Strategic Behavior Assessment in an Oligopolistic Electricity Market

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Abstract: - The paper adopts the Conjectural Variation model for investigating firms' strategic behaviors in the wholesale electricity market. The aim of the proposed approach is providing market actors with a tool able to simulate the oligopolistic market models. The tool, utilized by a Generating Company (GenCo), permits to foresee the rivals' behaviors and builds the suitable supply bid curve for its own generating units. If a Market Operator adopts the tool, it is possible to detect if and how a GenCo exercises the market power. The procedure is applied to a market place composed by 5 GenCos sharing 54 generating units.

Key-Words: - Oligopolistic Electricity Markets, Strategic Behaviors, Conjectural Variation model

1 Introduction

The emergent electricity market structure is more akin to oligopoly than perfect market competition. In an oligopolistic market, the action of one producer has an influence on the overall market, and prices and payoffs are influenced by the behavior of the producers. Very often, this influence on the market payoffs turns into manipulating prices that rise unreasonably well above the competitive market level (*market power*) [1].

A company has market power if it can influence the market equilibrium point. Where there is a price maker, there is some degree of market power. Typical mechanism by which firms exercise market power is the strategic bidding that involves bidding prices significantly above the marginal production costs, with the intent of forcing up the market-clearing price. Strategic bidding is facilitated when market structure requires the bids to be submitted by generating companies (GenCos) for the next 24-hour period. However, the fluctuations of demand over the day must be at the basis of the formulation of supply bids to the Market Operator (MO). A further element that a GenCo bidding-strategy has to take into account is rivals' reaction. The type of reaction has a crucial impact on the market results and, in particular, on bidding strategies. The literature provides various types of interactions ranging from intense competition to collusion.

According to the type of strategic variables by means of which the competition takes place and the way each firm anticipates the rivals' reaction to its decisions it is possible to classify the model of oligopolistic competition [2].

In *Bertrand competition model*, the strategic variables are the prices that each competing firm chooses to maximize its profit, considering as fixed the prices of its competitors. Less intense, and more commonly assumed, is *Cournot competition*, where the strategic variables are the quantities and each firm recognizes that its own decision affects the price though it assumes that such decision does not affect those of any other firms[3, 4]. The competition in which all players compete by their price-quantity functions is termed *Supply Function competition* [5], and is the basis of several power market models [6-8].

In this paper, the *conjectural variation* (CV) approach [9] is adopted for assessing GenCos' strategic behaviors in an oligopolistic competition. The basic idea is to consider that each firm expects a one-unit change in its quantity to lead to a variation of the *conjectural parameter* in the other firms' output. By varying the *conjectural parameter*, different strategic solutions, from the most competitive to the most collusive one, can be obtained [10]. The proposed procedure provides GenCos with a tool able to simulate the market equilibrium taking into account the possible firms' interactions, through the CV approach, and builds the strategic bidding curves that match the evaluated equilibrium point. If used by the MO, the tool permits to detect if and how a GenCo exercises market power.

2. Strategic behaviors in a competitive market

In a competitive environment, the GenCo decision problem is to maximize its own profit. Let us suppose that n_C GenCos are present in the market and denote the output of each generating firm as P_G^{ν} (for all $\nu = 1,...,n_C$)

$$\pi^{\nu} = \rho \cdot P_G^{\nu} - C\left(P_G^{\nu}\right) \quad (1)$$

where ρ is the spot electricity market price and $C(P_G^{\nu})$ the production cost.

It should be noted that in an oligopolistic market model, the spot price is not an external variable, as it is in the perfect competitive market model [11], but it is highly dependent on the total amount of power supplied. This means that the spot price can be represented as:

$$\rho = \rho\left(P_G^{1},\ldots,P_G^{\nu},\ldots,P_G^{n_C}\right) \quad (2)$$

or $$\rho = \rho\left(P_G^{\nu}, \boldsymbol{P}_G^{-\nu}\right) \tag{3}$$

where $\boldsymbol{P}_G^{-\nu} = \left[P_G^1, .., P_G^{\nu-1}, P_G^{\nu+1}, .., P_G^{n_C}\right]$, and each firm can affect the ρ-value by choosing a specific supply function. Thus the profit of the ν-*th* firm is a function of the outputs of the other firms and the eqn. (1) becomes:

$$\pi^{\nu}\left(P_G^{\nu}, \boldsymbol{P}_G^{-\nu}\right) = \rho\left(P_G^{\nu}, \boldsymbol{P}_G^{-\nu}\right) \cdot P_G^{\nu} - C\left(P_G^{\nu}\right) \tag{4}$$

The first order conditions for profit maximization are:

$$\frac{\partial \pi^{\nu}}{\partial P_G^{\nu}} = 0 \tag{5}$$

for all $\nu = 1, ..., n_C$.

By solving the n_C+1 system of equations given by (3) and (5), the market equilibrium can be obtained.

Most of the issues discussed in the followings, centre around how firms can implement profit maximizing actions. In mathematical terms, the results will depend on the assumptions made about the derivatives $\partial \boldsymbol{P}_G^{-\nu} / \partial P_G^{\nu}$ in differentiating the eqn. (4) to maximize the profit. In economic terms, the central question concerns how the ν-*th* firm assumes other firms react to its decision.

2.1 The Conjectural Variation model

The first-order conditions for maximizing eqn. (4) become:

$$\frac{\partial \pi^{\nu}}{\partial P_G^{\nu}} = \rho + P_G^{\nu}\left[\frac{\partial \rho}{\partial P_G^{\nu}} + \frac{\partial \rho}{\partial \boldsymbol{P}_G^{-\nu}} \frac{\partial \boldsymbol{P}_G^{-\nu}}{\partial P_G^{\nu}}\right] - MC\left(P_G^{\nu}\right) = 0 \tag{6}$$

for all $\nu = 1, ..., n_C$, where $MC\left(P_G^{\nu}\right) = \dfrac{\partial C\left(P_G^{\nu}\right)}{\partial P_G^{\nu}}$ is the marginal cost.

Under the assumption that no collusion occurs among firms, the expression of the derivatives $\partial \boldsymbol{P}_G^{-\nu} / \partial P_G^{\nu}$ will be speculative. Models based on various assumptions about its expression are termed *Conjectural Variation* model. That is, they are concerned with firm ν's *conjectures* about other firms' output variations. In this case, the firm is not only concerned with how its own output affects market price directly, but also it has to consider how variations in its own output will influence market price through their effect on other firms' output decisions. It can be noted that classical market strategic interactions can be obtained by the CV model assigning particular values to the *conjectural parameter* $\partial \boldsymbol{P}_G^{-\nu} / \partial P_G^{\nu}$.

2.2 Market Strategic Interactions

The definitions below refer to a kind of competition among suppliers in which all players get the market-clearing price, disregarding the fact that the demand is spatially distributed over a network.

<u>Cournot model</u>: In this model, it is assumed that each firm recognizes that its own decisions about P_G^{ν} affect the price but that any one firm's output decision does not affect those of any other firm. That is, each firm recognizes that $\partial \rho / \partial P_G^{\nu} \neq 0$ but assumes that $\partial \boldsymbol{P}_G^{-\nu} / \partial P_G^{\nu} = \boldsymbol{0}$. Using these assumptions, the first-order conditions for profit maximization are:

$$\frac{\partial \pi^{\nu}}{\partial P_G^{\nu}} = \rho + P_G^{\nu} \frac{\partial \rho}{\partial P_G^{\nu}} - MC\left(P_G^{\nu}\right) = 0 \tag{7}$$

for all $\nu = 1, ..., n_C$.

As it can be noted in this equation, the firm assumes that changes in P_G^{ν} affect its total revenue only through their direct effect on the market price of its own sales.

<u>Price Leadership model</u>: The market model in question is composed of a single Price-Leader and a fringe of Price-Takers (or followers). The relationship with previous model consists in the fact that the Price-Leader assumes a Cournot behavior trying to maximize its own profit on the basis of the consideration that $\partial \boldsymbol{P}_G^{-\nu} / \partial P_G^{\nu} = \boldsymbol{0}$, whereas each Price-Taker makes its bid supposing that its decision will not affect market price.

<u>Perfect Competition model</u>: In this model, each firm is a price taker. That is, each firm assumes that its decisions will not affect market price. In this case, the first order condition for profit maximization of the ν-*th* GenCo is that:

$$\frac{\partial \pi^{\nu}}{\partial P_G^{\nu}} = \rho - \frac{\partial C\left(P_G^{\nu}\right)}{\partial P_G^{\nu}} = 0 \tag{8}$$

for all $\nu = 1, ..., n_C$.

This corresponds to say that the spot price ρ equals the supply marginal cost $MC\left(P_G^{\nu}\right)$.

3. A Procedure for Strategic Behavior Assessment

The aim of the proposed approach is to provide the market participant with a tool able to foresee each other responses to its output in order to choose the best strategic bid for every generating unit. These strategic bids must be submitted to the wholesale electricity market whose organization is based on a compulsory power pool structure where all buying and selling activities converge under the MO control [12].

The methodology is made up of four different steps, and it is supposed to be applied for each hour of the day. The first step of the approach consists in building the firm aggregated cost curve for different levels of the dispatched generation. The *inverse demand function* is fitted in the second step. In the third step, the equilibrium of the imperfect competitive market is evaluated, on the basis of a CV approach. Finally, starting from the equilibrium condition, it can go back drawing the generator strategic supply curves.

3.1 Firm cost curve fitting

For the *i-th* generator belonging to the ν-*th* firm a quadratic production cost is supposed:

$$c_{h_i}\left(P_{g_i}\right)=\alpha_i+\beta_i\,P_{g_i}+\gamma_i\,P_{g_i}{}^2 \quad (9)$$

The production level P_{gi} is constrained to vary between $\underline{P}_{gi}$ (lower bound) and $\overline{P}_{gi}$ (upper bound). Assuming that $\tilde{P}_G^{\nu}$ is the assigned total production of the ν–*th* company, the best way to share out it, among the generating units of the company, is by minimizing the total costs, that corresponds to solve the following economic dispatch (ED) problem:

$$\begin{cases} \min\limits_{P_{g_i}} \sum\limits_{i\in\nu} c_{h_i}\left(P_{g_i}\right) \\ \sum\limits_{i\in\nu} P_{g_i} = \tilde{P}_G{}^{\nu} \\ \underline{P}_{gi} \le P_{g_i} \le \overline{P}_{gi} \ \text{ or } \ P_{gi}=0 \end{cases} \quad (10)$$

Let $\tilde{P}_{gi}\left(i\in\nu\right)$ and $C(P_G^{\nu})$ be, respectively, the solution of the problem (10) and the corresponding total production cost of the ν-*th* company. By varying $\tilde{P}_G^{\nu}$ between the lower bound $\underline{P}_G^{\nu}=\min\limits_{i\in\nu}(\underline{P}_{gi})$ and the upper bound $\overline{P}_G^{\nu}=\sum\limits_{i\in\nu}\overline{P}_{gi}$, and repeatedly solving the ED (10), all the couples $C(\tilde{P}_G^{\nu})=\sum\limits_{i\in\nu}C_{hi}(\tilde{P}_{gi})$ and $\tilde{P}_G{}^{\nu}$ can be fitted into a curve to obtain the cost function of the ν-*th* firm. In particular, choosing a quadratic approximation, the production cost function can be written as follows:

$$\mathrm{C}\left(\mathrm{P}_G^{\nu}\right)=\alpha^{\nu}+\beta^{\nu}\cdot\mathrm{P}_G^{\nu}+\gamma^{\nu}\cdot\mathrm{P}_G^{\nu 2} \quad (11)$$

Consequently, the linear marginal cost function $MC(P_G^{\nu})$ is derived:

$$MC\left(P_G^{\nu}\right) = \beta^{\nu}+2\cdot\gamma^{\nu}\cdot P_G^{\nu} \quad (12)$$

3.2 Inverse demand function

In order to take into account the relationship between the spot price ρ and the total electricity demand P_D, the *inverse demand function* [13] is considered:

$$\rho=\rho\left(P_D\right) \quad (13)$$

The most fitting representations of the inverse demand function are [10]:

1) linear function

$$\rho\left(P_D\right)=b+a\cdot P_D \ ; \ a<0 \quad (14)$$

2) constant elasticity function

$$\rho\left(P_D\right)=\alpha\cdot\left(P_D\right)^{\frac{1}{\eta}} \ ; \ \eta<0 \quad (15)$$

Neglecting the transmission losses, the following balancing condition can be considered:

$$\sum_{\nu=1}^{n_C} P_G^{\nu}=P_D \quad (16)$$

Taking into account eqn. (16), in the eqn. (13) the spot price ρ becomes a function of companies' outputs P_G^{ν} (for all $\nu=1,\dots,n_C$):

$$\rho\left(P_G^1,..,P_G^{\nu},..,P_G^{n_C}\right)=\rho\left(P_G^1+..+P_G^{\nu}+..+P_G^{n_C}\right) \quad (17)$$

3.3 Strategic behaviors and market equilibrium

The market equilibrium problem is evaluated by simultaneously optimizing firm profits linked together through the market price [9] and the balance between generated and demanded power .

Detailing the $MC\left(P_G^{\nu}\right)$ according (12) and taking into account eqns. (13) and (16), the profit maximization condition (6) becomes:

$$\frac{\partial\pi^{\nu}}{\partial P_G^{\nu}}=\rho+P_G^{\nu}\frac{d\rho}{dP_D}\left[1+\sum_{\substack{j=1\\ j\neq\nu}}^{n_C}\frac{\partial P_G^j}{\partial P_G^{\nu}}\right]-\left(\beta^{\nu}+2\gamma^{\nu}P_G^{\nu}\right)=0 \quad (18)$$

for all $\nu=1,\dots,n_C$.

Let us assume $CV^{\nu}=\sum\limits_{\substack{j=1\\ j\neq\nu}}^{n_C}\frac{\partial P_G^j}{\partial P_G^{\nu}}$. This parameter represents the market conjecture of each firm in maximizing its own profit. If $CV^{\nu}=-1$ for all $\nu=1,\dots,n_C$, the *Perfect Competition model* is supposed for the market; whereas the condition $CV^{\nu}=0$ for all $\nu=1,\dots,n_C$ corresponds to a *Cournot model* of the market. When the *Price Leadership model* is assumed, two different values of the *conjectural parameter* have to be considered: $CV^{\nu}=0$ for the Price-Leader and $CV^{\nu}=-1$ for the Price-Takers. Stated these conditions, the market static equilibrium is evaluated solving the following set of n_C+2 equations in n_C+2 unknowns:

$$\begin{cases} \frac{\partial\pi^{\nu}}{\partial P_G^{\nu}}=\rho+P_G^{\nu}\frac{d\rho}{dP_D}\left[1+CV^{\nu}\right]-\left(\beta^{\nu}+2\gamma^{\nu}P_G^{\nu}\right)=0 \ \ \nu=1,\dots,n_C \\ \rho-\rho\left(P_D\right)=0 \\ P_D-\sum\limits_{\nu=1}^{n_C}P_G^{\nu}=0 \\ \underline{P}_G^{\nu}\le P_G^{\nu}\le\overline{P}_G^{\nu} \quad \nu=1,\dots,n_C \end{cases} \quad (19)$$

where the unknowns are the n_C companies' outputs P_G^{ν} , the spot price ρ and the dispatched load P_D .

3.4 Bid strategy evaluation for generating units

The solution of the system (19) provides the set of firms' outputs $P_G^{\nu *}$, the spot price ρ^* and the scheduled power demand P_D^*, that represent the profit maximizing equilibrium under the conjectures assumed by a GenCo. In order to implement the conjectured strategies, updated bid curves of every generating unit need to be assessed.

To this purpose the following procedure is adopted:

1) evaluating the set $\left\{P_{gi}^* \mid \text{for all } i\in\nu\right\}$;

2) building strategic bid curves for every generating unit.

The ν-*th* company needs to share the power $P_G^{\nu*}$, assigned by the market equilibrium condition, among its own generating units in the most profitable way. Therefore, the set of the dispatched powers of the generating units belonging to ν-*th* firm is obtained by solving the ED problem (10) setting $\tilde{P}_G^{\nu} = P_G^{\nu*}$.

According to the market rules, every firm has to submit bids for each of its generating units. The firm evaluates the strategic supply curve for the i-*th* unit forcing the curve matching the point $\left(\rho^*, P_{gi}^*\right)$ in the P_{gi}-ρ plane, so that the market outcomes correspond to the equilibrium price ρ^* and the minimum cost dispatched power P_{gi}^*. To obtain the strategic bidding curve for the *i-th* generating unit, different solutions are suggested in literature [8, 14] starting from the marginal cost curve. One model supposes to manipulate the interception with the ρ-axis as reported in Fig. 1, where β_i^{st} is the strategic parameter.

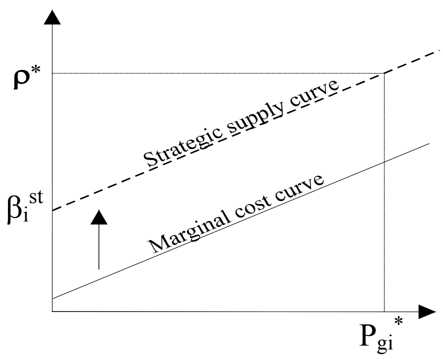

Fig. 1. The strategic supply curve due to parameter β_i^{st}

The strategic bid curve, in this case, is represented as:

$$\rho = \beta_i^{st} + 2\gamma_i P_{gi} \tag{20}$$

and β_i^{st} can be obtained from eqn. (20) substituting $\left(\rho^*, P_{gi}^*\right)$

$$\beta_i^{st} = \rho^* - 2\gamma_i P_{gi}^* \tag{21}$$

The second model considers as strategic parameter ξ_i^{st}, which multiplies both the intercept and the slope of the marginal cost curve as can be seen in Fig. 2.

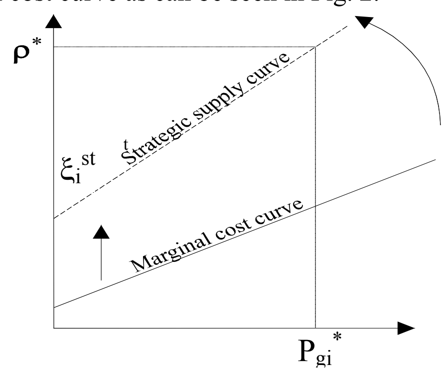

Fig. 2. The strategic supply bid curve due to parameter ξ_i^{st}

Then the strategic supply curve is represented as

$$\rho = \xi_i^{st}\left(\beta_i + 2\gamma_i P_{gi}\right) \tag{22}$$

Analogously the strategic parameter ξ_i^{st} is given by the following expression:

$$\xi_i^{st} = \frac{\rho^*}{\beta_i + 2\gamma_i P_{gi}^*} \tag{23}$$

3.5 The overall proposed procedure

The relationships among the steps of the proposed procedure for assessing strategic behaviors are summarized in the flowchart of Fig. 3.

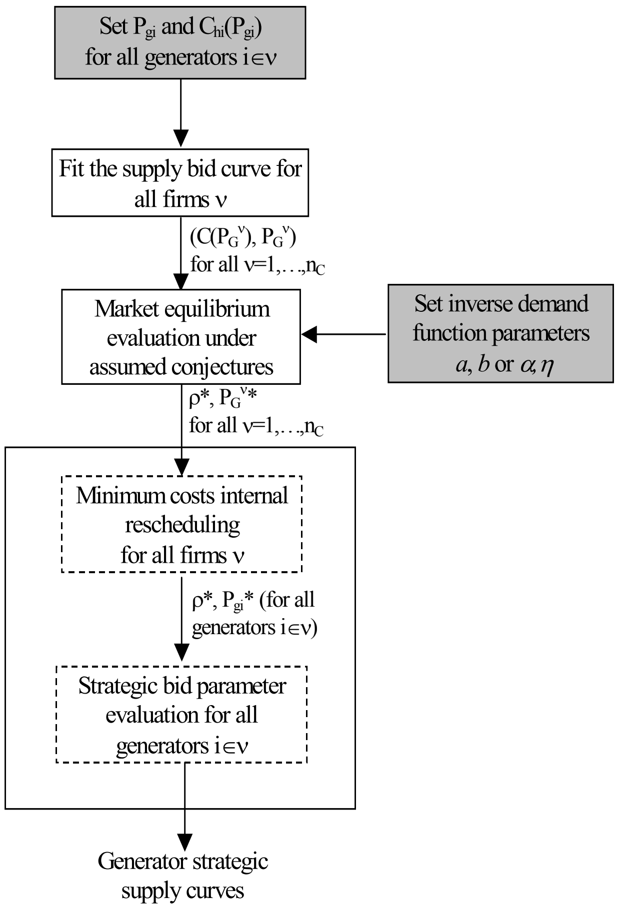

Fig. 3. The flowchart of the proposed approach.

On the basis of the production costs of the generating units and for a given inverse demand function, the cumulative bid curve for every firm is evaluated. Then the market equilibrium is obtained under specified conjectures, and the strategic bid curve is determined for each generating unit.

4. Test Results

In order to prove the effectiveness of the proposed approach, simulations have been carried out considering a marketplace with 5 GenCos that share 54 generating units. Basically, for rated powers and production costs, data of the standard IEEE-118 buses test grid have been assumed. The load profile over the next 24-hour period has been considered. For each hourly-demand level, a suitable linear inverse demand function according to eqn. (14) has been supposed.

The simulations have been addressed to put in evidence the effects of the conjectures on the market equilibrium (case 1). Furthermore, the influence of the different production technologies have been investigated (case 2).

Case 1. The conjecture influence on the market equilibrium

Principal data of every GenCo, for the selected marketplace, are shown in Table 1. Three production technologies have been considered: conventional steam-turbine generation (CSTG), combined-cycle gas-turbine (CCGT) and gas-turbine (GT).

We supposed that GenCo #1 makes conjectures on its own behavior and the rival GenCos' behavior.

Table 1. Production technologies

GenCo	Total Installed Power		No. of units	CSTG type	CCGT type	GT type
#	[MW]	%		[MW]	[MW]	[MW]
1	5345	54	29	4095	950	300
2	1405	14	6	600	805	0
3	781	8	3	781	0	0
4	1443	14	8	1443	0	0
5	992	10	7	692	200	100

To this purpose three types of interactions has been conjectured: Perfect Competition model (PCM), Cournot model and Price-Leader model. Since GenCo #1 has the greatest part of the installed power available in the market, it thinks it is the Price-Leader, in the third model. The Fig. 4 shows the behavior of spot price over the 24-hour period for the three types of conjectures.

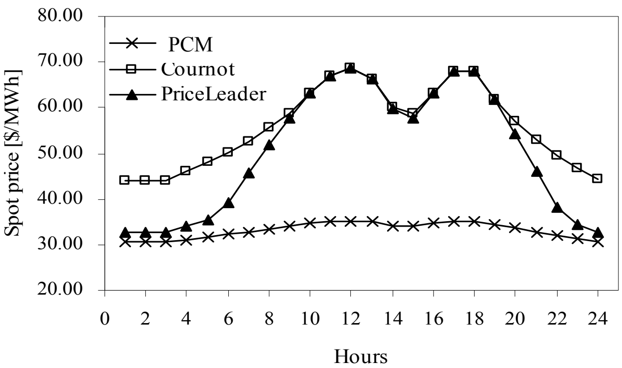

Figure 4. Spot market equilibrium behavior over the 24-hours

During the daily-peak load, the Price-Leader is able to raise the prices that assume the same values of the Cournot model. This implies an increase of the profits of all GenCos, which benefit by the high sale prices, since a uniform price market structure has been assumed.

The dispatched load is shown in Fig. 5. By comparing the various load profiles over the day, it can be noted that, when high prices are experienced by market, the dispatched load decreases due to the elasticity of the load demand curve.

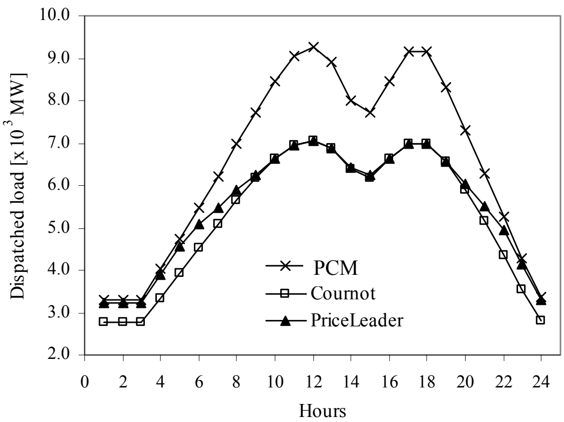

Figure 5. Dispatched load profile over the 24-hour period

The GenCo #1's profit is reported in Fig. 6. It can be seen how the adoption of Price-Leader behavior by GenCo #1 yields low profits (less than those obtained for the Cournot model) when load demand is low, and high profits during the daily-peak load. The rationale of this condition is that the Price-Leader is not able to influence the spot price during the off-peak periods.

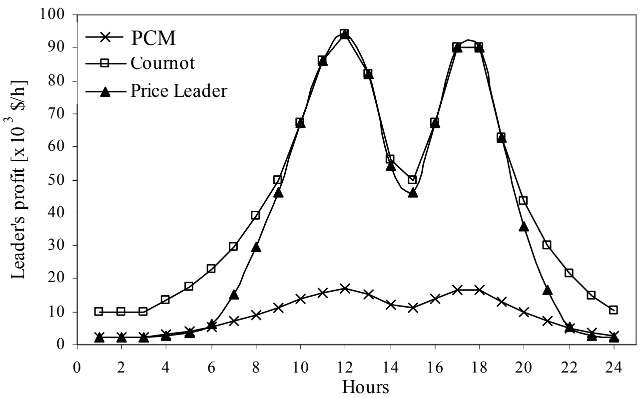

Figure 6. GenCo #1's profit over the 24-hours

On the basis of these considerations, the GenCo #1 draws up a strategy for all generating units bidding a supply curve able to match the equilibrium point evaluated for each hour of the day. The Table 2 shows the strategic parameters β^{st} , ξ^{st} and the dispatched load of the generating unit #29 (one of the greatest CSTG- 492 MW) belonging to GenCo #1 in different hours of the day. The original ρ-axis interception of the marginal cost curve of the unit #29 is β= 28.25 $/MWh.

As it can be noted in the fourth and seventh columns of the Table 2, during the off-peak period, the unit #29 is forced out of the market due to the high price of the strategic bid.

Table 2. The strategic parameters at unit #29

Hours	Cournot			Price-Leader		
	β^{st}	ξ^{st}	P_g	β^{st}	ξ^{st}	P_g
	$[\$/\text{MWh}]$		MW	$[\$/\text{MWh}]$		MW
2	44.14	1.56	0.0	32.60	1.15	0.0
4	44.25	1.57	0.0	33.90	1.20	0.0
6	44.56	1.58	0.0	39.18	1.39	0.0
8	53.35	1.82	227.2	50.41	1.74	156.4
10	60.37	2.04	257.8	60.37	2.04	257.8
12	65.47	2.18	314.6	65.47	2.18	314.6
14	57.80	1.96	234.4	57.35	1.95	234.1
16	60.37	2.04	257.8	60.37	2.04	257.8
18	64.65	2.15	313.4	64.65	2.15	313.4
20	54.55	1.86	228.3	52.01	1.78	227.5
22	49.58	1.75	0.0	38.12	1.35	0.0
24	44.30	1.57	0.0	32.70	1.16	0.0

Case 2. Production technology variation

In these simulations, the 44% of the generated power by GenCo #1, behaving as a Price-Leader, is supposed deriving by hydro-electrical plants. The Fig. 7 shows the profiles of the Leader dispatched power with 44% and 0% (case 1) of the hydro-electrical technology. Since the bid prices are assumed zero, the total amount of the available hydro-electrical power is dispatched over the 24-hour period. Because of the zero-production costs, the GenCo #1's profit is well above the values obtained in case 1, as can be observed in Fig. 8.

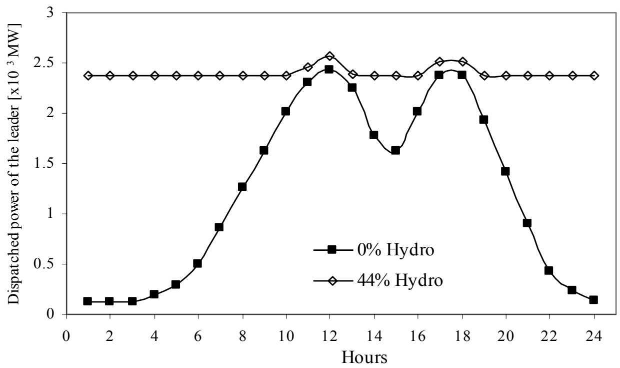

Fig. 7. The GenCo #1 dispatched power

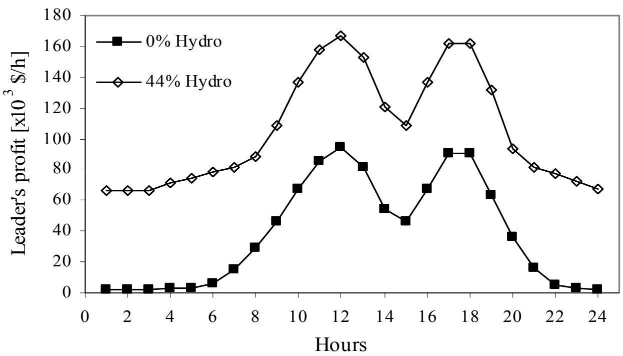

Figure 8. GenCo #1's profits over the 24-hours

Unlike the previous case, the adoption of a Price-Leader strategy by GenCo #1, leads to a condition where the remaining companies make the price, though they are bidding at the marginal costs.

The previously illustrated results show that the proposed approach proves to be useful to investigate various aspects of oligopolistic electricity markets.

5. Conclusions

Through the proposed procedure, market actors are provided with a tool able to simulate the market equilibrium taking into account the possible firms' interactions, through the CV model, and build the strategic bidding curves matching the evaluated equilibrium point. The flexibility of the approach has been proved by simulating possible conjectures on a marketplace where 5 GenCos are competing. The results of the simulations have put in evidence how the market equilibrium price can be affected by the conjectured firms' interactions. Furthermore, the market power exercised by the Price-Leader has been investigated with regard to the adoption of different production technologies and to an increase of the number of the GenCos competing in the marketplace.

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