Regulatory Support of Wind Power Producers against Strategic and Collusive Behavior of Conventional Thermal Units

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***Abstract*—Although wind power generation has extended a maturity in technology, there are still many concerns regarding the optimal support of regulatory bodies for renewable resources. In this context, the regulatory body should form a market structure or consider market rules and regulations to not only attract investors to renewable power plants, but also provide an efficient market that reflects a safe and clear competition environment. In this paper, an agent-based game-theoretic model is developed to investigate the electricity market behavior under oligopoly circumstances. The proposed model reveals the potential of collusive and strategic behavior of market participants. By employing the proposed model, impacts of different supportive schemes on the behavior of the wind power producer and conventional thermal units are investigated. According to the results obtained, if the regulatory bodies do not consider strategic collusion of market participants, adverse consequences for wind power producers might happen in the long-term horizon.**

***Index Terms*-- Collusive behavior, electricity market, regulatory body, strategic behavior, wind power producer.**

NOMENCLATURE

A. Indices (Sets)

i	index of Gencos
k	index of branches
m	index of coalitions
t (T)	index of time

B. Superscripts

cg	contingency
En	energy market
Res	spinning reserve market

C. Parameters and variables

a, b, c	cost coefficients of Gencos
d	demands
F	power flow
I	commitment binary variable
MD, MU	minimum down and up times
N	total number of Gencos
P, Q	active and reactive power
RD, RU	ramp down and up rates
SR	spinning reserve
t_c	time of explicit collusion
U	voltage magnitude
y, z	auxiliary variables to determine start-up and shut down times
δ	voltage angle
λ	price
$CollusionProfit$	obtained profit from explicit collusion

I. INTRODUCTION

A. Motivation and aims

Due to the increased environmental concerns and technological maturity of wind power generation, the deployment of this renewable resource in power systems has been growing throughout the world. However, the optimal support of renewable resources is still a major concern of regulatory bodies. On this basis, the regulatory body should support the wind power generation in order to attract investors to develop wind renewable power plants. To this end, the regulatory body forms a market structure or considers market rules and regulations. This should also provide an efficient market reflecting a safe and clear competition environment. In order to achieve this, the impacts of new forms of market structure or new rules and regulations should be simulated before implementation, because the experience of an electricity market cannot be directly utilized for another market. This paper aims at investigating the impacts of different supportive schemes on the behavior of wind power producers and conventional thermal units. To do so, a multi-agent model based on a game theory approach is developed to study the electricity market behavior under oligopolistic circumstances considering renewable energy resources i.e. under a market environment dominated by a small number of producers.

B. Literature review

Different models of oligopoly electricity market have been reported in the literature. The stochastic optimization [1], the incomplete information game [2], stochastic game theory [3], and the evolutionary game [4] are some of the reported methods to evaluate the market efficiency. Moreover, a large number of game-theoretic methods have been modeled the oligopolistic behavior of Gencos [5], [6]. Refs. [7] and [8] have gone a step further and modeled the oligopoly market considering network constraints using a DC power flow model.

There are several models of offering strategy in the literature like Bertrand, Cournot, Stackelberg and Supply Function Equilibria (SFE) [9]-[11]. Since the offered price in SFE is well associated with the offered quantity, it is the most accurate method to model the Gencos' behavior.

The regulatory body should detect Gencos with the potential of market power or collusion. Market participants can increase their market power by forming collusive coalitions; hence, it limits the consumers' benefits and consequently increases system costs. The market power is definitely a barrier for consumers' benefit because it deteriorates the advantages of the electricity market for customers [12]. Furthermore, some strategic behavior of market participants, such as limit-pricing, can significantly affect the market performance [13]. Thus, this kind of strategic behavior as well as collusive behavior should be modeled by the regulatory bodies and policy makers.

C. Background and Contributions

In this paper, a multi-agent game-theoretic model is provided to simulate the strategies of market participants in both energy and reserve markets in a 24-hours scheduling horizon. Due to the high accuracy of SFE in modeling the behavior of Gencos, this paper employs this model that enables market participants to choose both price and quantity for their offers. Moreover, the start-up and the shut down costs and operational constraints of thermal units such as ramp rates, minimum up/down times and prohibited operating zones are considered. Network and security constraints are also considered because there is a possibility that market participants manipulate these constraints to withhold power capacity and cause artificial congestion, which consequently reduce the market efficiency. To this end, security constrained unit commitment (SCUC) powered by an AC power flow model is utilized to clear the day-ahead electricity market.

This paper distinguishes tacit and explicit collusions from each other and separately investigates the impacts of market behavior arising from each collusion. The tacit collusion, also known as oligopoly behavior, can be introduced as the spontaneous cooperation obtained from strongly perceived interdependence that can set the market prices above the marginal costs. The rarely-reported explicit collusion is a secret agreement between some market participants in order to change the market prices to increase their joint profit.

Although many oligopoly market models have been reported in the literature, the presence of renewable energy resources has been rarely addressed. By employing the proposed model, impacts of different supportive schemes on the behavior of wind power producers and conventional thermal units are investigated.

To this end, various market rules and regulations are discussed and their impacts on collusive and strategic behavior of market participants are analyzed.

D. Paper organization

The remainder of this paper is organized as follows. Section II presents the proposed oligopoly electricity market model. In Section III, collusion and strategic behavior of Gencos are modeled. Section IV devotes to numerical studies. Finally, Section V concludes the paper.

II. The Proposed Electricity Market Model

In order to model the oligopoly electricity market, a multi-agent system based on bi-level optimization is developed. In the first level of optimization, each Genco is independently modeled as an agent, whose objective is to maximize its own profit, participating in day-ahead energy and reserve markets. The objective function of each Genco can be formulated as:

$$\text{Max}\{\text{Genco Profit}\} = \sum_{t=1}^{T} Profit_{i,t}^{Oligopoly} = \sum_{t=1}^{T} \left\{ \begin{array}{l} P_{i,t}^{En}\lambda_t^{En} + P_{i,t}^{Res}\lambda_t^{Res} \\ -\left(a_i P_{i,t}^2 + b_i P_{i,t}\right) - c_i I_{i,t} - \lambda_i^{up} y_{i,t} - \lambda_i^{down} z_{i,t} \end{array} \right\} \quad (1)$$

subject to:

$$P_i^{\min} I_{i,t} \le P_{i,t} \le P_i^{\max} I_{i,t} \quad (2)$$

$$I_{i,t} - I_{i,t-1} = y_{i,t} - z_{i,t} \quad (3)$$

$$y_{i,t} + z_{i,t} \le 1 \quad (4)$$

$$y_{i,t} + \sum_{j=1}^{MU_i - 1} z_{i,t+j} \le 1 \quad (5)$$

$$z_{i,t} + \sum_{j=1}^{MD_i - 1} y_{i,t+j} \le 1 \quad (6)$$

$$P_{i,t} - P_{i,t-1} \le RU_i + P_i^{\min} y_{i,t} \quad (7)$$

$$P_{i,t-1} - P_{i,t} \le RD_i + P_i^{\min} z_{i,t} \quad (8)$$

It should be noted that, λ_t^{En} and λ_t^{Res} are the prices of energy and reserve markets, respectively, and are obtained by a tradeoff between maximization of Gencos' profit and minimization of operation cost.

Constraint (2) denotes the unit output limits. It is noteworthy, when $I_{i,t}$ is zero, $P_{i,t}$ and consequently the fuel cost in (1) will be zero. Constraints of minimum up and down times are expressed in (3)-(6). Constraints of unit ramp up and ramp down are presented in (7) and (8), respectively.

At the end of the first level optimization, each Genco submits its offers to the market operator that is modeled by an SCUC problem. Therefore, in the second level, the market operator minimizes its objective function, that is the total operation cost. The interaction between these two optimization levels are carried out by using an iteration-based model presented in [14].

The SCUC solution determines the nodal prices and the quantity of each Genco. The objective function of the market operator is formulated as (9).

$$\text{Min}\{\text{Total Operation Cost}\} = \sum_{t=1}^{T} \sum_{i \in Gencos} \left(P_{i,t}^{En} \lambda_t^{En} + P_{i,t}^{Res} \lambda_t^{Res} \right) \quad (9)$$

subject to:

$$\sum_{i \in Gencos} P_{i,t}^{Res} \geq SR_t \quad (10)$$

Inequality (10) ensures the required spinning reserve. In this paper, the power flow solution in normal state and the sensitivity properties of the Jacobian matrix are utilized for power flow calculation in post-contingency. The state vector is computed and updated for small changes in power injections as (11) [15].

$$\begin{bmatrix} \Delta\delta \\ \Delta U \end{bmatrix} = [J_0]^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (11)$$

The Jacobian obtained at power flow in normal state is applied to calculate the changes in voltage magnitudes and angles in post-contingency. Hence, the obtained changes are added to the complex voltages of normal state to obtain post-contingency complex voltages. The details of the power flow formulation have been presented in [16].

Constraints (12) and (13) limit the power flow of branches in normal and contingency states, respectively.

$$-F_k^{\max} \leq F_{t,k} \leq F_k^{\max} \quad (12)$$

$$-F_k^{\max} \leq F_{t,k}^{cg} \leq F_k^{\max} \quad (13)$$

III. Modeling the Collusion and Strategic Behavior of Gencos

The electricity market model presented in Section II can simulate the oligopolistic behavior (i.e., tacit collusion) of market players; however, it is unable to consider the explicit collusion and strategic behavior of market participants. In order to model the explicit collusive and strategic behavior, in this section, two approaches are developed.

A. Modeling the explicit collusion

The explicit collusion is considered based on the concept that, after the market reaches the primary equilibrium presented in Section II, each Genco trials its interaction with other Gencos. To this end, each Genco takes part in several coalitions.

Each coalition aims at increasing its profit by changing the offers. The amount of increased profit is distributed among members of the coalition according to their internal agreement. On this basis, Gencos join a coalition where it can achieve the maximum profit.

Each collusion affects the offering strategies of the coalition members as well as the other Gencos, due to the game-theoretic model. On this basis, the profit of all Gencos is affected by explicit collusions. The flowchart of electricity market considering explicit collusion is shown in Fig. 1.

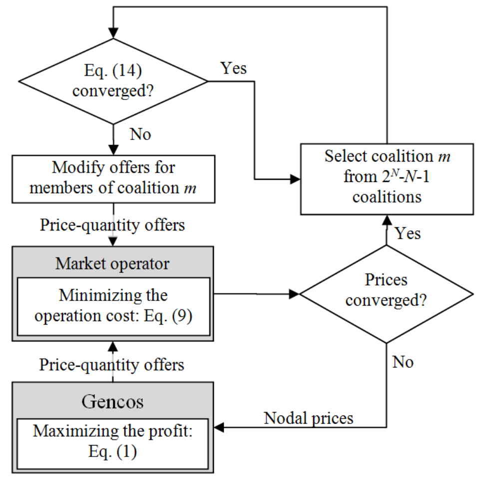

Figure 1. The electricity market flowchart considering explicit collusion

Based on Fig. 1, each Genco can trial participating in various coalitions. If N is the number of Gencos, in each hour 2^N combinations of coalitions are formed. Note that N combinations are single-member and one combination is associated with empty one (i.e., the primary equilibrium state). Therefore, $2^N - N - 1$ combinations of explicit collusion are taken into account.

For more clarification, if 3 Gencos take part in the market, 4 collusion combinations are formed as {*G1*, *G2*}, {*G1*, *G3*}, {*G2*, *G3*} and {*G1*, *G2*, *G3*}. It should be noted that, in each hour, each Genco can join only one coalition; thus, only one of the four combinations may happen.

Note that, in the combinations with two members, the joint profit is divided by two (i.e., the sharing factor is 0.5), while in the combination with three members the sharing factor is 0.33. Therefore, the Gencos agree the three-member coalition, if the joint profit is 50% higher than the two-member joint profit. This proves the Shapely rule that states coalitions with many members are not preferred. When a coalition is selected, the members rearrange the offering strategies to maximize their profits as defined in (14).

$$\max(CollusionProfit^{m,t_c}) = \max\left[\sum_{i \in m} \left(\sum_{t=1}^{T} (Profit_{i,t}^{m,t_c} - Profit_{i,t}^{oligopoly}) \right) \right] \;, t_c \in [1,T] \quad (14)$$

In (14), $Profit_{i,t}^{m,t_c}$ represents the profit of Genco i at time t obtained from exercising the explicit collusion of members of coalition m at time t_c. $Profit_{i,t}^{oligopoly}$ denotes the profit of Genco i without any explicit collusion that is obtained from (1).

Afterwards, for all hours ($t_c = 1, 2, ..., T$), the values of joint profit, $CollusionProfit^{m,t_c} / N_c$, are calculated for all coalitions, where N_c is the number of members in coalition m. Then, the coalitions with the highest values are selected.

B. Modeling the strategic behavior

The strategic behavior of Gencos is modeled by adding some steps to the mentioned explicit collusion model as illustrated in Fig. 2.

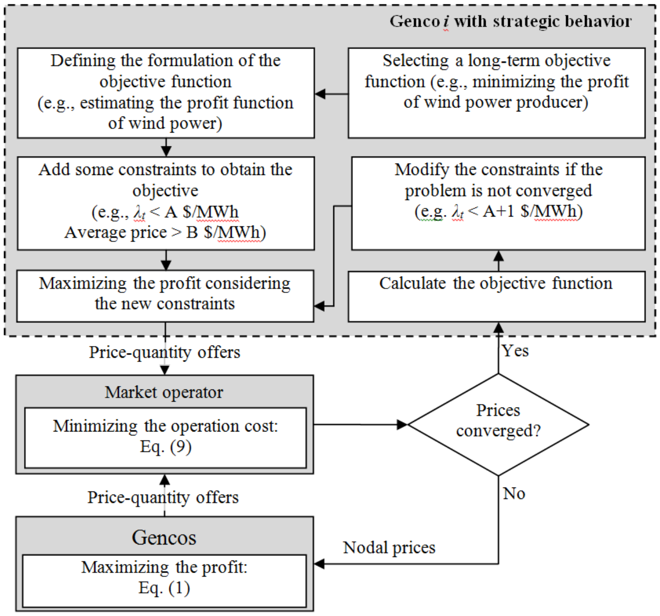

Figure 2. The electricity market flowchart for strategic behavior of Gencos

As it can be seen from Fig. 2, first, a long-term objective from a Gencos' viewpoint is considered. Then, some new constraints are added to the model. These constraints seem irrational in short-term horizon, but strategic in the long-term.

Afterwards, the results are analyzed and any required modification is made. For more clarification, if Genco *i* wants to reduce the profit of Genco *j*, to increase its own profit in the future; it may decrease the market prices. It is obvious that when Genco *j* withdraws, Genco *i* can compensate its profit reduction by exercising a higher market power.

On this basis, Genco *i* estimates the cost function of Genco *j*. Then, some limits on market prices (limit-pricing) are added to the model of Genco *i*. Moreover, a constraint (e.g., average market price) should be employed to guarantee the profit of Genco *i*. If Genco *i* cannot obtain appropriate results by using the constraints, they should be modified. It should be noted that, if Genco *i* has no power to reduce the profit of Genco *j*, the aforementioned approach is not converged. In this case, Genco *i* can join a coalition to collude against Genco *j*.

IV. NUMERICAL STUDIES

In order to investigate the impact of different regulatory rules and regulations on the behavior of thermal units and wind power producers, a modified IEEE 30-bus including four thermal power plants and one wind power (Genco 5) is used. The data of power plants are presented in [17].

In order to examine the regulatory supports of wind power producer two cases based on two different market regulations are studied. In case 1, in order to support the wind power generation, a fixed price equal to the average hourly price of the energy market is paid to this renewable energy producer. In case 2, the regulatory body decides that wind power producers take part in the energy market, the same as other Gencos. To support renewable Gencos, the purchasing price from the wind power producer is assumed to be 20 percent higher than the nodal price.

Two different models are also employed to study case 2. In the first model, the oligopoly and explicit collusive behavior of Gencos is considered. This means that the Gencos can have both tact and explicit collusions. In the second model, the explicit collusion associated with strategic behavior of thermal Gencos against the wind power producer is considered. The objective of the strategic behavior is to decrease the profit of the wind power producer in short-term by reducing the settling price. As a result, although this does not affect investments that are already carried out in wind power generation, it decreases the price signal in long-term planning, and consequently reduces its future investment.

The power production of Gencos in the aforementioned cases is illustrated in Fig. 3 to Fig. 5. As it can be seen, the power generation profile of Genco 5 follows the wind speed in all cases. According to Fig. 3 and Fig. 4, explicit collusion causes the generation of Genco 3 to increase in most of the hours. In addition, Genco 1, which is an economic generator, takes part in some coalitions, so that it reduces its generation to increase the market prices. Reduction of generation of Genco 4, which is also an inexpensive power plant, increases the market prices. By comparing Fig. 4 and Fig. 5, it can be seen that, the generation of Gencos in the strategic collusion is very similar to the one in the explicit collusion. However, the Gencos offered prices are totally changed in the strategic behavior. This can be directly reflected on the market prices.

The nodal prices of Genco 5 in different cases are presented in Fig. 6. As it can be seen, the explicit collusion can significantly increase the market prices in almost all hours. As strategic behavior of thermal Gencos against wind power producer, they decrease the market prices even less than their marginal cost between hours 1-15 and 23-24, when the generation of wind is quite high. While, during hours 17-21 when the wind speed is very low, the thermal Gencos increase the market prices by offering higher prices. This behavior can maintain the profit of thermal Gencos while such a high price results in insignificant profit for the wind power producer. The profit of wind power producer in the mentioned cases is compared in Fig. 7. This Genco can benefit from participating in the explicit collusion, so that the regulatory support enables the wind power producer to increase its profit. However, if a strategic collusion against this market player is formed, the profit of this Genco will be too low.

Table I shows the profit of thermal and wind power Gencos. Based on Table I, regulatory support of wind power producer in case 2 can double the profit of Genco 5. However, the situation is totally different in case of strategic behavior. As it can be observed, the profit of thermal Gencos in strategic collusion is not very low. The total profit of these thermal Gencos is even more than their profit in case 1.

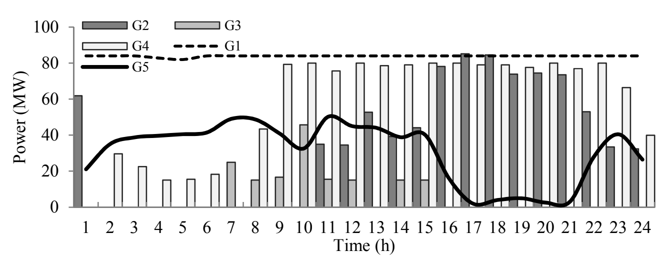

Figure 3. Power generation in Case 1 (fixed-price for wind power)

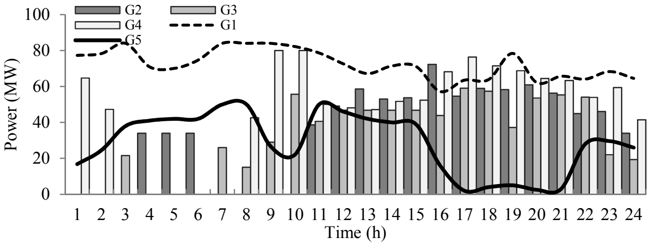

Figure 4. Power generation in Case 2 (explicit collusion)

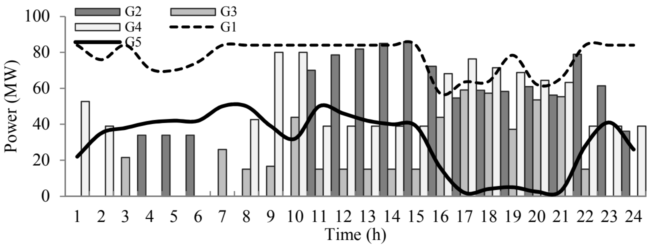

Figure 5. Power generation in Case 2 (strategic explicit collusion against wind power producer)

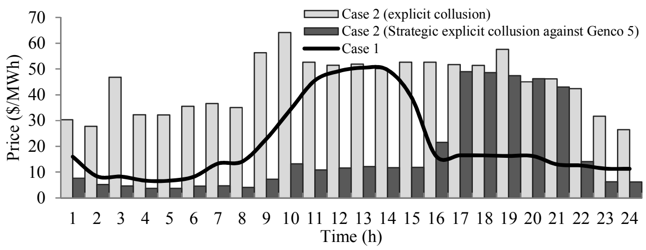

Figure 6. Market price in different cases

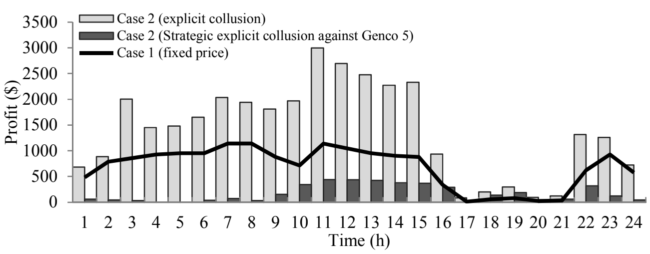

Figure 7. Wind power producer's profit in different cases

TABLE I. PROFIT OF GENCOS IN DIFFERENT CASES

Case	G1	G2	G3	G4	G5
Case 1 (fixed price)	19,096	5,225	5,150	13,640	16,399
Case 2 (explicit collusion)	69,578	26,644	33,281	44,211	33,682
Case 2 (Strategic explicit collusion against wind power)	12,030	9,268	12,829	13,483	**4,036**

It shows that, without any loss of profit, the thermal Gencos could decrease the profit of wind power producer by approximately 75%, which is a considerable amount.

V. CONCLUSIONS

In this paper, a model was proposed to reveal the potential of collusive and strategic behavior of Gencos. By using the model, impacts of two different regulatory support of wind power generation were investigated. The results indicated that, purchasing the power from the wind Gencos based on the market clearing price could increase the profit of these power plants, if strategic collusion against them was not performed. Results showed that, if the regulatory bodies did not consider strategic collusion of market participants, some adverse consequences for wind power producers might happen in the long-term horizon. This could bring a negative signal for investment in wind power generation.

ACKNOWLEDGMENT

This work was supported by FEDER funds (European Union) through COMPETE and by Portuguese funds through FCT, under Projects FCOMP-01-0124-FEDER-020282 (Ref. PTDC/EEA-EEL/118519/2010) and UID/CEC/50021/2013. Also, the research leading to these results has received funding from the EU Seventh Framework Programme FP7/2007-2013 under grant agreement no. 309048.

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