:

$$\begin{aligned} &\text{Max} \quad \pi_{i,t} = q_{i,t} \times (p_t - c_i) \\ &\text{ST} \quad q_{i,t} \in [0, q_{i,\max}] \end{aligned} \tag{2}$$

The adjustment strategy of the ith generator is to adjust price, and then adjust the generating capacity. Formula (3) is the bidding strategy of the ith generator:

$$p_{i,t+1} = \begin{cases} p_{i,t} + \Delta p & \text{if} \quad \pi_{i,t} - \pi_{i,t-1} > \varepsilon \\ p_{i,t} - \Delta p & \text{if} \quad \pi_{i,t} - \pi_{i,t-1} < -\varepsilon \\ p_{i,t} & \text{if} \quad |\pi_{i,t} - \pi_{i,t-1}| \le \varepsilon \end{cases} \tag{3}$$

Formula (4) is the capacity strategies of the ith generator:

$$q_{i,t} = \begin{cases} q_{i,t+1} = q_{i,t} + \Delta q & \text{if} \quad \pi_{i,t} - \pi_{i,t-1} > \xi, q_{i,t+1} < q_{i,\max} \\ q_{i,t+1} = q_{i,t} - \Delta q & \text{if} \quad \pi_{i,t} - \pi_{i,t-1} < -\xi, q_{i,t+1} \ge 0 \\ q_{i,t+1} = q_{i,t} & \text{if} \quad |\pi_{i,t} - \pi_{i,t-1}| \le \xi \end{cases} \tag{4}$$

3.3. Game rules of the electricity trading center

In the game process, the electricity trading center determines the transaction price, trading volume and market-clearing price of each generator with the trading mechanism based on the offer and corresponding generating capacity of the generators, and according to the market demand function,.

3.3.1. In the MCP trading mechanism

The trading center determines the market clearing price (the transaction price for each generator) based on the offer and corresponding generating capacity of the generators and the market demand curve. When the total volume of all the generators is less than the total electricity demand $Q_{\max}$, the market-clearing price will be determined according to the market demand curve. If the generator's offer is lower than the market-clearing price, the transaction price of generator is the market-clearing price. If the generator's offer is higher than the market-clearing price, then it will fail to reach a deal:

$$p_{i,t} = \begin{cases} p_{m+1,t} & \text{if} \quad \sum_{i=1}^{m} q_{i,t} \leqslant Q_{\max}, \sum_{i=1}^{m+1} q_{i,t} > Q_{\max}, \\ A - B \times \sum_{i=1}^{n} q_{i,t-1} & \text{if} \quad \sum_{i=1}^{n} q_{i,t} \leqslant Q_{\max} \\ 0 & \text{if} \quad \sum_{i=1}^{m} q_{i,t} \le Q_{\max}, \sum_{i=1}^{m+1} q_{i,t} > Q_{\max}, i > m+1 \end{cases} \tag{5}$$

The trading center determines the power supply of each generator based on the market demand curve, the offer and volume of each generator. If the price is less than the clearing price, then the volume was the generating capacity reported by generator. If the price is equal to clearing price, the volume is the declared volume multiplied by the proportion of the generating capacity in the total amount of electricity generated. If the offer is more than clearing price, then the volume is zero:

$$q_{j,t} = \begin{cases} q_{i,t-1} & \text{if} \quad p_{i,t-1} < p_{m,t} \\ \left(Q_{\max} - \sum_{j=1}^{i} q_{j,t}\right) \times q_{j,t} \Big/ \sum_{j=i+1}^{i+w-1} q_{j,t} & \text{if} \quad p_{i+1,t} = \cdots = p_{i+w-1,t} = p_{m,t} \\ 0 & \text{if} \quad p_{i,t-1} > p_{m,t} \end{cases} \tag{6}$$

In the trading process, each generator dynamically adjusts its price and power generation strategies using the same method. In the gaming process, each generator is only allowed to exchange information with the trading center. Price and volume information cannot be exchanged among the generators.

3.3.2. PAB trading mechanism

The trading center determines the transaction price of each generator based on the market demand curve, the offer and power supply of the various generators. As show in Eq. (7), the transaction price of generators whose price is not to the right of the split-line is the bid. The generators whose price is on the right of the split-line cannot take participate in the matching. When the volumes of all the generators is less than $Q_{\max}$, then the demand curve is a curve above the inflection point. The transaction price is determined by the total supply:

$$p_{i,t} = \begin{cases} p_{i,t-1} & \text{if} \quad \sum_{i=1}^{m} q_{i,t} \le Q_{\max}, \sum_{i=1}^{m+1} q_{i,t} > Q_{\max}, i \leqslant m+1 \\ A - B \times \sum_{i=1}^{n} q_{i,t-1} & \text{if} \quad \sum_{i=1}^{n} q_{i,t} \leqslant Q_{\max} \\ 0 & \text{if} \quad \sum_{i=1}^{m} q_{i,t} \le Q_{\max}, \sum_{i=1}^{m+1} q_{i,t} > Q_{\max}, i > m+1 \end{cases} \tag{7}$$

In the PAB mechanism, the market clearing price is the weighted average of the traded prices of all the generators:

$$p_t = \sum_{i=1}^{m+1} p_{i,t-1} \times q_{i,t-1} \Big/ \sum_{i=1}^{m+1} q_{i,t-1} \tag{8}$$

The trading center determines the power supply of the generators based on the market demand curve, the offer and power supply of each generator. If the offer is less than the highest bid, then the volume is the quantity declared by generator. The volume is the declared volume multiplied by the proportion of generating capacity in the total amount of electricity generated. If the offer is more than clearing price, then the volume is zero.

$$q_{j,t} = \begin{cases} q_{i,t-1} & \textit{if} \quad p_{i,t-1} < p_{m,t} \\ \left(Q_{\max} - \sum_{j=1}^{i} q_{j,t}\right) \times q_{j,t} \Big/ \sum_{j=i+1}^{i+w-1} q_{j,t} & \textit{if} \quad p_{i+1,t} = \cdots = p_{i+w-1,t} = p_{m,t} \\ 0 & \textit{if} \quad p_{i,t-1} > p_{m,t} \end{cases} \tag{9}$$

4. Swarm simulations

To evaluate the simulation model, as a scenario, the power market including seven generators in Chonging city of China was simulated by the Swarm-based simulation model proposed in Section 2. Taking into account price, power consumption, prices rise and GDP growth and other factors in Chongqing city, the demand function $Pd = 1.5986 - 0.0055Q_d$ of the electricity market can be generated by regression using Eviews. The inelastic market demand function is Q_d = 2300 MW h. The maximum power supply and the cost of each generator are as shown in Table 1. The step

Table 1
Maximal quantity and unit cost for each generator.

Generator	Volume (MW h)	Cost ($/MW h)
Generator 0	754	37.14
Generator 1	165	34.29
Generator 2	300	40.00
Generator 3	200	48.57
Generator 4	440	54.29
Generator 5	1440	44.29
Generator 6	406	47.14

size of price adjustment is $\Delta P = \pm 1.43\$$. The step size of volume adjustment is $\Delta Q = -1$ MW h.

To compare the operational efficiency of the two mechanisms, two simulation experiments were designed. The first experiment is a simulation on MCP mechanism. The second experiment is a simulation on PAB mechanism.

4.1. First simulation experiment

Fig. 2 shows the price of each generator in the MCP mechanism. Fig. 3 shows generating capacity of each generator in the MCP mechanism. At the beginning, the generators offer according to the cost, and the corresponding generating capacity. In the first round of the game, four of the seven power generation companies trade successfully. In the MCP mechanism, the generator can understand the market-clearing price quickly after one round of the game, and adjust its offer and capacity according to the market-clearing price in the previous round. At the beginning of the game, generators only adjust their price. When the price is adjusted to \$47.14, the seventh generator enters market. So the market supply exceeds demand and generators begin to adjust their capacity. The main reason is that the generator's volume will not be sold when it adjusts its price. Hence, to improve overall profit, the generator starts to adjust its power output, and raise prices at the same time.

4.2. Second simulation experiment

Fig. 4 shows the price of the generators with the PAB mechanism. Fig. 5 shows the capacities of the generators with the PAB mechanism. Initially, the generator declares the price according to the cost and the corresponding generating capacity because they have not exchanged enough information. In the first round, there are four generator transactions. To obtain higher profits, the four generators try to continue to raise prices. The generators are only fine-tuning on the basis of their bid because they do not know their opponents' transaction prices. The specific process is shown in Fig. 4. After 20 games, the fifth generator is on the split line, the sixth generator will enter the market if the fifth generator raises prices again. Therefore, the fifth generator starts to raise prices when it adjusts the output. The generators 2, 0 and 1 are adjusted to the market clearing price after 50, 70 and 90 rounds of the game, respectively. At this point, five generators are on the split line. In order to raise profits by an increase in prices, they have to adjust their volumes. The specific processes are shown in Fig. 5.

4.3. Analysis of the simulation results

Several phenomena can be observed by comparison and analysis of the results of the simulations using the different mechanisms.

(1) In the gaming equilibrium process, the market power of the generators is evident earlier and stronger in the MCP mechanism than it is in the PAB system. In the MCP mechanism, generators can implement their market power early because the market-clearing information can be acquired through the auction mechanism. In the PAB system, the generators cannot know about the market-clearing information to influence the market-clearing price and acquire more profits, they can only adjust their prices and output according to their own transaction price and volume. So, early in the game, their market power with the PAB mechanism should be weaker than with the MCP mechanism. This conclusion can also be reached by auction theory. A sealed auction reflects the costs of the generators better, but when a

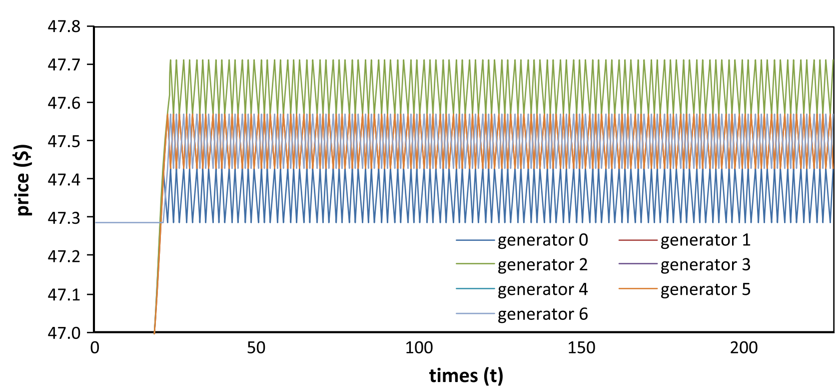

Fig. 2. Price declared by each generator in the MCP trading mechanism.

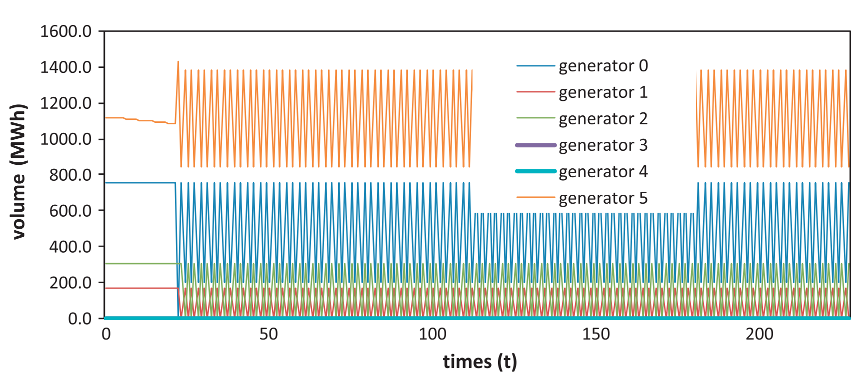

Fig. 3. Volume of each generator in the MCP trading mechanism.

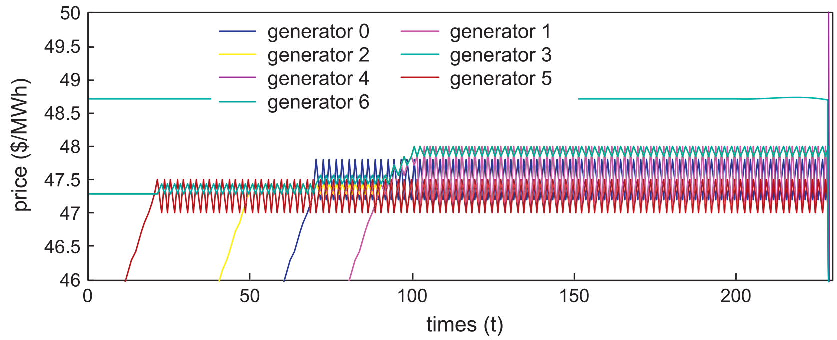

Fig. 4. The price for each generator in PAB mechanism.

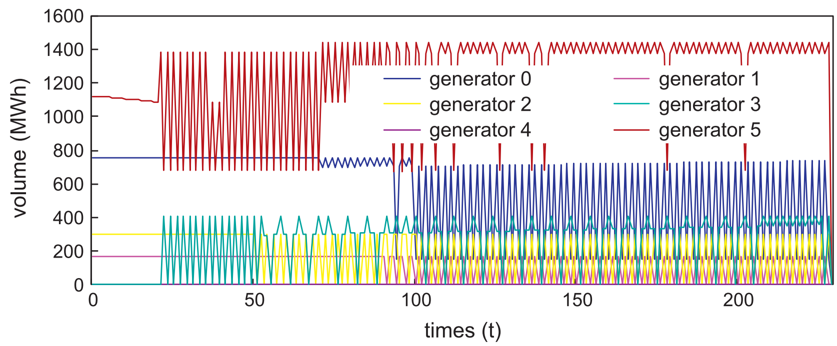

Fig. 5. Quantity for each generator in PAB mechanism.

sealed-bid auction is carried out several times, the ability of the mechanism to reveal the true role of the information known to the bidders will be weakened because bidders know about the bids of themselves and of their opponents.

(2) In the later stage of the gaming equilibrium process among the generators, the generators have stronger market power behavior in the PAB mechanism than in the MCP mechanism. The main reason is that the strategies of price and capacity adjustment are more efficient in the PAB mechanism than in the MCP mechanism because the transaction price is the offer of generators in the PAB mechanism. In the MCP system, the effect of the regulation strategy of the generator will be weakened because of the adjustments of the other generators. There are two main reasons: one is that the reverse adjustment of other power producers weakens the efficiency of the generators adjustments; the other is that the generator increases price through the adjustment, but the effect will be weakened because the other generators share the result of the adjustment.

(3) In the market equilibrium state, the volatility of electricity prices in the PAB mechanism is weaker than in the MCP mechanism. Price volatility can be directly observed from the transaction price curve in Figs. 2 and 4. The Standard deviation is 1.98 in MCP, but it is 0.76 in PAB. This conclusion more can be clearly found by putting the clearing price of the two experiments into Excel, from which Fig. 6 was produced. The volatility of each generator's volume can be directly observed from Figs. 3 and 5. The main reason is that in the gaming equilibrium process among generators in the PAB mechanism, the strategy and intent to adjust the volume and price is stronger because their bid is their offer. In the MCP system, the strategies of generators to adjust volume and price may be weakened by the same behavior by other generators. They may become a victim if they raise their offer. It can be clearly seen from Figs. 3 and 5 that

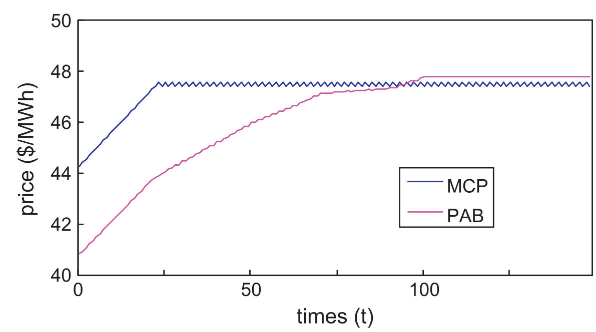

Fig. 6. Market clearing price in MCP and PAB mechanism.

the volume of the sixth generator in the PAB mechanism is volatile below 1440MWh, but the volatility is far less than it is in the MCP mechanism. Its average trading volume is also higher than it is with the MCP mechanism.

(4) It is found by simulation that the generator's offer is higher than its cost in both mechanisms. These two mechanisms could not completely remove the generator's market power. This phenomenon is usually interpreted as a result of conscious collusion between generators. But through the simulation experience, the unconscious collusion caused by the generators pursuing their own independent profit-maximizing led to market power.

In the simulation, there is no exchange of information between the generators. They only get their own volume and transaction prices from the electricity trading center, and adjust their generating capacity and price in the next game based on the objective of maximizing their profit. The result of the profit-maximizing behavior in the market is that of generators adjust prices and output together, leading to spikes in the market-clearing prices. Some literature has understood such acts as tacit collusion. However, in reality, even if the generators do not know whether other generators will increase their offers or reduce their capacity, those generators whose price is on the split line will adopt the strategies to adjust their price and capacity.

5. Conclusion

This paper proposes a complex model of a multi-agent game in an electricity market based on CAS theory. Quantitative analysis results were produced by a Swarm simulation to enable a comparative analysis of the behavior of generators under the MCP and PAB mechanisms. Through this simulation, it was found that the clearing price before the market equilibrium is lower with the PAB mechanism than with the MCP mechanism. However, when the market achieves equilibrium, the clearing price with the MCP mechanism is lower than it is with the PAB system. With the PAB system, the volatility of transaction volume and price of each generator is less than it is with the MCP system. The results will help us to design a new electricity market bidding mechanism. Neither the PAB nor the MCP mechanism is absolutely perfect for reducing the generator's market power. Each should be selected at a different stage of the electricity market-oriented reform. When the electricity market reached equilibrium, and the price was limit to a range, we should adopt other bidding mechanism.

The nature of market power in the electricity market is that a section of the market demand curve is completely rigid. This section is also the opportunity of generators to exercise market power. The primary means for solving this problem are the introduction of a demand side electricity market and an increase the gradient of the market demand curve. The scope of the generator's market power will be continuously decreased with higher prices and more generators entering the electricity market. As more generators enter into market, the chances to implement market power will be reduced; thus the probability of producing a conspiracy will be weakened. Therefore, the more small and medium sized generators are introduced into the electricity market, the more generators will enter into the market when some generators raise prices or reduce output. It will be more difficult to achieve synchronization among generators to implement market power when there are more generators in electricity market, so the market power of generators will be decreased.

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