An Adaptive Learning Game Model for Interacting Electric Power Markets

Christos C. Skoulidas, Costas D. Vournas and George P. Papavassilopoulos

Abstract— **In the present paper a simulation model of two interacting electric power markets is being introduced, with or with no restriction in the interconnection capacity, in order to study the behavior of the energy price under two different pricing methods: Uniform Pricing and Pay-As-Bid. The model simulates the operation of the two markets as a stochastic adaptive Nash game, where players use a learning algorithm to maximize their profit and counterbalance their lack of information. The comparison of the results between the independent operation of the markets and the one of the interacting operation shows that lower prices are recorded when both interconnected systems apply Uniform Pricing and markets are oligopolies, whereas higher prices arise when both markets apply the Pay-As-Bid rule and tend towards perfect competition. In the case where the two interacting markets apply different pricing methods the differences observed in the independent market operation are blunted and prices tend to converge in intermediary price levels. Finally, constrained interconnection capacity leads to slightly higher prices at all instances.**

Keywords: Adaptive Learning, Game Theory, Power Markets, Deregulation.

I. Introduction

The deregulation of electric power systems experienced in many countries in the last decades, along with the trend and prospect to merge national markets into wider regional markets, increases the necessity for further study of these markets. For regulatory authorities and system operators attention is mainly focused on issues related to the operational behavior of the market and players, price formation mechanisms and the identification of a proper regulatory framework that ensures competition, efficiency and security of supply. On the other hand, power generators focus more on the safe transition from the traditional to the new deregulated business environment seeking at the same time for new opportunities to increase profitability (see Ilic et al. (1998), Schweppe et al.(1988) and Fink et al. (1998)). All these issues become more complex, however, when examining the case of interconnection or integration of independent power markets, which may operate under different rules and conditions. Undoubtedly, there are many ways to approach an issue of such extensiveness and complexity, one of which is to use a game theory approach. (see Ilic et al. (1998)) Many considerable and interesting attempts have been made to cope with these issues, using game theoretical models (see Torre et al. (2004), Xiaomin Bai et al. (1997) and Ferrero et al. (1998)) and this paper further contributes by putting in the approach of stochastic adaptive games using learning algorithms, in order to study interconnected deregulated power systems.

The model we introduce is a generic model of a power market and it does not offer a detailed simulation of a power system. It aims to study price trends and market participants' behavior, when power markets with different or similar rules and operating conditions, come to restricted and/or unrestricted integration. Technical details, such as different generation technologies and costs, discrete (block-type) generation offers, demand forecasting, proximity of generators to the physical interconnections, or existence of transmission fees, cost of ancillary services, ramp up times for the thermal units etc., could certainly increase the model's simulation accuracy and complexity. However, they have deliberately not been included in the modeling since the emphasis is on the general trend of results and not on a specific market analysis.

The original model of a power market presented as an adaptive learning game (see Skoulidas et al., (2002)) is here used in a rather extended version, in order to study the contemporary trend and need for power markets integration. Simulation focuses on price trends for all possible combinations of cases where integrated markets (i) operate under the same or different pricing regime and (ii) the interconnection capability is restricted or unrestricted. The same comparisons are conducted for all the intermediate market types, regarding the number of participants, from oligopoly to perfect competition.

More specifically, we introduce a non-cooperative game with incomplete information in a market model of two interconnected power systems each one with its own Independent System Operator and a number of generators who have the ability to participate in both markets. Participants have learning skills which they use to counterbalance the lack of information. All possible combinations of two different pricing rules (Uniform Pricing and Pay-As-Bid) are examined and results concerning price behavior for different number of participants are compared to the ones that arise when the two markets operate independently. At the same time the impact of the interconnection capacity on game results is examined by comparing the cases of theoretically infinite interconnection capacity, the one of constrained capacity and the case where the two markets are not interconnected. Additionally, the experimental results of the latter case are compared to theoretical solution of the corresponding Nash game.

II. DESCRIPTION OF THE MODEL

A. *The Market Model*

The modeled market consists of two individual power systems, each one of them comprising:

1) An Independent System Operator (ISO), who receives the offers being submitted by generators and purchases quantities from them aiming to cover, in the most economically efficient way, system demand D_s and

2) N Power Generators (players), each with a capacity range $[Q_{i_{\min}}, Q_{i_{\max}}]$ and total generation cost can sufficiently approximated as an incremental quadratic function of the following form (see Ilic et al. (1998)):

$$TC_i(Q) = FC_i + a_i \cdot Q + b_i \cdot Q^2 \qquad (1)$$

where FC_i is generation's fixed costs and a_i, b_i the cost coefficients $(a_i, b_i > 0)$.

The two power systems are interconnected and generators are allowed to submit offers in any of the two systems, or even to both of them by splitting their offered capacity, irrespective of their physical location. However, market clearance is conducted separately for each system by the corresponding System Operator and takes into account only the offers submitted to that system. Generation quantities generated in one system and sold to the other are offset, always in respect of the existing interconnection capacity, so that physical power transfer takes place only from the one system to the other (Fig. 1).

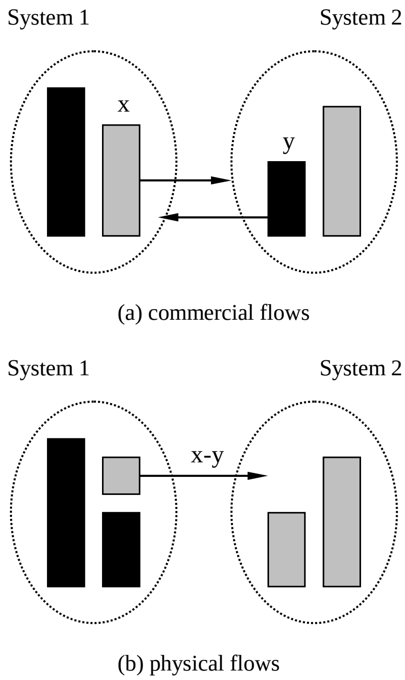

Fig. 1. The general market model of the two interacting power systems where (a) the commercial and (b) the physical flows between the two systems. The black and grey blocks correspond to generation that is (a) sold to and (b) consumed in System 1 and System 2 respectively, where *x* and *y* are the quantities sold from one system to the other while *x-y* is the quantity that is physically transferred.

The total interconnection capacity is defined as the sum of the capacities of all the physical interconnections between the two systems. Due to the generic nature of the model, we also assume that there are no limitations on transmission capability of generation from one point to another within each system. Although transmission fees may have some effect on price, they have not been taken into account in the model since they would increase its complexity without affecting the resulting price trends.

Each generator submits one offer in the form of a Price-Quantity curve for its entire generation capacity range, defining which part is offered to the one system and which to the other. Offers must be in the same form of generators marginal cost function, i.e. an increasing linear function:

$$P_i(Q) = A_i + B_i \cdot Q \qquad (2)$$

where $A_i, B_i > 0$, the offer coefficients.

The generators can modify the offer coefficients according to their own free judgment. However, the offered price must not exceed, for any generation quantity level, a specified upper price bound (*Price Cap*) that is defined for each system by the corresponding System Operator. The Price Cap is set significantly higher (e.g. 10 times more) than the price where each system would balance if all local generators had offered their entire generation capacity to that system at their marginal cost. The total capacity of generators located in one system exceeds sufficiently the total demand of that system. Demand may vary both in its maximum value and in its elasticity parameters.

Each System Operator may apply one of the following pricing methods for generators remuneration:

1) The *Uniform Pricing* method, where the generators are paid for the entire generating quantity they sold in that system at the *System Marginal Price* (SMP), defined as the offer price of the most expensive quantity needed to cover the demand.

2) The *Pay-As-Bid* pricing method, where the generators are paid for the different levels of generated quantity at the price they have defined in their offer.

The two power systems can operate under the same or different pricing rules. Though an exhaustive comparison of the two pricing rules has already been done (see Skoulidas et al., (2002)), we here focus mostly on market operation in case of interconnected systems applying the same or different price rules.

B. *The Adaptive Learning Game*

Each generator only knows its own production cost, its previous offers and the corresponding payoffs. Actually, this is a Nash game where players are not aware of the costs, the choices and the results of their competitors (see Basar and Olsen (1982)) and therefore they use a stochastic adaptive learning algorithm to counterbalance this lack of information and at the same time to maximize their profit (see Lakshmivarahan (1981) and Papavassilopoulos, (1989)) .

The game consists of n sequential rounds and the generators remain in the game regardless of their effectiveness to get a market share. At each round, they are allowed to modify one of their offer coefficients (A_i or B_i) by increasing, decreasing or keeping its value constant. Their choice each time is randomly made out of a probabilistic distribution of the potential actions, which is gradually and continuously revised by appraising the impact of the last readjustment of the same offer coefficient in its income, by awarding or punishing the corresponding action.

Generators can modify just one of the offer coefficients, at each round, and only the same coefficient for a predefined number of sequential rounds (modification period). The duration of these periods may vary per generator and per coefficient and it is assigned at the beginning of the game. The modification of the coefficient consists in the increase or decrease of the coefficient's value by a small percentage called *step* (e_{Ai} and e_{Bi} respectively). The third option that the generators have is to maintain the same value of the coefficient (stabilization). Different step values per generator and per cost coefficient reflect the differences in generators' reactivity pattern.

For each offer coefficient the action (increase, decrease or keep the same) to be followed is randomly selected by a probability distribution of values corresponding to each action. Therefore, to each coefficient per generator correspond three probability values P^{in}, P^{de}, P^{st} which refer to the three actions respectively, such that for generator i:

$$P_{i_A}^{in} + P_{i_A}^{de} + P_{i_A}^{st} = 1$$

$$P_{i_B}^{in} + P_{i_B}^{de} + P_{i_B}^{st} = 1 \qquad (3)$$

In each round, generators compare their payoff, in terms of profit, with the one of the previous round and if an improvement is recorded they increase the probability value of the last randomly chosen action (reward) by a small percentage, called *adaptivity step* (t), and equally decrease the values of the other actions. In case that the result is inferior to the one of the previous round the probability value of the last selected action is decreased (punishment) by the same step t and the probability values of the other two actions are respectively increased. The new randomly chosen action from the adjusted probability distribution determines the value of the offer coefficient and consequently the next offer. Modifications of the actions probability distribution values are always made with regard to the equations (3). The adaptivity step size can differ per generator, signifying diversification in the generator learning capability (see Skoulidas et al. (2002)).

The generators can split their offer, if they consider it purposeful, by offering the first part of their capacity to the one system (*primary system*) and the second part to the other (*secondary system*). It is important to define the primary system both for the generator and the game in the sense that, the primary system always receives the offer for the lower part of its capacity, cost wise (Fig. 2). The location of the generator is significant only at the commencement of the game, since this generator shall consider as primary system the one where it is located.

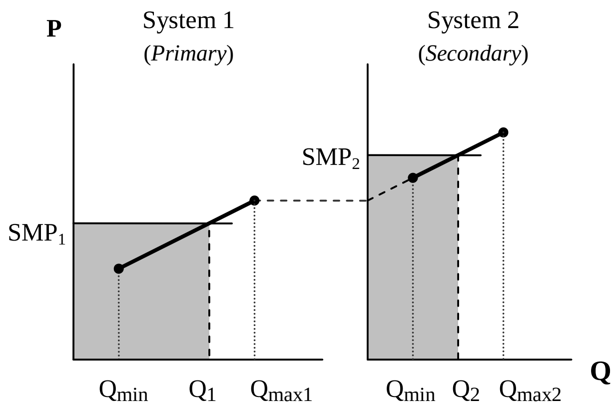

Fig. 2. Illustration of a generator's offer in two systems along with the generated quantities (Q_1 and Q_2) and corresponding revenues (shadowed areas) in Uniform Pricing. The generator allocates its maximum generation capacity (Q_{max}) in the two systems (Q_{max1} and Q_{max2} respectively) as shown, considering System 1 as primary.

Throughout the game, generators may change primary system many times, depending on the game evolution. The offer of each generator is considered to be uniform and simply one part is submitted to the secondary system, depending on which system the generator considers primary at the specific stage of the game, irrespective of its location. For each generator the results arising from both systems in every round of the game are evaluated by the learning algorithm in their entirety.

The decision process affecting the distribution of the offered capacity in the two systems is not entailed in the same adaptive learning process that forms and evaluates generators offers. It rather operates autonomously and consists in evaluating the sales efficiency by comparing the short term average profit per unit sold to each system. Thus, when the profitability of sales becomes more attractive in one system than its corresponding in the other system by a specific size (*tolerance*) then the generator increases the quantity offered to the more attractive system by a small predefined percentage. Again, these two magnitudes can differ per generator reflecting, thus, differences in their behavioral attributes.

It is obvious, that if a generator submits offers to both systems at least the technical minimum must be offered to each one. Practically, this means that the generator each time can modify the distribution of the offered capacity in the two systems, only for the part of its total capacity that is equal to the difference of its maximum capacity minus two times its technical minimum. Should a generator, at a certain stage of the game, sell only its technical minimum to the less attractive system, he cannot transfer this quantity to the other system, no matter its attractiveness, except in the case that he fails to sell it. Then and only then the generator may offer in one system its entire capacity. The only possibility to submit again an offer to what is now considered as secondary system, is when the generator is not able to sell in the primary system the quantity equivalent to its technical minimum and in addition the secondary system is more attractive on the given moment.

C. Congestion

In the theoretical case of unconstrained interconnection capacity between the two systems, the outcome of the game is not affected by the generator location since all transactions are normally executed. However, in the event of a constrained interconnection capacity then congestion may be recorded. In terms of the game, this may occur if after the clearance of the two markets the total quantity of power that has to be transferred from one system to the other exceeds the interconnection capacity. In this case, a selection from the power quantity to be dispatched by generators located in the adjacent system is made based on the cost efficiency of their initial offers. The resulting energy deficit in the affected system is then covered by local generation, initially been offered to that system but failed to be sold. Since these quantities concern more expensive generation we normally expect an increase in the electricity price of that system. Generators of the other system that were obliged to reduce their generation due to the interconnection capacity constraint are not compensated for the quantities that finally did not generate.

III. Results and Conclusions

A. The Performed Games

In the framework of the present paper, we studied the behavior of two interconnected systems under all pricing methods combinations and for a different number of generators each time. More specifically, we examined the case where both System Operators apply the same pricing method (either Uniform Pricing or Pay-As-Bid) and the case where they apply different method in each system. In order to facilitate the comparison, it was considered that both systems have each time the same number of generators with similar technical features (generation technology, cost and capacity) and exactly the same learning skills and behavioral attributes. Generators capacity and costs are randomly spread within an interval ±25% from the corresponding values of the first generator who participates in all the games irrespective of the number of participants. For all the aforementioned combinations of pricing methods equivalent games were applied with 4, 6, 8, 10, 12, 14, 16, 18 and 20 generators in each system. For simplicity reasons we assumed that demand in each system remains constant and inelastic. More specifically, the demand in each system was set equal to one third of the maximum capacity of all generators installed in the corresponding system.

To evaluate the game results, equivalent games were applied in two power systems and in a single power system under the same rules and conditions. However, the game comparison in a single and in two systems, especially when comparing sizes such as the power price, is qualitative rather than quantitative. Additionally, the game results from the single system are compared to the theoretical Nash Equilibrium solution of the game.

Finally, regarding the interconnection capacity, all the games related to two systems were applied with:

(a) Unconstrained interconnection capacity and

(b) Interconnection capacity equal to 30% of the total capacity of the generators installed in the first system.

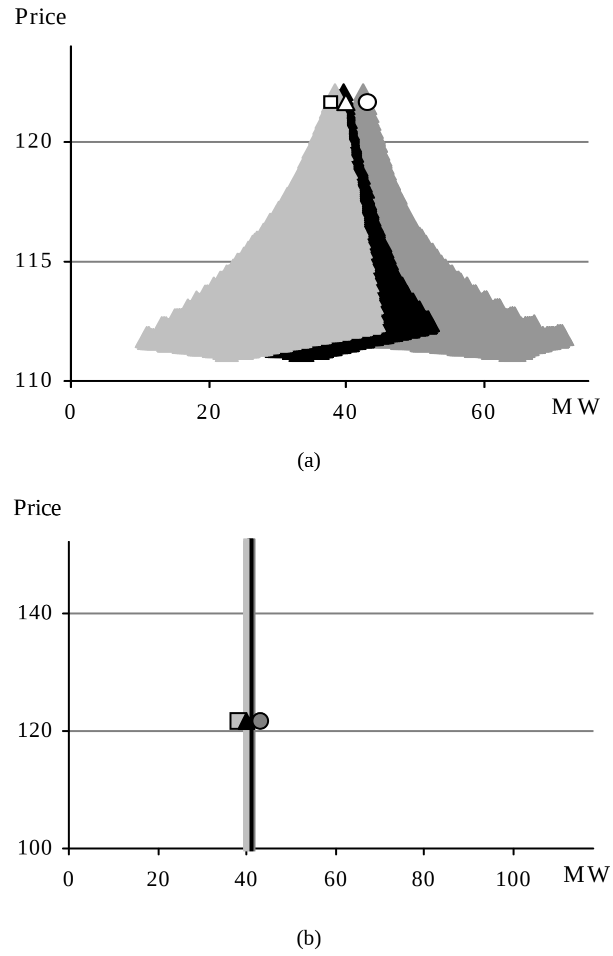

Fig. 3. Comparison of the Nash Equilibrium solutions and of the modeled game results for one market with 3 generators. Both Uniform Pricing (a) and Pay-As-Bid (b) result in multiple Nash equillibria (shaded areas). Moreover, the model converges in certain Nash solutions (square, triangular and round marks) which are always Nash equillibria.

Each game consists of 500,000 rounds of offer submissions and market clearances and as game results are considered the convergence values of the game payoffs. Every such game is successively repeated 100 times, and the average values of the results are finally taking into account. Thus, 3.6 billion market clearances were totally performed in 7,200 repetitions of 72 different games. A special software application was developed in Visual Fortran programming language in order to model and perform the games.

B. The Nash sub-game

The model results concerning the independent market operation are compared with the Nash equillibria of that game in order to evaluate the adaptive learning game model described above and its results. For demonstration reasons and in order to facilitate the comparison we present a simple game with only three generators applying both pricing methods. In the case of Uniform Pricing the game has multiple Nash equillibria which in a price-quantity graph are concentrated in a rather small area compared to the area that all possible outcomes would define.

Figure 3.a illustrates the corresponding Nash solutions for the three generators (the 3 triangle-like shaded areas). The solution areas consist of points that represent a price-quantity pair. To every point of one generator's area correspond two other points, each one of them located in the other two areas. These three price-quantity pairs define a Nash equilibrium.

For each generator the results of the same game performed by the adaptive learning model are always within the corresponding Nash equillibria area and in addition, result values converge impressively close to the most profitable point of the area. This means that the generators are led by the adaptive learning model close to the most attractive solution amongst all Nash equillibria.

In the Pay-As-Bid game we also have multiple Nash equillibria which correspond to equal market shares for all generators at all possible price levels. In Figure 3.b these equillibria are illustrated as three vertical lines, one on to the other, at the one third of the system's demand. However, in this case the model result values converge very close to that specific level of generation but much lower than at the maximum price level allowed (Price Cap).

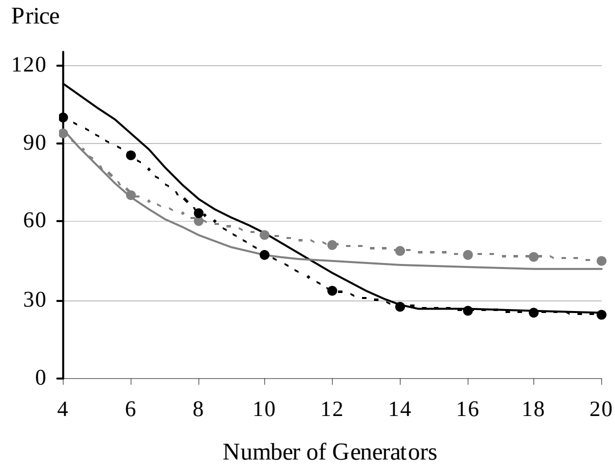

Fig. 4. Relation between the electricity price and the number of generators in two systems operating under the same pricing rule: either (a) Uniform Pricing (black lines) or (b) Pay-As-Bid (grey lines). The dashed lines correspond to interconnected market operation and the continuous lines to independent market operation.

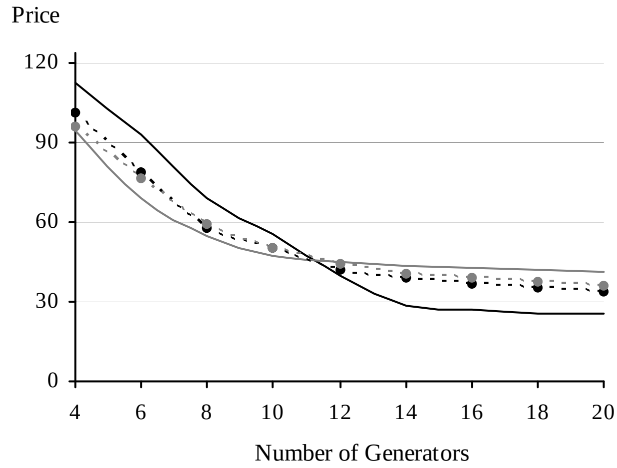

Fig. 5. Relation between the electricity price and the number of generators in two systems operating under different pricing rule: (a) Uniform Pricing (black lines) and (b) Pay-As-Bid (grey lines). The dashed lines correspond to interconnected market operation and the continuous lines to independent market operation.

C. The Interacting Markets Game

In the case of the unconstrained interconnection capacity and when both systems operate under the same pricing method the prices of both systems always converge almost on the same price. Furthermore, when Uniform Pricing is applied, the price in the two interconnected systems, compared to the price resulting from the independent operation, converges at a lower level when markets are oligopolies and at the same level as the markets tend towards perfect competition. On the contrary, when the Pay-As-Bid method is applied the price in both interconnected systems converges at the same level with the independent market operation under Pay-As-Bid, but at relatively higher level as the markets moves to perfect competition (Fig. 4).

When applying different pricing methods in the two interconnected systems, the resulting price is different in each system for any number of generators. However, the wide variations recorded when the same markets operate independently are now blunted and tend to converge in intermediary price levels (Fig. 5).

Finally, the results from the same games with constrained interconnection capacity reveal that limitation in interconnection capacity leads to higher power price in both systems, irrespective of the pricing method applied. This is due to the fact that the limitation impedes the participation of more generators that would probably result in a further price reduction through competition.

As a general conclusion regulators, market operators or governments should encourage the establishment of close and organized co-operation between their markets. It seems that wide scale cross-border commercial transactions and trading between power markets can boost competition, increase overall efficiency and lead to lower price levels. However, the above positive effects resulting from markets integration can be significantly restricted by capacity limitations of the physical interconnections.

A further extension of the presented work could be the use of the model for the performance of games between interacting markets with heterogeneous characteristics concerning e.g. the type and the size of the generators or the demand. A more interesting extension could be the cost assessment for the use of limited interconnection capacity between electric power systems.

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CAPTIONS

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