Power Engineering Letters

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Adaptive Game Modeling of Deregulated Power Markets

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Abstract: We describe an adaptive game representation of a deregulated power market consisting of an independent system operator (ISO) and power generators (players) who submit their offers to the ISO in the form of curves. The power generators do not know the costs, the offers, or the payoffs of their competitors and, therefore, they use an adaptive learning tool to compensate for their lack of knowledge in trying to maximize their profit. The ISO purchases energy from the generators, starting from the more economical offer in order to cover the electricity demand. Sequential iterations of the game for different numbers of participants and with varied adaptation and reaction capabilities are conducted in order to study the impact on spot price convergence and volatility, and the corresponding cost for the ISO. After repeated runs of the simulation model, many interesting phenomenon have been observed regarding the spot price behavior and the stability of the market.

Keywords: Adaptive learning, game theory, power markets, deregulation.

Introduction: The ongoing restructuring of electrical energy markets, combined with the experience of California's electricity market crisis, motivates further analysis of the energy markets and the behavior of their participants in the new deregulated environment. Power generators, challenged to act in this new business environment characterized by imperfect information and the absence of historical data, are interested mainly in issues such as strategy formulation and risk minimization, while regulatory authorities and organizations, designated to ensure security of supply and to eliminate market power, address issues concerning the formation and optimization of the regulatory framework, competition, and price mechanisms [1], [2].

Many attempts were made to cope with the newly emerged issues concerning the deregulated electricity markets [3] and a number use game theoretical models [4]-[6] to approach various market structures with different rules and assumptions. The present paper introduces a different approach to study electricity markets, using a power market model where players with adaptive learning skills act in an incomplete information environment. More specifically, we simulate a deregulated power market consisting of an ISO and independent power generators who know only their own cost, previous offers, and corresponding payoffs. Generators use a stochastic learning algorithm in order to maximize their profit. Each generator readjusts its offers by altering its offer curve parameters. Randomly chosen values from a probabilistic profile of behavior define the readjustment of the offer for each generator. This behavior profile is gradually and continuously formed by evaluating the impact of its last readjustment of the offer curve to its income. In fact, we are dealing with a Nash game [7] where players don't know each other's costs, actions, or payoffs and, therefore, they use an adaptive learning scheme to counterbalance their lack of knowledge [8]-[10]. The present paper focuses on the impact of the number of market participants and of their adaptation and reaction capability, on-spot price volatility, and convergence.

Description of the Game: A general theoretical model of a power market, based on some simplified assumptions, has been developed in order to apply the learning process and study the behavior of the market through it. The modeled power market consists of:

- An ISO whose aim is to cover the demand D and therefore purchases electricity from the power generators starting from the lower offer
- i power generators (players) characterized by a capacity range $[x_{i_{\min}}, x_{i_{\max}}]$, which implies that for each generator there are: (*i*) a *technical minimum* below which the generator cannot operate and (*ii*) a *maximum output* that can be generated. The total generators capacity exceeds the expected demand. Generator *total cost* is given by a quadratic function of the following form:

$$TC_i(x) = FC_i + a_i x + b_i x^2 \quad (1)$$

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

The generators submit their offers in the same form as of their marginal cost, i.e., $MC_i(x) = a_i + 2b_i x$, by increasing, decreasing, or keeping constant their offer curve coefficients. Their choice is made randomly and is defined by a probabilistic distribution of their potential actions. Each generator submits its offer for its whole capacity range in the form of an increasing linear function such that the offered price does not exceed the upper bound that the ISO sets for the offered prices (*price cap*). A price cap is determined approximately as a multiple of the price where power generators would balance if they submit their actual marginal cost.

The *system's marginal price* (SMP) is set as the lower price level where the corresponding offered quantities are equal to or exceed the demand. This principle, combined with the constraints set by the generators' capacity range and the fact that there is no demand side bidding, may create discontinuity problems and may oblige the dispatching of a generator at its technical minimum even though this exceeds the demand. Generators are paid at the SMP the whole quantity they sell to the system operator (*uniform pricing*). In Figure 1 we illustrate a system with three power generators who submit offers for their range of capacity and the system operator covers the demand D, purchasing only from two of them (x_2 and x_3, respectively, such that $x_2 + x_3 = D$) at the SMP.

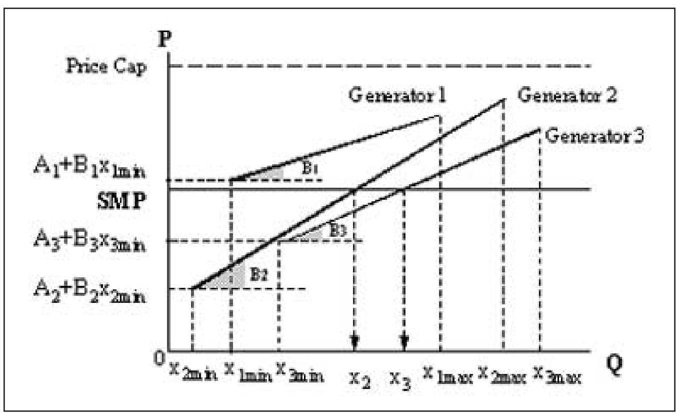

Figure 1. Calculation of the SMP and the corresponding power generation in a system with three power generators, where only two of them are dispatched

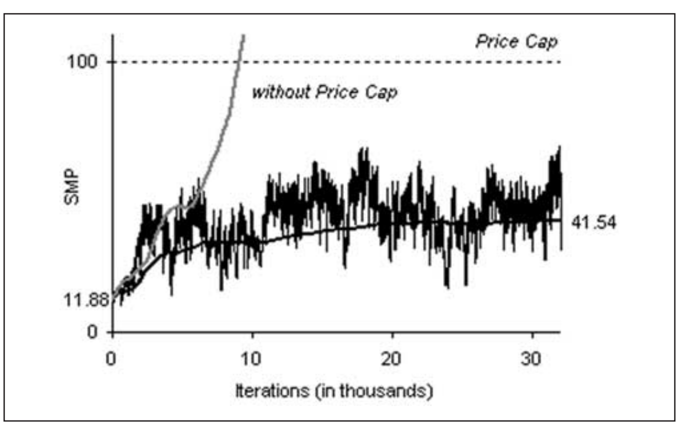

Figure 2. SMP for a ten-players game with step e=5% and its moving average with and without the price cap constraint

During the game, generators submit offers for n sequential rounds and remain into the game even if they don't manage to get a market share for long periods of time. The generators do not know each other's costs, offers, and payoffs and at the end of each round are acquainted only with their own market share and the SMP. They compare the result, in terms of profit, with that of the previous round and if it is better they reward the last randomly chosen action by increasing its probability in the probability distribution of potential actions. Otherwise, they decrease that probability value. New randomly chosen values from the adjusted probability distribution define the next offer. The sizes of the alterations in the actions' probability values and in the values of the offer curve coefficients are defined at the beginning of the game and they are called steps. Thus, during the game each player gradually forms a probabilistic profile regarding its potential moves, which is actually a behavioral tool based on its recent experience, guiding him to react proportionately to different market's trends.

Starting the Game: The first offer that the players submit to the system operator is their actual marginal cost and has the following form:

$$F_{i_1}(x) = A_{i_1} + B_{i_1} x, \quad (2)$$

where

$$A_{i_{1=}} = a_i \text{ and } B_{i_1} = 2b_i. \quad (3)$$

The SMP and dispatched generation (x_{i_1}) for each generator are then calculated. The corresponding net revenue for each player is

$$J_{i_1} = x_{i_1} . SMP1 - TC_i\left(x_{i_1}\right). \quad (4)$$

At the end of the round, generator i knows only the SMP and the quantity x_{i_1} the ISO purchased from it.

At the beginning of the next round, generators may modify their offer, before they submit it to the system operator, by changing the values of the coefficients $(A_{i,}, B_{i,})$. Players can modify one of the coefficients of their offer 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 player and per coefficient, and it is assigned at the beginning of the game.

The modification of the in turn coefficient consists in the increment or decrement of the coefficient's value by a percentage equal to the corresponding step (e_{Ai} or e_{Bi}). A third option players have is to maintain the same value of the coefficient (stabilization). We can assign different step values per player and per cost coefficient in order to portray the differentiation in players' reaction capabilities.

The *action* (increase, decrease, or stabilization) to be followed is randomly selected from a probability distribution of values corresponding to each action. Therefore, to each coefficient per player correspond three probability values P^{in}, P^{de}, P^{st} (increase, decrease, stabilization), such that for player i

$$P_{i_A}^{\ in} + P_{i_A}^{\ de} + P_{i_A}^{\ st} = 1 \quad (5)$$

$$P_{i_B}^{\ in} + P_{i_B}^{\ de} + P_{i_B}^{\ st} = 1. \quad (6)$$

The initial, arbitrarily defined, probability distribution of the three actions for each coefficient might not necessarily be equiponderant regarding the actions.

During round n, the randomly selected action, depending on the in turn coefficient's modification period, defines the new coefficient values of the offer to be submitted to the system operator, as follows:

If modification period for A: $A_{i_n} = A_{i_{n-1}} .(1+\varepsilon)$ and $B_{i_n} = B_{i_{n-1}}$ or

If modification period for B: $A_{i_n} = A_{i_{n-1}}$ and $B_{i_n} = B_{i_{n-1}} .(1+\varepsilon)$

where

$$\varepsilon = \begin{cases} e_{A_i} \text{ or } e_{B_i} & \text{if the selected action is } \textit{increase} \\ 0 & \text{if the selected action is } \textit{stabilization} \\ -e_{A_i} \text{ or } -e_{B_i} & \text{if the selected action is } \textit{decrease}. \end{cases}$$

The net revenue J_{i_n} for player *i* resulting after round *n* is compared with the net revenue $J_{i_{n-1}}$ of the previous round and the probability distribution of player's available actions is then adjusted. If, for player *i*, the difference $(J_{i_n} - J_{i_{n-1}})$ corresponding to two sequential rounds is positive, then the probability value of the selected action in round *n* is increased (*reward*) by a predefined step θ, expressed as a percentage, and the probability values of the other two actions are equally decreased. In the case where the net revenue is inferior to the one of the previous round, the probability value of the selected action is decreased (*punishment*) by the same step θ and the probability values of the other two actions are equally increased. Step size can be different per player, signifying diversification in players' learning capability.

An Application of the Game: Based on the power market model and the game described above, we applied a limited version of the game with specific features in order to test the model and extract some general conclusions. Therefore, some parameters of the game were assumed static while differentiation among players was minimized.

More specifically, we assumed that electricity demand *D* remains constant throughout the game and each time is equal to the half of the summation of maximum outputs of all the players participating in the game. Generators have the same generation capacity range (7 MW - 15 MW), and they all use the same fuel and the same generation technology (e.g., small oil-fired steam plants). Their fixed cost (FC_i) and cost coefficients (a_i, b_i) are randomly spread within an interval ±25% from the corresponding values of the first player. For player #1 we consider

$$FC_1 = 7{,}000 \quad a_1 = 8.40 \quad b_i = 0.00020.$$

All players are considered as equivalent regarding their adaptation and learning capability, and therefore the values of steps *e* and θ are equal for all players and all coefficients in each game. The initial values of probability P^{in}, P^{de}, P^{st} that correspond to the three actions are taken also to be equal per player and per coefficient while they vary per action

$$P_i^{in} = P_i^{de} = 35\% \quad \text{and} \quad P_i^{st} = 30\%.$$

The number of consecutive iterations defining each coefficient modification period for each player is randomly selected from a common interval of values between 30 and 80 offers. The random values applied in the first game remain the same for all the repeated games. The price cap is set up to 100, which is approximately ten times more than the initial SMP.

Every game consists of 32,000 consecutive offers (iterations), and experience gained from these offers is used only during the current game, while repetitions of the same game start from zero point regarding players' experience. Ten (10) different game types, with 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20 players, respectively, were simulated, assigning in every game type, equally in amount the values of 2%, 5%, 10%, 15%, and 20% to step *e*. On the other hand, the value of step θ was set equal to 5% for all the game types and their repeated simulations. Each game type has been repeated 100 times, raising thus the total number of conducted games to 5,000 and the total number of rounds to 160 million.

In the two-players game type only the first two players participate (#1 and #2) and each time we proceed to the next game type (e.g., four players) we add the next two players in the row (e.g., #3 and #4). Thus, the first two players take part in all the executed games while the last two players (#19 and #20) only in the 20-players game type.

For every game and iteration the following are recorded: a) SMP, b) players' market shares x_i and revenues, c) offer curve coefficients A_i, B_i, d) surplus capacity purchased by the ISO and corresponding cost, and e) moving averages of all the precedents. Great importance for the necessary comparisons have the first value of SMP in each game, when offers are the actual marginal cost, the market shares players obtain at the first round of each game, and the actual cost coefficients (a_i, b_i) of each player.

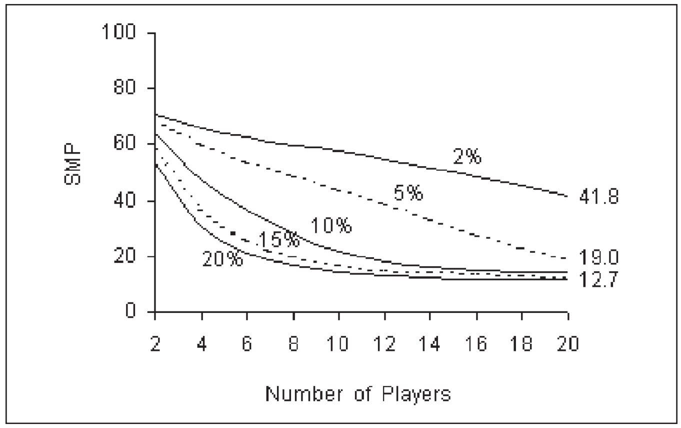

Figure 3. Average SMP in function of number of players for various adaptability levels

Results and Observations: Although intense variations of the SMP have been observed during the games, its moving average converges and it converges always to higher value levels compared to the initial SMP of the corresponding game. Two main factors seem to affect SMP's behavior:

- The number of players participating in the market affects the convergence value of SMP's moving average and the time SMP takes to converge as well. Namely, SMP converges at a higher value and at a slower rate as the number of market participants was decreased.
- Players' adaptation ability strongly affects SMP's convergence value in a similar way the number of participants does (i.e., the higher the value of step *e*, the lower the value and the faster the rate that SMP converges). However, greater values of *e*-step lead to greater volatility of the SMP and, consequently, to a more unstable market. Figure 3 illustrates the way SMP is affected by the number of players and the value of step *e*.

The basic conclusion is that participants in a power market where prices are defined through an offer-based procedure with uniform pricing tend to lead prices, through their offers, at levels significantly higher than these of their real marginal cost. However, prices gradually decrease as the number of players increases, i.e., as competition increases. It has also been observed that the more aggressive generators' behavior becomes (i.e., by allowing them to alter each time their offers within a wider range of values), the lower the spot price converges, though its volatility considerably increases. On the other hand, the system operator is obliged to dispatch larger quantities of extra capacity as the number of participants decreases and as generators' reaction capabilities become more restricted. The impact of generators' adaptability on the surplus energy purchases does not seem to be of the same importance as that of the number of market participants.

Limited numbers of additional runs, conducted without the price cap constraint, have shown that SMP does not converge in that case as players, through their offers, lead the price continually at higher levels for their own benefit. The relation of price cap level and SMP convergence, quantitatively defined, thus introduces an interesting issue for further research. Another interesting field currently studied is the use of the same theoretical modeling in a pay-as-bid pool market in order to compare the behavior of the market for the two different pricing approaches.

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Power Engineering Letters

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IEEE PES contracted with Scholar One to develop a Web-based submission and review process for Power Engineering Letters. This is the same arrangement we have for the three PES *Transactions*. The new Web site (http://pesl-ieee.manuscriptcentral.com) allows authors to submit (upload) their Letters manuscripts electronically.

Currently, Power Engineering Letters submissions are sent to editor-in-chief Mohammed El-Hawary. After 1 August 2002, he will no longer accept hard copy. Any letters received after that date will be returned for direct upload by the author.

The same author upload process has been in effect for the *Transactions* papers since January 2002. Although a slightly different version of the software has been implemented for the Power Engineering Letters site, the process is basically the same.

It is expected that the Manuscript Central upload and review process for Letters will add the same improvements as it did for the *Transactions* papers: simplifying the author's submission, adding online tracking capability, and improving the turnaround time for decisions.

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