Tacit Collusion and Capacity Withholding: Reliability Assessment of a Double Price Cap Electricity Market

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Abstract

Increasing overall liberalization and improving reliability indexes are the two prime but often conflicting objectives of electricity markets. Proper embedding of regulatory intervention of price caps provides an effective means to tradeoff between these two objectives. Surprisingly, in the context of the infinitely repeated game paradigm, as in the case of actual electricity markets, the dominance of tacit collusion and capacity withholding highlights the role of non-pivotal firms in frustrating price caps and deteriorating reliability indexes. An agent-based simulation framework is proposed to evaluate both individual behavior of non-pivotal firms within the market and the emergent collusive behavior arising from interaction between firms. Mathematically speaking, to put the capacity withholding into action, we propose embedding a hybrid-control problem in the supply function equilibrium (SFE) modeling assumptions. As a consequence, non-pivotal firms are granted supply curves with vertical segments that obviate the slope constraint of the SFE modeling. A simulation using the generation portfolio of the Iranian electricity industry illuminates the impacts of tacit collusion on reliability indexes.

Keywords: Non-pivotal Firms, Tacit Collusion, Capacity Withholding, Reliability Indexes.

1. Introduction

One of the most critical issues in electricity industry deregulation is electricity market design. Some argue that there is no need for regulatory intervention, while others argue that they are essential for efficient market operation [1], [2]. Responding to the controversy, many studies have been performed on electricity market design [3], [4].

With the emergence of price volatility, occasional sharp price spikes and poorly planned investment in simple auction-based liberalized electricity markets, regulators look on regulatory intervention of double price caps as electricity markets' salvation [5]-[7]. Double price caps can have a number of advantages over a simple auction-based market. It can reduce prices, increase competition, and produce a scarcity rent which is necessary to promote generation adequacy. On the other hand, repeated auction paradigm, as in the case in actual electricity markets, bring about two types of problems that a regulator faces conducting his interventions. Firstly, firms could engage in tacit collusion inherent in repeated auction-based electricity market. This might harm reliability and certainly challenges the realization of competitive context. Secondly, the problem of issuing the correct strategies arises and is constrained by regulator's capabilities for information processing and decision making. So, in addition to costs of intervention, the choice of a regulator depends on his answering two questions: whether the firms are inattentive to collusion; and whether the strategy is elaborately designed.

There has been a great deal of studies to understand tacit collusion in electricity market [8]-[11]. Based on trial-and-error searches, these studies have focused on learning mark-ups on the bids or setting aside a portion of the capacity that can be interpreted as capacity withholding. This has led to an embarrassment of riches, i.e., almost everything is equilibrium. However, little interest has been given to the incorporation of questions regarding how collusion frustrates the regulatory intervention of price caps and how it affects reliability indexes. To see how collusion can construct a collective strategic behavior of non-pivotal firms that is tantamount to frustration of price caps and deterioration of reliability indexes, one must delve into principles of liberalized electricity market. Because the availability of capacity cannot be directly managed by the system operator of the market, the non-pivotal firms may engage in tacit collusion and collective capacity withholding which harm short-term generation adequacy, increasing the probability of occasional capacity shortage. Looking at the literature in reliability analysis of traditional power systems we

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notice that many methods have been developed to calculate the reliability indexes of power system generation [12], [13]. These methods can be divided into two main categories: analytical methods and simulation methods using Mont Carlo technique. Since in traditional methods of reliability analysis, it is difficult to accommodate the principles of the liberalized electricity markets, in this paper, we wish to depart from tradition by devising a more comprehensive framework. It helps with analyzing reliability indexes affected by interactions and relationships between physical and market-based layers of electricity market. To do this, one must focus attention on a chain of critical issues: first, regulatory intervention of price caps, that the regulators restrict the supply bids to the offer cap

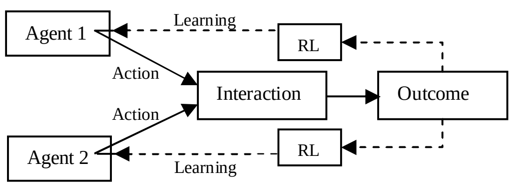

Fig. 1 Agent-based modeling

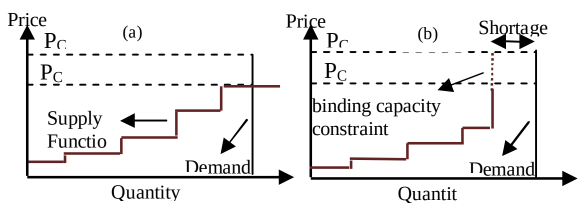

Fig. 2 Overview of the double price cap electricity market

and provide the opportunity of gaining scarcity rents at market cap for suppliers; second, repeated auction paradigm, that the infinitely repeated game tempts market players into engaging in collusion diversifying one stage market outcome to embrace a wider range of equilibriums; third, capacity withholding, that the market players' behaviors threatens the reliability indexes with intentional capacity shortage; and finally, physical outages, that is an inherent characteristic of liberalized electricity markets and traditional delivery systems alike.

The complexities of technical and economical aspects of electricity markets rush most classical modeling toward their restrictions. Game theoretical analysis usually limited to stylized trading situation among few actors, and place rigid assumptions on the players' behavior [14]. Agent-based (AB) modeling is one of the appealing new methodologies that have the potential to overcome some shortcomings of traditional methods [15]-[17]. An AB model is a class of computational models for simulating the actions and interactions of autonomous agents with a view to assessing their effects on the outcome of the system. The model uses reinforcement learning (RL) mechanism that advances the simulation and stimulates the agents' preferences to be influential in improving gaming strategies (see Fig. 1).

In this paper, agent-based simulation framework is born out of a need for reinforcement learning, clarifying the rationale behind tacit collusion and capacity withholding. Therefore, in the context of repeated double price cap electricity market, we conceive of an agent-based simulation framework that can analyze the emergence of capacity withholding, mimic the tacit collusion of non-pivotal firms behind it, and give a clear understanding of why and how electricity market players' behaviors affect reliability indexes. In this paper, the set of admissible bids are extended by a hybrid control problem, and are embedded in the SFE modeling, as a supporting tool for vertical segments of supply curve and capacity withholding decision. By doing so, we depart from traditional reliability analysis and, thus, the regulatory interventions of the price caps, which can be abused by non-pivotal firms, are accounted for.

The agent-based simulation, proposed by the authors of this study [18], had two types of myopic and foresight agents who were equipped with learning capabilities for tacit collusion and capacity withholding. In the final analysis of [18], the results of collusion centered around the converged collusive behavior of non-pivotal firms that brought about a change in reliability indexes. The missing question was why different firms with different preferences engage in collusion and how a collusive deterioration of reliability indexes occurs. Thus, this study includes expansion on the course of action which firms go through to reach a collusive point that deteriorates the reliability indexes. To do this, comparing homogeneous and asymmetric preferences emerging endogenously through the discount factors are presented to examine the path where the firms are in accord with collusive behavior of capacity withholding and deterioration of reliability indexes.

3.Double Price Cap Electricity Market

The introduction of regulatory intervention into the market clearing mechanism is somewhat complex to provide robust and autonomous auction process, but it has the potential to increase efficiency. An antitrust authority will make the proper trade-off between efficiency and internal complexity which design flaws are possible with an attendant risk of collusion and gaming. Although there is nearly universal agreement that the wholesale electric power prices should rise when demand increase relative to supply, as prices do in other competitive industries, regulators protect the customers by ranging bids between price floor and price caps. When inelastic demand for electricity is high or supply low, relatively high-cost suppliers are called into the market and market clearing price rises. At such times, there is still adequate supply to serve the inelastic demand while firms are being forced to bid less or equal to the relatively high offer cap P_{c1}, Fig. 2(a), which is also termed as “maximum prices without scarcity”. If, instead, market clearing is infeasible due to capacity shortage, a scarcity situation exists. Demand would exceed supply, requiring some nonmarket approach to deciding which demand will and will not be served. Economists depict this by showing a vertical segment of the supply curve to exhibit binding capacity constraint. The market prices in these cases are the administratively set market cap P_{c2}, Fig. 2(b), which is also termed as “scarcity prices”. The caps satisfy $P_{c2} > P_{c1}$, allowing firms to gain scarcity rents which is necessary to promote resource adequacy. Scarcity situations can be very profitable for suppliers, so it is not surprising that pivotal suppliers are tempted to take actions to withhold capacity that give the appearance that capacity is scarcer than it really is.

On the other hand, non-pivotal firms just want a chance of collusion to show what they can do. In this case, total operating capacity in the market without the capacity of an arbitrary firm is still sufficient to meet market demand. That is, even if any firm withdraws all its capacity from the market, the price would still be close to competitive levels. Surprisingly, even with non-pivotal suppliers, whose unilateral withholding would not result in load curtailment, scarcity opportunities do appear that can be interpreted as tacit collusion inherent in repeated auctions. Based on this intuition, an agent-based simulation framework has been organized to show that non-pivotal firms have the incentive to join forces to give birth to a pivotal cartel capable of excluding an impressive capacity from the market and imposing shortage.

2.Collective Contribution of Non-pivotal Firms to Capacity Withholding

In this section, the model used for the simulation of the double price cap electricity market is set out. The firms are considered autonomous agents which learn through interaction how to tune the slope of the bidding decision and when to declare binding slope constraints for mutually beneficial capacity withholding. In III.A, the sets of admissible bids of non-pivotal firms are extended by a hybrid control problem based on the developed Gateaux derivative concepts in [14], and are embedded in the SFE assumptions, as a supporting tool for individual capacity withholding decisions. The extension allows for supply function with vertical segments and overcomes the slope constraints of the standard SFE first order conditions. In III.B, the main aspects of tacit collusion are captured in a repeated game framework. The chief objective behind developing this repeated game is to incorporate non-pivotal firms into a pivotal cartel, that is, when non-pivotal firms behave in a cooperative pivotal manner to join individual forces, they could create pivotal cartel capable of imposing capacity shortage. In other words, by capturing the effects of repeated game paradigm, each firm’s individual capacity withholding is timed to coincide with its rivals’ capacity withholding. Thus, a collection of individual vertical segments of each supply function will form an impressive collective capacity withholding of non-pivotal firms.

A. Capacity Withholding Arranged by a Non-pivotal Firm

In our market model, capacity shortage lead the market to scarcity price and this change the strategy of the firms. So, we must provide the firms with comprehensive bidding mechanism, in which capacity withholding would emerge as a vertical segment of bidding decision. Then, a clear understanding about how and when the firms will declare a fictitious binding capacity constraint is to be expected. Intuitively, we need to construct a model that is theoretically capable of representing biddings in more flexible manner over a wide range of decisions in which full capacity bidding and intentional capacity withholding are possible. In this way, firms involved in the double price cap electricity market can tune the slope of bidding or break the supply function with a vertical segment when the situation imposes full capacity bidding or capacity withholding, respectively. Mathematically speaking, such vertical segments introduce discontinuities in the differential equation that invalidate the assumptions ordinarily required for the standard SFE to apply.

Formulation of a desirable vertical segment in the state variable is also reported as a challenging problem in econometrics and control science [20]. Using Gateuax derivative concept and hybrid control problem, Kyung in [19], derived impulsive variational inequalities and then passed them to a numerical algorithm stands to tune the slope of the state variable or to incline it to jump, so as to create a vertical segment in the movement of the state variable. Here, this hybrid control problem is employed to develop the bidding mechanism of non-pivotal firms. Thus, capacity withholding is said to be put into practice if the state variable of the hybrid control problem is inclined to jump.

The authors assume a daily repeated double price cap auction of N non-pivotal firms competing for inelastic demand d in which each firm i has constant marginal cost of production, mc_i, up to its available capacity constraint k_i^a. The firms make, at the beginning of each daily contracting round, the bidding decision of their capacity. The supply function of each firm $S_i(p)$, which is required to be non-decreasing is defined as a function of price to quantity, where p is the market price. As competitors follow the equilibrium, the inverse function comes into being and is denoted by $p(q_i)$, which is considered the bidding decision of each firm. Also, it is assumed that $S(p)$ denotes market aggregated supply function and $S_{-i}(p)$ rivals' aggregated supply function. Bidding decision of each firm i is formulated as a hybrid control problem as follows:

$$\max_{\psi_i, u_i} \int_0^{k_i^a} f(p(q_i), q_i)\, dq_i, \qquad \forall i \tag{1}$$

subject to the following constraints:

$$p'(q_i) = u(q_i), \qquad \forall i \tag{2}$$

$$p(q_{ij}^+) = p(q_{ij}^-) + w_{ij} F(q_{ij}, v_{ij}), \qquad \forall i, j \tag{3}$$

$$p(0) = mc_i, \quad p(q_i) \le P_{c1} \qquad \forall i \tag{4}$$

$$w_{ij} \in \{0,1\}, \qquad \forall i, j \tag{5}$$

$$\psi_i = \{(q_{ij}, v_{ij}, w_{ij})\}. \quad \forall i, j \tag{6}$$

where the *continuous control* $u_i(q_i)$ in addition to the *impulse control* $\psi_i = (\{q_{ij}, v_{ij}, w_{ij}\})$ characterizes optimal bidding decision $p(q_i)$ as the state variable of each firm. Tuning the slope of the state variable, when capacity withholding cannot be optimal, is governed by the $u_i(q_i)$; otherwise, ψ_i with impulse quantity q_{ij}, impulse volume v_{ij} and binary impulse decision w_{ij} will lead state variable to vertical jump, making it similar to the case when capacity withholding occurs. j is the number of vertical jumps; q_{ij}^- is the pre-jump quantity; and q_{ij}^+ is the post-jump quantity. At vertical segment quantity q_{ij}, the system is controlled impulsively with the impulse scale v_{ij} with its effect $F(q_{ij}, v_{ij})$ if $w_{ij} = 1$. If firm i produces the residual demand of the rival firms to meet the market clearing condition, then the integral term $f(.)$ can be written as:

$$f(p(q_i), q_i) = (p(q_i) - mc_i)(d - S_{-i}(p(q_i))) \tag{7}$$

Thus, the solution to (1)-(6) requires an estimation of $S_{-i}(p(q_i))$ to form (7) serving as an input of the hybrid optimal control problem.

If a non-pivotal firm takes pivotal position in estimating rivals' supply function, this will cause a vertical segment in the output of the control problem, mimicking a capacity withholding decision. Considering the profit function of a company U_i, we have

$$U_i = p.q_i - c_i(q_i). \tag{8}$$

$$S_i(p) = q_i \tag{9}$$

$$S_{-i}(p) = \sum_{\forall j \ne i} q_j \tag{10}$$

Setting the derivative of profit function to zero, we obtain an optimality condition

$$S_i(p) - \frac{\partial S_{-i}}{\partial p} \cdot \left(p - \frac{\partial c_i}{\partial q_i} \right) = 0 \tag{11}$$

Applying homogeneity condition (12) to (11), we can alleviate the difficulties. This allows for the implementation of estimations in SFE assumptions.

$$S_i(p) = \beta_i . S(p), \; S_{-i}(p) = \beta_{-i} . S(p) \tag{12}$$

The authors introduced firms' contribution α_i to exhibit the level of their pivotal position while estimating $S_{-i}(p(q_i))$. If contribution α_i is taken to reflect the pivotal position, it must be interpreted as the level of the residual demand that is beyond the rivals' control. In contrast, $(1-\alpha_i)$ portion of the demand is exposed to the competition. So, this contribution was applied to the SFE assumption as:

$$\beta_i + \beta_{-i} = (1-\alpha_i) \tag{13}$$

$$S_i(p) + S_{-i}(p) = (\beta_i + \beta_{-i})S(p) = (1-\alpha_i).d \tag{14}$$

Now, by Substituting (12), (13) and (14) into (11), one obtains

$$\frac{\partial p}{\partial S(p)} = (\theta_i - 1)\left[\frac{p}{S(p)} - \frac{c'(\beta_i . S(p))}{S(p)}\right] \tag{15}$$

The solution of this equation results in

$$S_{-i}(p(q_i)) = \frac{1-\alpha_i}{\beta_i}.[(p(q_i) - mc_i\, S^*(p(q_i))^{-\theta_i+1})$$

$$.1/(\frac{p_{c1}}{S^*(p(q_i))^{\theta_i-1}} - mc_i\, S^*(p(q_i))^{-\theta_i+1})]^{\frac{1}{\theta_i-1}}. \tag{16}$$

where S^* is a peak hour supply function. It is important to note that the above SFE assumptions are the basis of the estimation. This estimation, which contains α_i, is being applied as an input to the hybrid control problem. The state variable $p(q_i)$, as the output, is dependent on α_i: a vertical segment in $p(q_i)$ is expected if the firm chooses a pivotal position $\alpha_i > 0$, and tuning the slope of $p(q_i)$ makes sense if $\alpha_i = 0$ is selected.

B. Repeated Game and Simulation Framework

To explore how the repeated game affects the outcome of double price cap electricity market, we assume that each firm i can choose mixed strategies where $p_{i,w}$ and $1-p_{i,w}$ are the probability of choosing capacity withholding and full capacity bidding, respectively. As there is no pivotal firm in the market model assumed here, it is not surprising that the contribution $\alpha_i = 0$ and the probability of capacity withholding $p_{i,w} = 0$ would be chosen by the firms to achieve the most possible portion of the demand. This selfish selection is the result of one-stage game, restraining the firms from cooperative bidding strategies. This implies that, as in the well-known Nash Equilibrium (NE) concept, double price cap electricity market involves non-pivotal firms in selecting the best responses $\alpha_i = 0$ and $p_{i,w} = 0$ in relation to other firms' strategies. On the other hand, t-round repeated game gives non-pivotal firms a chance to engage in tacit collusion. From the game theory literature, considering a firm that has a discount factor of δ, the existence of equilibrium that Pareto dominates the one stage NE is given by the Folk theorem [21].

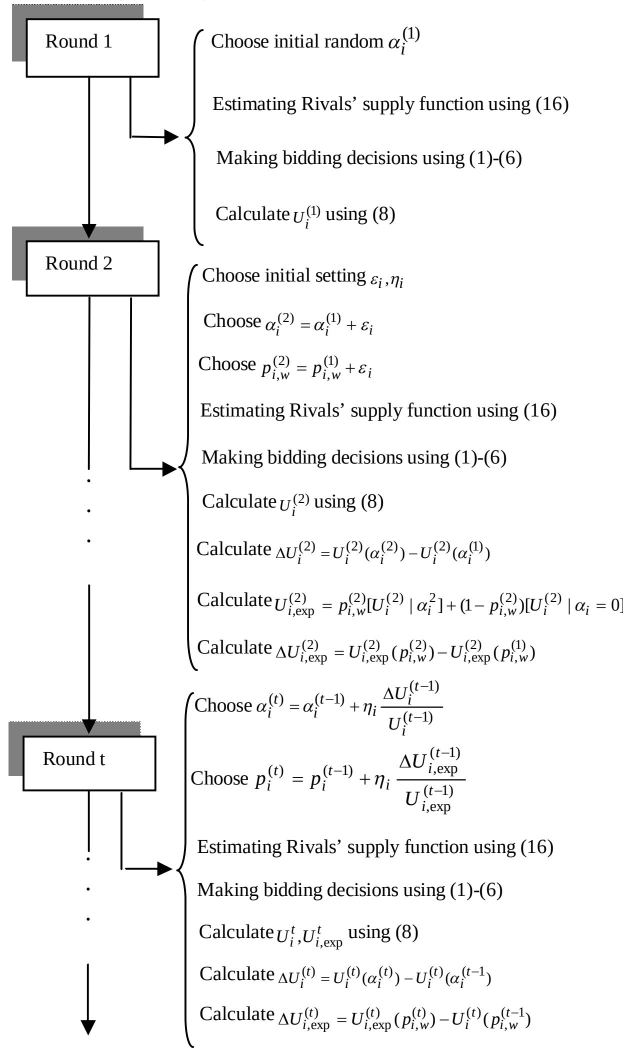

Fig.3 Agent-based simulation framework and reinforcement learning

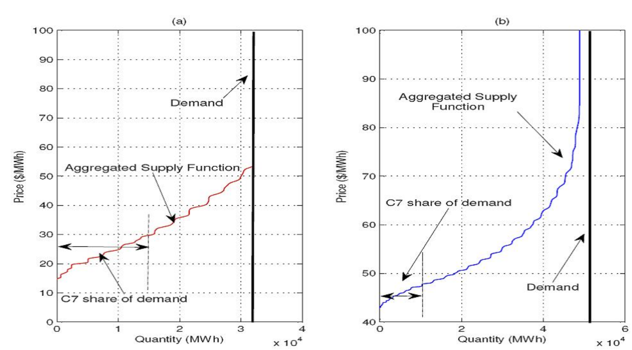

Fig. 4 ASF of a typical (a) off-peak and (b) peak hour

Table 1 Capacity (GW) and number (in parenthesis) units by firms

$/MWh	C1	C2	C3	C4	C5	C6	C7
0-15	1.5(2)	1(3)	2.2(2)	3.1(2)	1.8(3)	1.2(4)	1.5(3)
15-20	0.3(6)	0.3(3)	0.11(4)	0.21(3)	0.45(5)	0.3(5)	0.25(3)
20-30	0.26(6)	0.11(4)	0.35(7)	0.7(5)	0.31(4)	0.2(6)	0.38(5)
30-45	0.4(3)	0.8(4)	0.55(2)	0.56(4)	0.68(6)	0.2(7)	0.21(2)

Folk Theorem: There exists critical discount factor $\underline{\delta} \in (0,1)$ such that for all $\delta \in (\underline{\delta},1)$, there exists equilibrium of the infinitely repeated game with discount factor δ in which firm i average utility is greater than one stage NE.

The game normalized average discounted utility function is given by:

$$U_i^{\infty} = (1-\delta)\sum_{t=1}^{\infty}\delta^{(t-1)}U_i^{(t)} \tag{17}$$

where $U_i^{(t)}$ is the profit of firm i at each stage of game (8) played at round t. If the selection of α_i and $p_{i,w}$ occurred in a tacitly colluded manner and led to a fraction of demand being covered, the non-pivotal firms will collaborate to create a pivotal cartel capable of creating capacity shortage.

As the only information the firm can observe is the effect of change of contribution on its own utility function, the best way for the firm to learn the contribution α_i is to gradually slide the value of α_i and monitor if the utility function improves. Thus, if increasing their selected contribution α_i last round induced an increase (decrease) in their profits, then they will increase (decrease) α_i this round. This adjustment can be done by sliding the instruction for changing the contribution. Simulation framework is characterized by agent-based concept whose learning and bidding decisions are summarized in Fig. 3. The first step in learning is the contribution selection of the pivotal position, where the firms decide on the level of demand at which rivals' capacities start binding. The contribution selection observes the discounted profit of each hour obtained in the previous auction round and adapts that contribution according to the change it caused in the profits. Once the contribution of pivotal position calculated, the second step is to estimate rivals' aggregated supply function. This estimated supply function forms the input for the third step in making the bidding decision $p(q_i)$ of each company; exhibit either a vertical segment to create capacity withholding or continuous segments to handle slope competition.

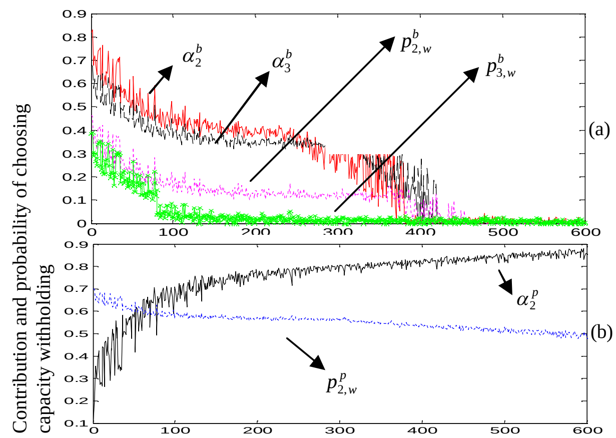

Fig. 5 Contribution and probability in (a) base load and (b) peak load

4. System Details and Simulation Results

To investigate the viability of the simulation framework, we performed simulations on Iranian generation side portfolio. It distinguishes peak from off-peak hours. A daily load duration curve was introduced and exposed to repeated double price cap gaming of generation side. The allocation of generation side portfolio among non-pivotal generation firms C1 to C6 as price makers and C7 as price taker, each of different size and generation technology portfolio, arranged by marginal cost, is

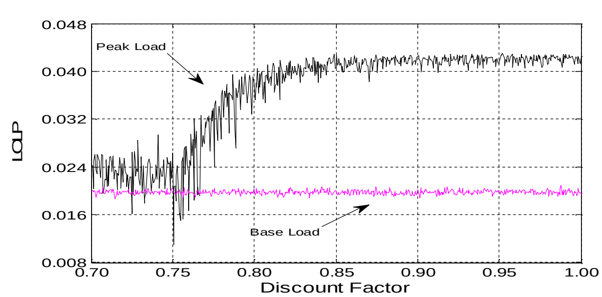

Fig. 6 Reliability index of LOLP

shown in Table I. The parameters for learning algorithm are listed as follows: $\varepsilon = 0.3$ and $\eta = 0.35$. The selected contribution was bounded by 0.9 and δ is set to 0.8. The caps

For the first results, concerning the 100 rounds that elapsed since the game started, the focus was on the aggregated supply function (ASF) during typical peak and off-peak hours in which there was no pivotal firm in the market. In Fig. 4, quite meaningfully, it can be seen that the firms learnt to rely on the capacity withholding during peak hour and on slope competition during off-peak hour. The firms adopted slope competition approach because the contribution of the pivotal position was bounded by $\alpha_{\max} = 0.9$. Therefore, during off-peak hour, although the strategic sellers with reinforcement learning try to create capacity shortage by converging to tacitly colluded strategies, this iterative process will not finally reach the feasible capacity withholding circumstances owing to the price takers' ability to cover more than 43% of the off- peak demand. Strategic sellers could compete, in a radical manner, for 6*10=60% of the off-peak demand by selecting their own contributions close to $\alpha_{\max} = 0.9$. Consequently, in the presence of price takers, the capacity during the off-peak period far exceeds the demand and, therefore, strategic sellers cannot be a collusive pivotal cartel. That is, even though converging to the maximum pivotal position could not provide firms with optimal capacity withholding opportunity and the slope competition in the best interest of the price taker is in the best interest of price makers. Peak hour, in contrast to off-peak hour, would provide the firms with capacity withholding opportunity; from Fig. 4(b), it can be seen that price taker currently meets strictly below 24% of the demand. It is clear that it is better off for the firms to conform to the capacity withholding strategy by converging to the contribution of pivotal position ranging from $\alpha_i = 0$ to $\alpha_i = 0.9$. Obviously, at this time, as the firms get more aggressive by approaching $\alpha_i = 0.9$, the expected market capacity shortage will asymptotically reach close to 100 - (24+6*10) = 16% of the peak-hour demand. Thus, it makes sense that to assume that price makers evolve their strategies even if the price taker bids full capacity. Therefore, some of the feasible capacity shortage, ranging from 0 to 16% of the demand, might arise in the market outcome.

These remarkable bidding decisions, along with different emergent strategic behavior, slope competition during base load and capacity withholding during peak load, suggest the need for a closer look at the detailed decisions. C2 and C3 as samples of representative non-pivotal firm are selected. The variables are with superscripts “b” and “p” for the base and peak segments, respectively. The simulation results, Fig. 5(a), have demonstrated that the firms learn to avoid creating a pivotal cartel. α_i and $p_{i,w}$ have converged to zero, implying that a pure strategy of full capacity bidding is dominant. A direct result of peak load is that, in contrast to base load segment, when the share of price taker is such that price makers can impose capacity shortage on market, collusive contributions can be supported for a wide range of capacity withholding strategy. Fig. 5(b) shows that this will be the case when both probability of choosing capacity withholding strategy and relevant contribution are allowed to take values. After playing the double price cap game and observing the vertical segments of bidding decisions, we were determined to address how the probability of choosing capacity withholding strategy affects the reliability index of loss of load probability (LOLP). In other words, we want to cope with the question of how the fictitious binding capacity constraint, devised from the collusive vertical segments of bidding decisions, can exacerbate the problem of short-term generation adequacy. The values of reliability indexes are computed using conditional probability on the values of probability of choosing capacity withholding. Physical outage rate of generation side portfolio

Table 2 Five cases with different profiles of discount factors

	C1	C2	C3	C4	C5	C6
Case1	0.2	0.3	0.3	0.4	0.4	0.4
Case2	0.8	0.8	0.8	0.8	0.8	0.8
Case3	0.6	0.6	0.6	0.6	0.6	0.6
Case4	0.7	0.7	0.7	0.6	0.2	0.2
Case5	0.9	0.4	0.9	0.9	0.1	0.1

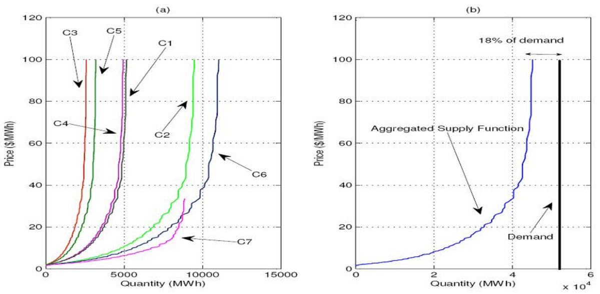

Fig. 7 Average LOLP of the system per round consisting different profiles of the discount factors

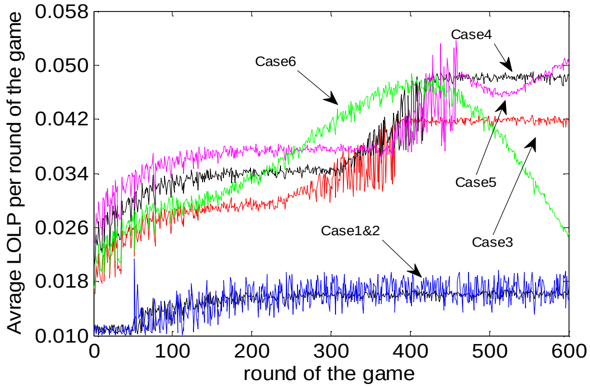

Fig.8 (a) Individual bidding decisions and (b) ASF of case 2

is also considered using the upper bound of the Mont Carlo simulation. As can be seen from Fig 6, during base load segment, while the discount factor is varying from myopic firms with low discount factors to foresight firms with high discount factors, LOLP is uniformly distributed and is not influenced by the strategic behavior of price makers. In this case, LOLP is just due to the physical generation outage. This is consistent with the results of Fig. 4(a) where the price makers were incapable of creating a pivotal cartel. During peak load segment, LOLP suffers from a growing trend that has been started when the discount factors reached a critical value. The pattern of this trend is consistent with Folk theorem. In this case, when the discount factor reaches its critical value, firms are capable of engaging in tacit collusion and capacity

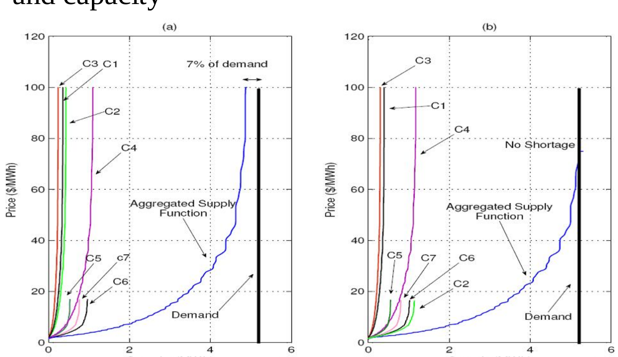

Fig. 9 (a) Individual bidding decisions and (b) ASF of case 3

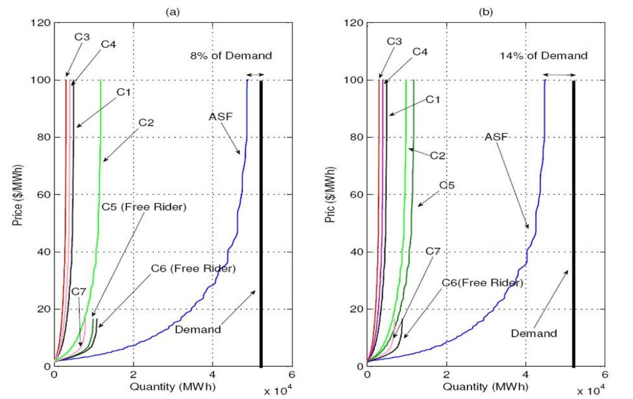

Fig. 10 Individual and aggregated bidding decision of the firms in the (a) upper and (b) lower side of the LOLP fluctuations

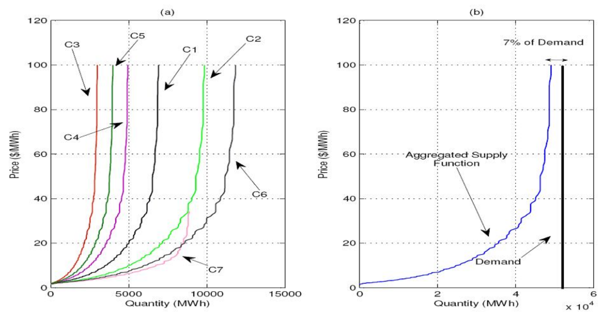

Fig. 11 Individual and aggregated bidding decision of the firms in the (a) upward and (b) downward rounds of the average LOLP

withholding, dropping the operative capacity in the market and exacerbating the reliability index of LOLP.

Another interesting application of the simulation consists in comparing homogeneous and asymmetric preferences emerging endogenously through the discount factors. To ensure consistency and eliminate errors due to randomly distributed initial selected contributions, the simulation results of peak hour were averaged over 20 runs, lasting 600 rounds each. It is attempted to form a plausible explanation to why different preferences adopt strategic behavior and how it affects the reliability indexes as a whole when it happens. For this, five cases with different profiles of discount factors are shown in Table II. Under this scenario, where the average LOLP of the system per round is under investigation (Fig 7), one can see that different structures of the preferences have substantial effects on the pattern of system reliability indexes. As shown in the figure, differences exist in the patterns of the average LOLP between market outcomes that use different profiles of discount factors. In case 1, evolutionary traces for the asymmetric setting of the firms, characterized by δ in the ranges of (0.2, 0.4), show that the average LOLP attained the lowest value after 600 rounds. This evolutionary path contains no significant upward trend, indicating that the firms are ineligible for convergence to the optimal capacity withholding strategy. In comparison to this, in case 2, the firms characterized by $\delta = 0.8$ may experience an upward deviation and reach higher average LOLP as their strategies converge to the tacit collusion and capacity withholding. It also provides a clear indication of the collusion in cases 3 and 4 wherein the firms with homogenous and asymmetric preferences contribute and thus the average LOLP per round experiences the same upward trend. Case 5 of asymmetric oriented preferences, appears to reach collusion because of the upward trend in the LOLP pattern, but the sustainability of collusion is doubtful. In this case, where the firms convey a deeper gap in their preferences, one can clearly see the collapse of tacit collusion and LOLP. In case 5, after applying capacity withholding as a market power to raise the LOLP, the firms can interact with each other by evolving their strategies and suddenly giving birth to a downward slide of LOLP.

In the collusive cases, despite the same underlying upward trends in the average LOLP, which results from the aforementioned homogenous and asymmetric discount factors, the eventual LOLP that the system may derive shows some differences. Moreover, when asymmetric case 4 is capable of inflicting capacity shortage, the pattern of LOLP demonstrates some fluctuating behavior by the firms in the subsequent rounds of capacity withholding. On the other hand, such coalitions can disband when the firms suffer from diverse preferences and regress to a divisive state, case 5. These remarkable observations, along with different rounds marked by upward trend, suggest the need for a closer look at the detailed bidding decisions with different profiles of discount factors. Scrutiny of the collusive cases mentioned above could shed some light on the features of the discount factors that average LOLP patterns ignore. Figs. 8 and 9 show the bidding decisions and the ASF of the firms in cases 2 and 3. All the price makers of case 2 are unanimous in assuming that the firms are pivotal (Fig. 8 [a]), and that the capacity shortage margin of 18% rises simply by collusion of vertical segments (Fig. 8 [b]), so that the firms are cooperative; they are conformist in attempting to do what they believe others are also doing. In case 3, the lowering of the homogenous discount factor produces a similar capacity shortage, albeit with less aggressive firms (Fig. 9 [a]), converging to a less capacity shortage margin of 7% (Fig. 9 [b]). Reducing the intensity of the discount factors and supporting more moderate contribution selection clog the capacity withholding. Thus, capacity shortage is realized in the market, where all the firms collectively put the shortage into practice with lower pace and margin. Knowing these reasonable details of bidding helps one understand what the round of upward trend, as well as what the converged LOLP of such homogenous cases 2 and 3 must be. While less aggression leads the average profit of case 3 to rise in a more recent round, less converged capacity shortage margin provides case 3 with a higher average LOLP as they appear in Fig. 7.

To illustrate the fluctuating behavior of case 4, detailed bidding decisions are introduced in the rounds where the fluctuation is from one extreme to the other. In the lower and upper sides, Figs. 10(a) & 10(b) show what bidding decisions are made for the given firms characterized by asymmetric discount factors in the range of (0.2, 0.7), respectively. ASF have evidently converged toward capacity withholding, and it just so happens that some firms are inconsistent with this strategy. The result of this case denotes the emergence of a dynamic post-cooperation behavior. Firms of oligopoly are seen to initially make collusion and temporarily form a unisonous cartel. One or more of these implicit partners, C5 and C6 in the upper side and C6 in the lower side of fluctuation, may, however, ultimately engage in self-oriented defections, breaking the tacitly colluded vertical segments of the bidding decisions. When these divisive firms, characterized by lower discount factors, realize a cheating condition, they are prompted to abandon their vertical bidding decision and selfishly look for a slope competitive bidding. In this case, they engage in full capacity bidding and acquire a high market share, pushing the capacity shortage margin toward the brittle value of 8%. From a myopic perspective of choosing a selfish contribution, it is not surprising that the capacity shortage margin appears to fluctuate. Interestingly, the foresight firms C1, C2, C3 and C4, which apply high discount factors, are authoritative enough in taking a pivotal position to execute and in bidding vertical segments to survive the capacity shortage. Thus, myopic firms, characterized by lower discount factors, are able to free ride on the exercise of capacity withholding by the foresight firms. That is, myopic firms enjoy capacity shortage without any contribution.

To sustain an implicit collusion of capacity withholding, the firms must remain homogenously loyal to the vertical segment of bidding decisions, as in cases 2 and 3, or the foresight firms in asymmetric environment must be authoritative enough to struggle and suppress the conspiracy of myopic firms that engage in free riding by bidding full capacity. The mere possibility of free riding poses a big challenge to the strategic behavior of foresight firms. In case 4, it has been explained how foresight firms can retain, although with some fluctuations, the original capacity shortage via vertical segments. Unfortunately, from the perspective of foresight firms, there is no genuine method to guarantee a priori that they can permanently impose an unconditional restraint on the myopic firms and retain the original collusion. For a better understanding of the struggle of counter oriented firms, further discussion must focus on the detailed bidding decision of case 5, wherein the system endures an upward trend and enjoys a downward trend in the scheme of average LOLP pattern. Fig. 11(a) shows that, in the round where the average LOLP experiences an upward trend, C1, C3 and C4 with high discount factors, and C2 with relatively moderate discount factors, have greater dominance than the firms C5 and C6 that choose the strategy of not to conform. After the collusive period, firms follow the interaction path given by the evolutionary strategies. This successive reciprocal process, along with different preferences it entails, will intensify the role of the intermediate firm C2. When this firm enjoys a collusive market outcome, as can be seen in Fig. 7, it is prompted to abandon the bidding strategy it has been following and look for a more profitable one (see Fig. 11[b]). Contrary to case 4, where the market is biased in favor of capacity withholding, defection of firm C2 leads to reversing the bias in favor of full capacity bidding. With deeper gap being modeled as counter offensive firms, C5 and C6 contrast sharply with C1, C3 and C4, thus facilitating the intermediate firm C2 to take over the role of the dominant player that determines the market outcome. This appears, as can be seen from Figs. 7 and 11(b), to be a good testing ground to examine whether foresight firms are authoritative enough to cope with nonconformist rivals. In this case, the existence of the intermediate oriented firm poses a threat to the collapse of collusive withholding for which the foresight firms have no satisfactory preemptive solution to retain the original collusion. Thus, it is not surprising that the average LOLP switches over to a downward trend.

5. Conclusion

Through agent-based simulation and examination of double price cap electricity market, it is shown that there are non-pivotal firms whose collusive behavior of capacity withholding can deteriorate reliability index. Thus, the illusion of a simple regulatory intervention of price caps is absent and repeated auction paradigm, as in the case in actual electricity markets diverts pro-competitive regulatory intervention to pro-collusive catalyst. To illuminate the nature of capacity withholding and tacit collusion behind it, a bidding model has been developed in this study, according to which, each firm independently decides how to choose its contribution to capacity withholding. The next step was to establish plausible reasons for resultant market outcomes, demonstrating a significant connection between scarcity, capacity withholding, and price caps. It is shown that this simulation framework is suitable and versatile enough to deal with a range of issues including the level of authority by which the non-pivotal firms can create a pivotal cartel, different strategies in different load segments of load duration curve, price takers whose full capacity bidding restrains the price makers from capacity withholding, and the extent to which reliability index are affected by capacity withholding and tacit collusion.

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