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Market power analysis in electricity markets using supply function equilibrium model

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This paper presents a surveillance method based on the game theory which is used by the ISO to find whether a power supplier in an electricity market has market power. The paper uses the supply function equilibrium model to analyse the generation suppliers' bidding behaviour and models the ISO's market power monitoring problem as a bi-level multi-objective problem. The outer sub-problem is a multi-objective problem which maximizes suppliers' payoffs, while the inner one is the ISO's market clearing problem based on the locational marginal pricing mechanism. A discrete method is adopted to find 'good enough' solutions, in a continuous bidding strategy space, which are the intersection of all suppliers' optimal response spaces according to Nash equilibrium. The paper utilizes the IEEE 118-bus system to illustrate the application of the proposed method with three suppliers as price setters in the energy market and the other generators as price takers. The numerical results show that the transmission congestion may enhance the suppliers' ability to exercise market power. Likewise, suppliers' gaming behaviour could relieve the transmission congestion. It is shown that applying price caps is an efficient way of mitigating market power.

Keywords: electricity market; game theory; market power; supply function equilibrium; Nash equilibrium; price cap; Cournot model.

1. Introduction

The energy crisis in California led many engineering analysts to study the market power phenomenon in electricity markets. Market power is defined as the ability of a seller to profitably maintain prices above competitive levels for a significant period of time (Shahidehpour *et al.*, 2002; Shahidehpour & Alomoush, 2001). According to the US Department of Justice (DOJ), a significant period of time means 1 or 2 years. However, the electricity market in California has shown that a supplier's ability to exercise market power for a shorter time period can result in a significant damage to the intended free competition in an electricity market. Economists define market power as the ability to alter away prices profitably from competitive levels. We adopt this definition to analyse market power. If consumers restrict their electricity consumption, they can also exercise market

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power. However, the experience with the restructured market has shown that generation suppliers are in a much better position to exercise market power. We focus our analysis of market power on the generation resources in electricity markets.

Normally, there are two ways for generation suppliers to exercise market power: economic withholding or physical withholding. Economic withholding means bidding excessively above the marginal cost of power production in order to drive up prices. Physical withholding means a supplier does not schedule for bidding or bid some of its generating capacity into the market in order to effectively reduce the available supply in the market and possibly drive the prices up (Rahimi & Sheffrin, 2003).

When market power is exercised, the most obvious effect is the transfer of wealth from consumers to suppliers (Stoft, 2002). For example, the Californians suffered greatly from high prices of electricity in the summer of 2000. The second consequence of market power is the dead-weight welfare loss, which means that an increase in market price will reduce the consumers' benefit more than increasing the suppliers' profit. That is to say, the social welfare will not be maximized. The third consequence is its impact on economy and generation investment. While high prices should spur new investment and entry in electricity production, these investments may not be efficient if motivated by high prices caused by market power. Also, high prices can lead some firms not to invest in productive enterprises that require significant use of electricity, or to inefficiently resort to less electric-intensive production technologies (Borenstein *et al.*, 2002).

Many factors can provide opportunities for exercising market power. First, market suppliers with dominant positions in the market can be price setters in the sense that they can dictate market prices through economic withholding or physical withholding or both. Second, transmission bottlenecks can result in locational market power. Even though a local transmission congestion may exist only for short periods, substantial profits may be extracted through the exercise of market power. Finally, flaws in a market design, operation procedures, and regulatory measures can lead to the exercise of market power by generation suppliers. There are many measures to mitigate market power such as generation divestiture, bidding contracts, price caps, and contracts for difference.

A method based on the forecasting of the market clearing price is proposed in Conejo *et al.* (2002) for price-takers who bid under price uncertainty. The paper assumes that the price-takers will not game the electricity market. In this paper, we apply the game theory to analyse the market power among suppliers in electricity markets. Game theory is generally used in practice to analyse the problems of conflict among interacting decision makers. In electricity markets, game theory is widely used to analyse the competition among power suppliers (Shahidehpour *et al.*, 2002; Bai *et al.*, 1997; Ferrero *et al.*, 1998, 1997). Gaming refers to scenarios whereby market suppliers take advantage of certain market rules and system conditions and intend to deviate from normal bidding, scheduling, and operational patterns in order to increase their profit. Gaming may result in a substantial cost to the system reliability, economic loss to certain suppliers, and the deterioration of efficiency in the power market operation.

The Nash equilibrium method is the universally adopted concept for the solution of games. At Nash equilibrium, a player's payoff will decrease if the player changes its strategy unilaterally while the other players retain their strategies. That is to say, at Nash equilibrium, each player's bidding strategy is optimal for the given strategies of other players.

The cooperative game theory was used to analyse possible collusions and coalitions among suppliers (Shahidehpour *et al.*, 2002; Ferrero *et al.*, 1997). The non-cooperative game theory was employed to study the competition among suppliers. A framework is proposed in Keyhani (2003) using the leader–follower game theory for the control of energy services in light of market players' profit motives as well as the system reliability and security.

This paper uses the supply function equilibrium model to analyse the generation suppliers' bidding behaviour and models the ISO's market power monitoring problem as a bi-level multi-objective problem. The supply function is currently the most accurate model for generators' bidding. A discrete method is adopted, in lieu of a straightforward method, for finding the Nash equilibrium in a continuous bidding strategy space.

This paper is organized as follows. Section 2 introduced the methods to analyse market power; our proposed model for examining market power is proposed in Section 3; numerical results are shown in Section 4; conclusions are discussed and summarized in Section 5.

2. Methods for analysing market power

Generally, there are three approaches to analysing market power in electricity markets: market shares and market concentration analysis, benchmark price and actual market price analysis, and oligopoly equilibrium analysis. These approaches are summarized as follows.

2.1 *Market shares and market concentration analysis*

In this approach, two indices calculated from participants' market shares are used to monitor the operation of electricity markets. The two indices are used to analyse market shares of suppliers and market concentration. The comparison of actual indices and given indices will indicate whether market power exists. These two indices are Herfindahl Hersichman index (HHI) and residual supply index (RSI). HHI is defined as

$$\mathrm{HHI} = 10\,000 \times \sum_{i=1}^{n} q_i^2 \tag{1}$$

where n is the number of market suppliers and q_i is the market share of each supplier.

HHI for a monopoly market would be $10\,000 \times 1 = 10\,000$, while HHI would be a small number when n is very large and no supplier has more than say 5% of the market share. The DOJ and Federal Trade Commission (FTC) standards state that the HHI under 1000 is considered an unconcentrated market that is unlikely to have adverse competitive effects; HHI between 1000 and 1800 is considered to be moderately concentrated; HHI above 1800 is deemed to be highly concentrated. The suppliers' ability to increase HHI by more than 100 points is viewed as likely to create or enhance market power (DOJ & FTC, 1984). HHI is not an accurate method for analysing the market power because markets with apparently competitive HHIs can yield prices well above the competitive levels, but HHI provides a rough estimate of the market concentration.

Another index is RSI. For a particular market at a particular hour, the total capacity bid into the market by each firm can be represented by $q_1, q_2, \ldots, q_n$ where n is the number of suppliers in the market. Let D represent the total market demand, and $S_i = q_i/D$ be the maximum supply share provided by firm i. Then the total market bid sufficiency is calculated as follows:

$$BS = \sum_{i=1}^{n} q_i/D. \tag{2}$$

The residual supply index (RSI) for firm i, which measures the percentage of residual supply left in the market after taking out the firm i's maximum share of supply, is defined as

$$RSI_i = BS - S_i. \tag{3}$$

When a residual supply for firm i is greater than 100%, other suppliers have enough capacity to meet the demand of the market, and firm i has less influence on the market clearing price. On the other hand, if residual supply is less than 100% of demand, firm i is needed to meet the demand, and is, therefore, a pivotal supplier in the market. As a pivotal supplier, firm i has complete control of the market clearing price and can set the price as high as the price cap allows. The RSI of a market in a given time period (e.g. an hour) is the minimum of RSI_i among all suppliers in the market. Based on the empirical evidence compiled by the CAISO Department of Market Analysis, an RSI exceeding 150% is an indicator of a reasonably competitive market (Rahimi & Sheffrin, 2003).

HHI and RSI do not consider the impact of transmission network. In a transmission network, the incremental change in flows associated with a particular direction (from a power source to a power sink) is defined by FERC as the power transfer distribution factors (PTDF). PTDF values provide a linear approximation of power flow changes between a specified source and sink. The PTDF values are applied for analysing the market power in large power systems.

2.2 *Benchmark price and actual market price analysis*

In this approach, the benchmark marginal cost based on the generating cost information is calculated and compared with the actual market price. When the actual market price exceeds the benchmark price, market power is assumed to exist in the market. When calculating the short-term marginal costs (benchmark prices), many factors should be taken into account such as electricity market design rules, types of software employed to calculate market clearing price, and the operation cost of generation (e.g. start up and shut down costs). One approach based on the comparison between market prices and benchmark prices was presented in Borenstein *et al.* (2002) for analysing market inefficiencies in the California wholesale electricity market. The method examined whether the market will set up competitive prices given the market suppliers' generating capacities. The method is less informative on specific manifestations of market power but is used for estimating the scope and severity of market power as well as identifying deviations from competitive outcomes over time.

2.3 *Oligopoly equilibrium analysis*

In this approach, the simulation of market participants' bidding strategies based on generating costs and network information will indicate whether market power exists in electricity markets. There are several models for analysing the oligopoly equilibrium in electricity markets, such as the Bertrand model, Cournot model, Stackelberg model and supply function equilibrium (SFE) model (Rahimi & Sheffrin, 2003; Hobbs *et al.*, 2001). These models are summarized as follows:

(1) Bertrand model: In this model, each firm will compete in the market based on the pricing of its products.
(2) Cournot model: In this model, all firms choose their production quantities simultaneously in order to maximize their profits taking into account the competitors' expected production. Market price is determined by the intersection of the aggregated supply and market demand curves.
(3) Stackelberg model: In this model, each firm will compete based on the quantity of its products. It is similar to the Cournot model. However, the competitors do not choose their outputs simultaneously. The so-called 'leader' will move first. Then the followers will move taking into account the leader's action.
(4) SFE model: The concept of SFE was originally developed by Klemperer and Meyer as a way of modelling competitors' profit-maximizing equilibria in a marketplace with uncertain demand. Each firm will choose a supply schedule or bid function including price and quantity as its bidding strategy. The SFE model was used by Green & Newbery (1992) to model strategic biddings in a competitive electricity market.

The Cournot and SFE models are widely applied to analysing the market power in electricity markets. The Cournot model is used to analyse market power in transmission networks (Cunningham *et al.*, 2002; Yu *et al.*, 2002; Nguyen & Wong, 2002). In Yu *et al.* (2002), the Kuhn–Tucker vector optimization theory (KTVOT) was used to find the equilibria of such problems. The method requires convex objective functions, which is difficult or even impractical to satisfy in electricity markets. Genetic algorithm (GA) was used to find multiple Cournot equilibria in Nguyen & Wong (2002).

3. Proposed model for analysing market power

3.1 *Modelling suppliers' bidding behaviour*

Among the four equilibrium models introduced in Section 2.3, only the SFE model enables a firm to link the bidding price of its product with its bidding quantity. It constitutes a good compromise between the Cournot and Bertrand models. So, we assume in this paper that generation suppliers will decide on their bids based on the SFE model. Generally, most literature (Baldick, 2002; Weber & Overbye, 1999) considers the convex quadratic bid function since it is a simple and reasonable cost function of generation. The quadratic bid function is defined as follows:

$$f(P_i) = x_i P_i^2 + y_i P_i \tag{4}$$

where P_i is the provided generation and x_i, y_i are strategic variables.

Each firm can adjust the values for x_i and y_i which are referred to as strategic variables. However, x_i should be non-negative while the choice of x_i and y_i is often restricted. Four different parametrizations of strategic variables are: x-parametrization, y-parametrization, $(x \propto y)$-parametrization and (x, y)-parametrization. Though (x, y)-parametrization is the closest to a real competitive market since it has two strategic variables, it brings inconvenience and difficulties to the operation of an electricity market. So, we choose the $(x \propto y)$-parametrization since it has only one strategic variable and its format is similar to the true production cost function.

Suppose a generation supplier has n generators with generation cost represented as

$$C_i = C(P_i) = a_i P_i^2 + b_i P_i + c_i (i = 1, 2, \ldots, n) \tag{5}$$

where P_i is the generator i's power generation and a_i, b_i, c_i are the generation cost coefficients.

We suppose generation suppliers choose their bid functions according to generation costs and compete using the following linear supply function for generator i:

$$\rho_i = k_i \frac{\partial f(P_i)}{\partial P_i} = k_i (2a_i P_i + b_i) \tag{6}$$

where ρ_i is the bidding price, k_i is the bidding strategy (a real number), also called the markup, and k_i is 1 for price takers and $\frac{\partial f(P_i)}{\partial P_i}$ is the marginal cost of generator i.

The bid pair submitted to the market is (P_i, ρ_i). The presented approach to model suppliers' bids in this section is based on the SFE model proposed by Klemperer and Meyer. The $(x \propto y)$-parametrization is employed to simplify the procedure for finding the Nash equilibrium in the following sections.

3.2 *Market clearing model*

In an electricity market, prices of electricity should be set by market forces based on an auction mechanism rather than by market operators or regulators. An auction is a market institution with an explicit set of rules for resource allocation and setting prices on the basis of market suppliers' bids. For example, in the California electricity market, market suppliers, such as GENCOs and load serving entities (LSEs), submit supply and demand bids for the day-ahead and hour-ahead energy markets in a sealed bid format. The market operator aggregates the supply and demand bid curves to determine market clearing prices as well as the corresponding supply and demand schedules.

In our model, we do not consider the demand side bidding because the load is almost inelastic in the spot electricity market. The ISO minimizes the cost of supplying the load while satisfying the system constraints, such as transmission flow constraints. We assume that the ISO uses the following model for clearing the market:

$$\begin{aligned}
&\min \sum_{i=1}^{N} \rho_i P_i \\
&\text{s.t.} \\
&B\theta = P_G - P_D \\
&F_{\min j} \leqslant F_j \leqslant F_{\max j} (j = 1, 2, \ldots, L) \\
&P_{\min i} \leqslant P_i \leqslant P_{\max i} (i = 1, 2, \ldots, N)
\end{aligned} \tag{7}$$

where B is the conductance matrix; θ is the vector of bus voltage angles in the system; P_G is the vector of bus generation in the system; P_D is the vector of bus loads in the system; F_j is the flow on line j; $F_{\max j}$, $F_{\min j}$ are upper and lower limits of flow on line j; L is the number of transmission lines in the system; N is the number of generators in the system; ρ_i, P_i are bidding price and quantity of generator i and $P_{\min i}$, $P_{\max i}$ are lower and upper power limits of generator i.

The first constraint above represents the power flow equation. The locational marginal price (LMP) at each bus is the Lagrangian multiplier of the corresponding power flow equation. In this model, the market clearing price for generator i is the LMP of the corresponding bus. The second constraint is the transmission line flow limit. The third is the generating unit limit in the system.

In order to evaluate the market price sensitivity, we use the average locational marginal price (ALMP) as

$$ALMP = \left(\sum_{i=1}^{i=ND} P_{Di} LMP_i \right) \Big/ \left(\sum_{i=1}^{i=ND} P_{Di} \right) \tag{8}$$

where ND is the number of buses; P_{Di} is the load at bus i; LMP_i is the locational marginal cost at bus i.

If the ALMP is high, the market price for LSEs is presumably high. After the energy market is cleared by ISO, the payoff for the power supplier j is

$$R_j = \sum_{i=1}^{n} LMP_i \times P_i - \sum_{i=1}^{n} (a_i P_i^2 + b_i P_i + c_i) \tag{9}$$

where n is the number of generators of supplier j; LMP_i is the market clearing price for generating unit i and P_i is the awarded generation to generator i.

3.3 *The model for analysing market power*

In order to find out whether a generation supplier has market power, the ISO simulates the generation suppliers' bidding behaviour as they maximize their individual profits regardless of other suppliers' revenues. Considering that the suppliers can choose different bidding strategies, the ISO tries to find the equilibria where suppliers' payoffs are maximized. The model is formulated as the following two-level multi-objective optimization problem:

$$\max[R_1, R_2, \ldots, R_M]$$
$$\text{s.t.}$$
$$\left\{\begin{array}{c} k_{\min i} \leqslant k_i \leqslant k_{\max i}(i = 1, 2, \ldots, N) \\ \min \sum_{i=1}^{N} \rho_i P_i \\ \text{s.t.} \\ \rho_i = k_i * (2a_i P_i + b_i) \\ B\theta = P_G - P_D \\ F_{\min j} \leqslant F_j \leqslant F_{\max j}(j = 1, 2, \ldots, L) \\ P_{\min i} \leqslant P_i \leqslant P_{\max i}(i = 1, 2, \ldots, N) \end{array}\right\} \tag{10}$$

where M is the number of generation suppliers in the market; R_j is the generation supplier j's payoff, $j = 1, 2, \ldots, M$; $k_{\min i}, k_{\max i}$ are lower and upper limits on generator i's bidding strategy and k_i is the generator i's bidding strategy.

The above optimization problem maximizes suppliers' payoffs subject to market clearing prices and generations awarded in the sub-optimization problem. So, the problem here is to find generators' optimal bidding strategies for maximizing suppliers' payoffs. Nash equilibria are the solutions of the problem. There are four possible solution scenarios:

(1) Nash equilibrium does not exist;
(2) only one Nash equilibrium exists;
(3) many Nash equilibria exist;
(4) Nash equilibrium exists in mixed strategies.

In other words, a supplier chooses its various strategies with certain probabilities. The suppliers' incentive for choosing a mixed strategy is that they can disguise their strategy in the competition with their opponents. We do not consider Nash equilibria for mixed strategies in this paper. Game theory makes no assertion about the existence of several Nash equilibria. Each equilibrium point is a possible solution. This is not expected by market operators.

3.4 *Calculation of optimal bidding strategies*

Suppose there are M generation suppliers in an electricity market with bidding strategies listed as $k_1, k_2, \ldots, k_M$ respectively. The lower and upper bounds for the bidding price of supplier i are $K_{\min i}$ and $K_{\max i}$ respectively. It is conceivable that Nash equilibria would be difficult to find because generators' bidding strategies are continuous variables rather than finite discrete sets. Here, we use an iterative method to find the equilibria. We discretize the strategy space of each power supplier. Suppose the supplier i's discrete step is $\Delta k_i (i = 1, 2, \ldots, M)$. Given the opponents' bidding strategies as $k_1, k_2, \ldots, k_{i-1}, k_{i+1}, \ldots, k_M$, we search the supplier i's strategy space to find the optimal bidding strategy k_i^*. We use the opponents' combination of bidding strategies to find the optimal response of supplier i. Using the same method, we find the optimal response space for all suppliers. The intersection of suppliers' optimal response strategy spaces is the Nash equilibrium of

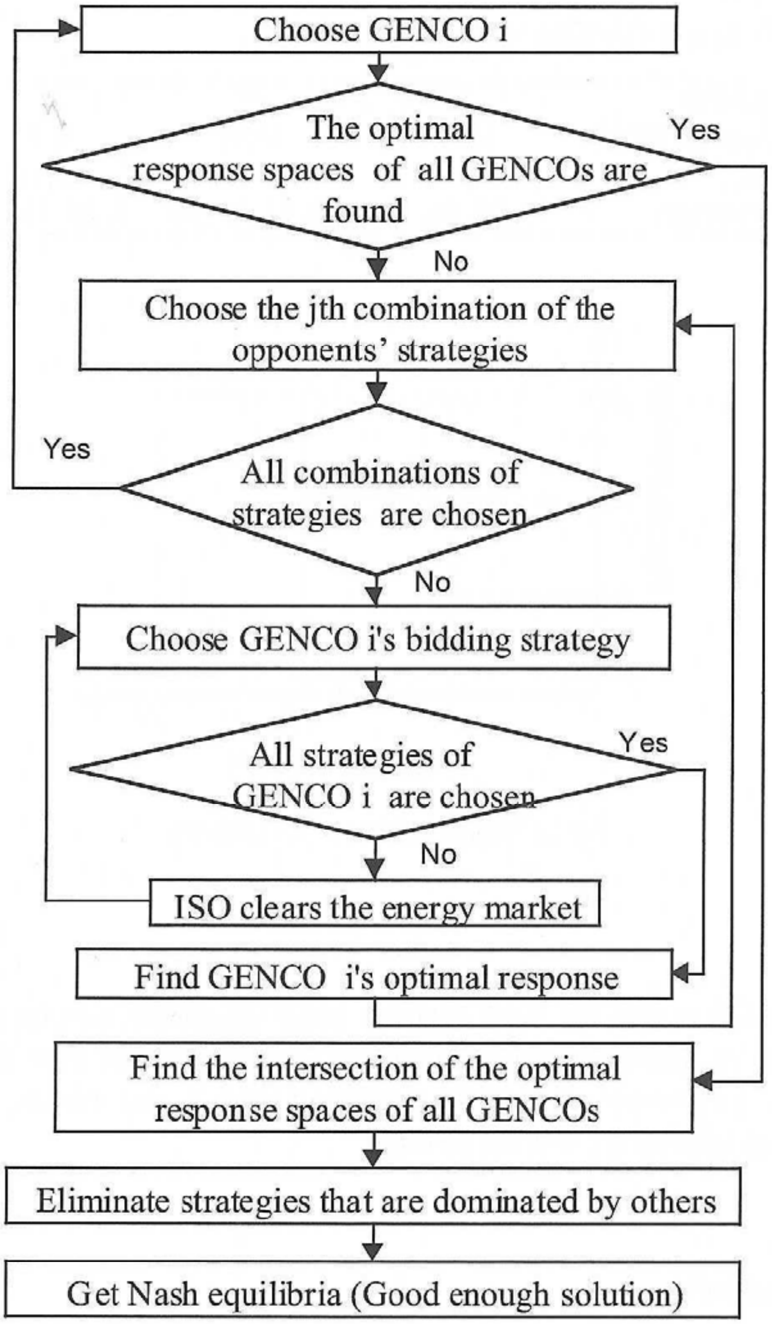

FIG. 1. Flowchart for searching for Nash equilibria.

the game. However, there may be no intersection when we discretize the strategy space. Suppose $(k_{i1}^*, k_{i2}^*, \ldots, k_{iM}^*)$ is a strategy set in the optimal response space of supplier i and $(k_{j1}^*, k_{j2}^*, \ldots, k_{jM}^*)$ is a strategy set in the optimal response space of supplier j. If $|k_{il}^* - k_{jl}^*| \leqslant \Delta k_l$ for $l = 1, 2, \ldots, M$, these two strategy sets are within the space where optimal response spaces of i and j intersect. We employ the same method to find the intersection space for all suppliers. Strictly speaking, these intersections are not Nash equilibria, but represent 'good enough' solutions if discrete steps are small. Some of the good enough solutions may be dominated by other strategies, so we eliminate the dominated solutions after finding the good enough solutions.

The flowchart for searching Nash equilibria is shown in Fig. 1. We emphasize that

TABLE 1 *GENCOs' information*

GENCO	1	2	3
Capacity (MW)	1023	1010	967
Bus	1	49	87,89
Generators	10, 27, 28, 34	20, 21, 29, 30	5, 26, 31, 36

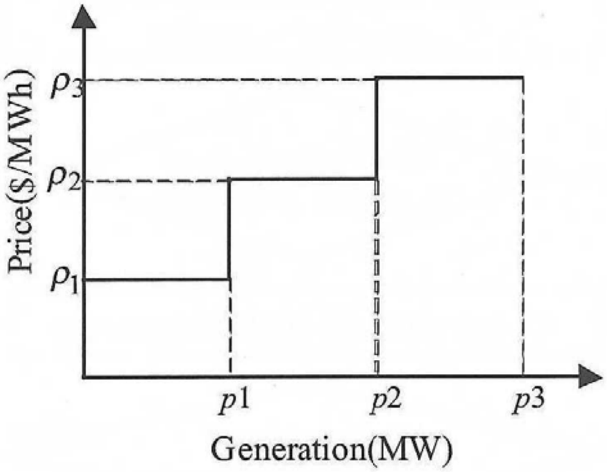

FIG. 2. Supply bid curve for a generator.

the size of the discrete step for each supplier could affect the accuracy of our solution. However, we tend to choose the proper step size according to the experience of the ISO's personnel with a specific power market, governing rules in the market, and computation bottlenecks for calculating the market power.

4. Numerical example

We employ the IEEE 118-bus system as our example system. The data for generators, load and transmission network are shown in Shahidehpour *et al.* (2002). The total system load is 4911 MW and the total generation capacity is 6183 MW. The system represents 36 generators. In order to simplify the analyses, we suppose the first three suppliers (GENCOs) are price setters and the other GENCOs are price takers. The price setters will bid strategically and the price takers will bid at their marginal costs. The generation capacity and generators of the first three suppliers and the buses where the suppliers are located are shown in Table 1.

We assume each supplier uses a single bidding strategy for its generating assets. The selection of reference bus may affect the solution and we choose bus 1 as the reference bus of the system.

The bid function of each generator is a three-segment piecewise linear curve as shown in Fig. 2. Accordingly, the ISO's market clearing problem is a linear program. The supply bids submitted to the ISO by each generator are (p_1, ρ_1), $(p_2 - p_1, \rho_2)$, and $(p_3 - p_2, \rho_3)$.

TABLE 2 *Competition in a perfect electricity market*

Case	GENCO's MW			ALMP	GENCO's Payoff ($/h)		
	1	2	3	($/MWh)	1	2	3
A.1	836	1010	750	23·51	10 224	11 651	9 362
A.2	488	1010	846	27·83	426	10 887	9 743
A.3	455	1010	814	118·88	416	39 637	10 855

4.1 *Perfect competition in the electricity market*

First, we assume that all suppliers are competing in a perfect electricity market, which means that they bid at their marginal costs in order to maximize their individual revenues. The following three scenarios are analysed:

A.1 transmission flow limits are ignored;
A.2 transmission flows are limited to 300 MW;
A.3 transmission flows are limited to 280 MW.

Table 2 shows the ALMP, awarded generations, and payoffs for the first three GENCOs. The table shows that ALMP in the A.1 scenario (i.e. no transmission limit) is the lowest and that of A.3 is the highest. Table 2 shows that GENCO 2 will sell its entire generation as its four generators have almost the lowest marginal costs in the system. The four generators of GENCO 1 are located at bus 1 and are connected by lines 1 (bus 1 to 2) and 2 (bus 1 to 3) to the outside system. The flow on line 1 will be affected when line 2 is congested in A.2. So, as the transmission capacity drops from A.2 to A.3, the flow on line 1 will also drop since line 2 remains congested. The generation dispatch of GENCO 3 (expensive unit) is increased in A.3 as compared to A.1. This is because the transmission congestion enhances the opportunity for more expensive generators in A.3 (e.g. generator 26) to supply the load. The congested lines in A.2 are: line 2 (bus 1 to 3), line 138 (bus 89 to 90), and line 186 (bus 76 to 118). In Case A.3, congested lines are 100 (bus 62 to 66) as well as 2, 138, and 186.

Table 2 is used as a benchmark to analyse GENCOs' market power in Case B below.

4.2 *Imperfect competition environment*

The practical electricity market is more like an oligopoly than a perfect one. So, market suppliers may try to maximize their revenues by gaming. In order to determine whether or not a GENCO has market power, we consider the following three factors:

(1) whether a GENCO is profiting more than that under a perfect competition;
(2) whether the market price (ALMP) is higher than that in a perfect market;
(3) whether the bidding behaviour of a GENCO reveals any market power.

We study these issues in this section as GENCOs consider exercising market power by submitting bids that are higher than their marginal costs, withholding their power generation, or both. Sometimes, it is impossible to determine whether GENCOs have market power when a GENCO makes more profit as others exercise market power.

We examine the corresponding scenarios in an imperfect competition. For cases B.1 to B.3, we limit the range of bidding strategies from 0·8 to 1·8 and use a discrete step of 0·2 for each GENCO. Case B.4 is the same as B.2 except the bidding strategy ranges from 0·8 to 2·8.

4.2.1 *Case* B.1: *Transmission flow limits are ignored.* A list of 'good enough' bidding strategies for the first three GENCOs and the resulting market prices are shown in Table 3. Table 4 shows that the payoffs and generations of the first three GENCOs, at good enough solutions, are almost the same as that of the perfect competition (A.1) in Table 2. Table 4 shows the incremental payoff which is in comparison with A.1. Furthermore, the incremental ALMP is the normalized difference between ALMPs of imperfect competition (B.1) and the perfect competition (A.1). Since the ALMP is not changing much (0·26%) under gaming, GENCOs will not gain much by bidding strategically. In this case, market price (Table 3) and generation (Table 4) of the three GENCOs are almost the same as that of A.1 (Table 2) because the three GENCOs do not possess the marginal units which would set the market clearing prices in the market. These results show that the three GENCOs cannot exercise market power extensively while there is enough transmission capacity available in the system. The drop in GENCO 1's generation, compared with A.1, indicates that GENCO 1's generation is not entirely awarded when the bid is high.

4.2.2 *Case* B.2: *Transmission line flows are limited to* 300 MW. The transmission flow is limited to 300 MW in this case. Table 5 shows the 'good enough' bidding strategies for the first three GENCOs, market prices, and congested lines. The corresponding payoffs and generations are shown in Table 6. in which the incremental payoff is in comparison with A.2. In this case, ALMP is increased by 7·3% and the three GENCOs profit more than that under a perfect competition (A.2).

There is no incentive for GENCO 2 to bid strategically because its profit remains the same at the four good enough solutions. So GENCO 2 may choose to bid at its marginal cost, while GENCOs 1 and 3 will profit more by exercising market power. The interesting result here is that the congestion is relieved by GENCOs' strategic bidding. Line 138 is no longer congested as was the case in A.2, while the power generations of GENCOs 1 and 2 are the same. GENCO 2 was dispatched to generate its maximum capacity because of its low marginal costs. Accordingly, the LMP at bus 49 of GENCO 2 is decided by other generators at the four good enough solutions, which is higher than the corresponding bidding price of GENCO 2. So, these four good enough solutions represent the same ALMP which explains the cases B.3 and B.4 as well.

4.2.3 *Case* B.3: *Transmission line flows are limited to* 280 MW. The 'good enough' bidding strategies for the first three GENCOs, market prices, and congested lines are shown in Table 7. The payoffs and generations of the first three GENCOs at good enough solutions are the same as A.3 as shown in Table 8.

The incremental payoff is in comparison with A.3. Under this condition, GENCOs 1 and 3 profit more than that in the perfect market by bidding higher than their marginal costs. GENCO 2 maintains the same level of profit as before and has no incentive to bid

TABLE 3 *'Good enough' bidding strategy*

Strategy #	GENCO's strategy 1	2	3	ALMP ($/MWh)
1	1·2	0·8	1·0	23·57
2	1·2	0·8	1·2	23·57
3	1·2	0·8	1·6	23·57
4	1·2	1·0	1·6	23·57
5	1·2	1·2	1·2	23·57
6	1·2	1·2	1·4	23·57
7	1·2	1·2	1·6	23·57
8	1·2	1·4	1·4	23·57
9	1·2	1·4	1·6	23·57
10	1·4	0·8	1·2	23·57
11	1·4	0·8	1·4	23·57
12	1·4	0·8	1·6	23·57
13	1·4	1·0	1·0	23·57
14	1·4	1·0	1·2	23·57
15	1·4	1·0	1·4	23·57
16	1·4	1·2	1·4	23·57
17	1·4	1·4	1·0	23·57
18	1·4	1·4	1·2	23·57
19	1·4	1·6	1·2	23·57
20	1·4	1·6	1·4	23·57
21	1·6	0·8	1·0	23·57
22	1·6	0·8	1·2	23·57
23	1·6	1·0	1·4	23·57
24	1·6	1·2	1·0	23·57
25	1·6	1·2	1·4	23·57
26	1·6	1·4	1·4	23·57
27	1·6	1·4	1·6	23·57
28	1·6	1·6	1·0	23·57
29	1·6	1·6	1·6	23·57

TABLE 4 *Generation and payoff at good enough solutions*

GENCO	Generation (MW)	Payoff ($/h)	Incremental Payoff ($/h)	Incremental ALMP
1	826	10269	45	0·26%
2	1010	11712	61	
3	750	9407	45	

strategically. The $2 drop in GENCO 2's profit is merely a computational imprecision. The LMP at bus 49 is $51.2182/MWh for A.3 and $51.2157/MWh for B.3. Though the ALMP does not change much in comparison with A.3, it is much higher than that of B.1 when there is no congestion in the system. So, the transmission reinforcement and expansion will have an important role in electricity markets.

TABLE 5 *'Good enough' bidding strategy*

Strategy #	GENCO's strategy 1	2	3	ALMP ($/MWh)	Congested lines
1	1·6	0·8	1·6	29·56	2, 186
2	1·6	1·0	1·6	29·56	2, 186
3	1·6	1·4	1·6	29·56	2, 186
4	1·6	1·6	1·6	29·56	2, 186

TABLE 6 *Generation and Payoff at good enough solutions*

GENCO	Generation (MW)	Payoff ($/h)	Incremental Payoff ($/h)	Incremental ALMP
1	488	3754	3 328	
2	1010	11 537	650	7·3%
3	808	21 374	11 631	

TABLE 7 *'Good enough' strategy and congested lines*

Strategy #	GENCO's Strategy 1	2	3	ALMP ($/MWh)	Congested lines
1	1·6	1·0	1·6	119·12	2, 100, 138, 186
2	1·6	1·2	1·6	119·12	2, 100, 138, 186
3	1·6	1·4	1·6	119·12	2, 100, 138, 186

4.2.4 *Case* B.4: *Effect of price cap.* Here, the bidding strategy ranges from 0·8 to 2·8 which is higher than that of B.2. Accordingly, the bidding price cap in B.4 will be higher for the same marginal cost. The remaining system information used in this case is the same as that in B.2. The 'good enough' bidding strategies for the first three GENCOs, market prices, and congested lines are shown in Table 9. The payoffs and generations of the first three GENCOs at these good enough solutions are shown in Table 10.

The ALMP in this case is higher than that of A.2 which increases the cost of power delivery to consumers more than that in the perfect competition. GENCOs 1 and 3 will profit more by gaming when the price cap is set higher in this case. GENCO 2 will not have an incentive to bid higher than its marginal cost and will have a higher profit as the other two GENCOs exercise market power. So, the comparison between B.2 and B.4

TABLE 8 *Generation and payoff at good enough solutions*

GENCO	Generation (MW)	Payoff ($/h)	Incremental Payoff ($/h)	Incremental ALMP
1	455	3 522	3 106	
2	1010	39 635	−2	2·0 %
3	814	22 470	11 615	

TABLE 9 *'Good enough' strategy and congested lines*

Strategy #	GENCO's Strategy 1	2	3	ALMP ($/MWh)	Congested Lines
1	2·6	0·8	2·6	42·72	2, 186
2	2·6	1·0	2·6	42·72	2, 186
3	2·6	2·2	2·6	42·72	2, 186

TABLE 10 *Generation and payoff at good enough solutions*

GENCO	Generation (MW)	Payoff ($/h)	Incremental Payoff ($/h)	Incremental ALMP
1	488	9 300	8 874	53·50%
2	1010	17 167	6 280	
3	805	40 618	30 875	

points out that setting a lower price cap is a proper measure for mitigating market power in electricity markets.

5. Conclusions

This paper reviewed three methods used by the ISO for analysing the market power in electricity markets. The paper proposed an iterative method to determine whether a power supplier has market power in an electricity market. Supply function equilibrium was employed to model generation suppliers' bidding behaviours. The discrete method was adopted to find a power supplier's 'good enough' bidding strategies base on the game theory. The IEEE 118-bus system was used to illustrate the method. The presented results show that

- the transmission capacity may provide additional opportunities for GENCOs to exercise market power (see B.1 and B.2);
- GENCOs' strategic bidding behaviours may relieve the congestion in power systems (see A.2 and B.2);
- when exercising market power, GENCOs do not have to withhold their generating capacity (see A.3 and B.3);
- setting a lower price cap is a proper measure for mitigating market power in electricity markets (see B.2 and B.4).

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