A New Approach for Market Power Detection in Renewable-based Electricity Markets

Neda Hajibandeh[1], Miadreza Shafie-khah[1], Gerardo J. Osório[1], João P.S. Catalão[1,2,3]

[1]C-MAST/UBI, Covilha; [2]INESC TEC and FEUP, Porto; [3]INESC-ID/IST-UL, Lisbon, Portugal
neda.hajibandeh@ubi.pt; miadreza@ubi.pt; gjosilva@gmail.com; catalao@fe.up.pt

***Abstract*—This work proposes a new approach to detect the market power in power systems consisting of renewable energy sources. A model powered by game theory and agent-based systems is proposed to analyze the behaviors of each market player from the regulatory body's viewpoint. The proposed method considers both the tacit collusive behavior of Generation Companies, and the possibility of explicit collusion. In addition, three new market power indexes are introduced to quantify the market power level as well as to precise its causes. In order to evaluate the efficiency of the methodology, various numerical studies are carried out, and the effect of several market regulations is investigated on the market behaviors.**

***Keywords*—Index; market power; agent-based; renewable;**

I. NOMENCLATURE

A. Subscript

i	Index of Gencos
t	Index of time interval

B. Superscripts

En	Energy
Cg	Contingency
f	Forecasted amount
LB, UB	Lower and upper boundaries
m	Coalition
M&O	Maintenance and operation
q	Segment of modeling the valve point effect
Res, NRes	Spinning and non-spinning reserves
SFE	Supply function equilibrium

C. Parameters and Variables

P	Power (MW)
EC, FC	Emission and fuel costs ($/h)
SD	Shut-down cost ($/each)
SUC	Start-up cost ($)
u	Binary variable of unit commitment
w	Variable of decommitted time (h)
y, z	Binary variables of start-up and shut-down
α, β	Variables of offering strategy
λ	Price ($)

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II. INTRODUCTION

A major target of each electricity regulatory body is to create a competitive and clear market. Therefore, the regulatory body needs to monitor and evaluate each regulation, rule and structure of the market before these changes implement that leads the market to efficiency [1].

The ex-ante assessment is carried out to evaluate the conditions of the future market taking various situations of the electrical systems and regulatory body's plans into account [2], [3]. However, the estimation of market power would be absolutely problematical when the electricity market consists of renewable-based units. Because, these sources are energy-limited and the main parts of their behaviors are forced by weather conditions.

In the electricity market, the efficiency can be attained when Generation Companies (Gencos) create their offering strategies according to the marginal variable costs. Nevertheless, there is exclusion for energy-limited generators, e.g., renewable-based producers. The offering strategies of the mentioned power plants are not only based on the variable costs at the associated hour, but also the opportunity costs of Genco for the previous hours should be counted [4], [5].

Considering the applied features of electricity market (such as non-convexity of cost functions) to find the accurate solutions are very difficult [6], consequently, a large number of simplifications have been already taken into account in the literature to model the market behavior as follows:

- Disregarding energy-limited sources;
- Discounting the impacts of grid and security necessities;
- Disregarding the start-up/shut-down cost and physical constraints;
- Considering the market at each time slot, so that disregarding the linking limits between time slots.

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To overcome the above-mentioned disadvantages, a model powered by game is developed to model the electricity markets. The collusive behaviors between Gencos enable them to exercise the market power [7]. On this basis, the present work models both kinds of collusive behaviors, tacit and explicit. In addition, three new indexes are introduced to assess the market power. These indexes would be employed for each single time slot and individual Gencos.

Furthermore, these indexes are able to provide some information about the main reason of the market power. This means that the indexes designate the market power to grid limits, oligopoly behaviors of Gencos, and explicit collusions. In addition, the introduced indexes can be used for the pay-as-bid mechanisms, in contrast with the indexes based on the Lerner Index that are only appropriate for uniform mechanisms.

III. The Proposed Approach

To make a decision Gencos are dealt with substantial levels of uncertainty due to prices and demand side loads. A considerable number of approaches have been presented in previous researches to formulate these kinds of uncertainties in electricity systems. Probabilistic approaches uncertainties are faced by the familiar probability density function (PDF). Monte-Carlo simulation (MCS) approaches [8] are one of the most accurate methods between stochastic modeling methods nevertheless they have a considerable amount of calculations.

Point estimation method [9] as an efficient and reliable approximation to model the uncertainty in power systems. Although the point estimation method does not employ the definitive procedure to find the statistical times of output random variables, compared with MCS need simulations less. These two methods and scenario generation method [10] are extensively employed in power system researches.

Robust optimization method [11]–[13] is one of the methods are employed when there is limited information about the uncertain items. However, these models have been presented for modeling of wind energy in the power system studies in detailed as much as possible. Interval optimization method [14] as well as information gap decision theory (IGDT) [15] are the other kinds of such methods.

In [16] Gencos bidding strategy in the electricity market is formulated as a robust optimization method. Fuzzy methods [18] are employed while the uncertain terms are explained with their fuzzy membership functions (FMF). Stochastic programming method associated with scenario generation approach has been extensively deployed in problems which include uncertainties [18]–[20]. In this programming approach, the uncertain terms are exemplified as stochastic variables and proposed with scenarios.

In this current work, the proposed approach to model the market and detect the market power is a multi-agent approach to model the electricity markets from the regulator's perspective. On this basis, the bi-level programming is taken into account, and all the market players are individually simulated via agents that maximize their profits, whereas the independent system operator would minimize operation cost. The approach can simulate both tacit and explicit collusive behaviors. The proposed approach for modeling the electricity market and detecting the market power is illustrated in Fig. 1.

According to Fig. 1, all individual agents forecast the market price and submit their offering to the market. All the agents employ a supply function equilibria to determine their strategic behaviors in the energy and reserve markets.

To this end, as regard to the predicted prices, all thermal and renewable-based Gencos maximize their self-scheduling problem, and each submits the SFE vector $(\alpha_{i,t}^{SFE}, \beta_{i,t}^{SFE})$ to the markets.

$$\max(\text{Thermal Genco Profit}) = \text{Max} \sum_{t=1}^{T} \begin{Bmatrix} P_{i,t}^{En}.\lambda_t^{En\,f} + P_{i,t}^{Res}.\lambda_t^{Res\,f} + P_{i,t}^{NRes}.\lambda_t^{NRes\,f} \\ -\left(FC_{i,t} + EC_{i,t}\right)u_{i,t} - SUC_i - SD_i.z_{i,t} \end{Bmatrix} \quad (1)$$

Then, on the second level, a Security Constrained Unit Commitment (SCUC) will be implemented for market clearance and determination of the auctions as:

$$\min(\text{Total Cost}) = \text{Min} \left\{ \sum_{t=1}^{T} \sum_{i} P_{i,t}^{En}.\lambda_t^{En} + P_{i,t}^{Res}.\lambda_t^{Res} + P_{i,t}^{NRes}.\lambda_t^{NRes} \right\} \quad (2)$$

For modeling the explicit collusion, every single Genco player trials interact with other Gencos, when primary oligopoly equilibrium is reached.

To do so, all the agents take part in entire potential coalitions. The coalitions would aim at augmenting the joint benefit by adjusting their offering strategy. The additional profit would be divided among the coalition's Gencos.

Each Genco chooses a coalition that delivers the maximum profits. The collusions affect the offers of the coalition's Gencos as well as the other Gencos. The offering strategies of coalition's Gencos are modified by Particle Swarm Optimization (PSO) approach. Equation (3) is denoted the objective function:

$$\max(Explicit\,\Pr ofit^{m,t_m}) = \max \sum_{i \in m} \left(\sum_{t=1}^{T} (Profit_{i,t}^{m,t_m} - Profit_{i,t}^{Tacit}) \right) \;,\; t_m \in [1, T] \quad (3)$$

where $Profit_{i,t}^{m,t_m}$ denotes the advantage of Genco i who has joint coalition m at time t_m; $Profit_{i,t}^{Tacit}$ addresses the advantage of the mentioned Genco in the tacit collusion level. For the time ($t_m = 1, 2, \ldots, T$), the coalitions with the most significant profit sharing (i.e. $Explicit\,Profit^{m,t_m}/N$) are chosen such that that Genco i joins majority one coalition.

Three indices are introduced for detection of market power. The indices are Network Constraint Index (NCI) that evaluates the effect of the grid on the market power; Tacit Collusion Index (TCI) that identifies the potentials of market power associated with oligopoly behaviors of market players, and Explicit Collusion Index (ECI) that indicates the market power associated with explicit collusions between Gencos.

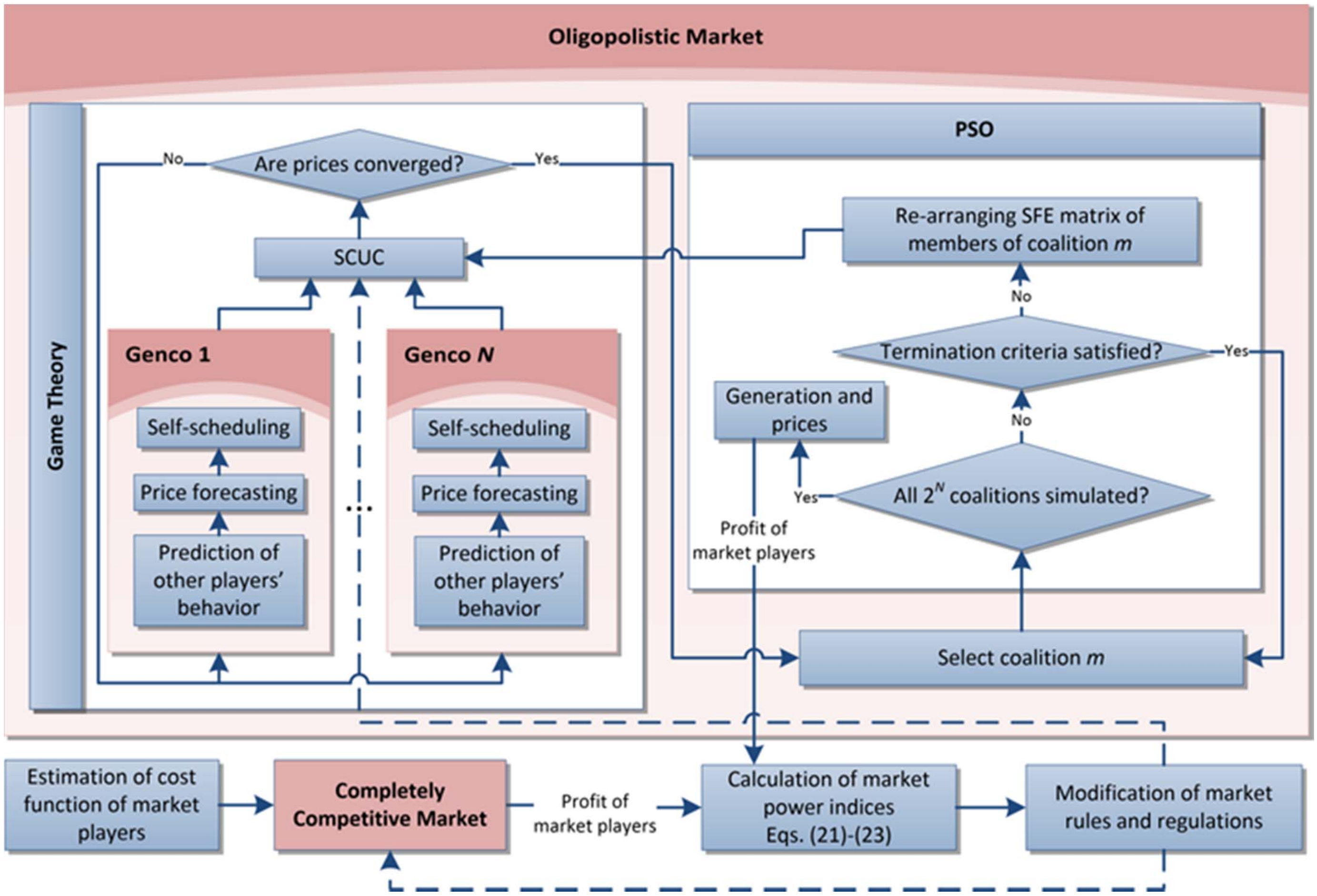

Fig. 1. The proposed approach to detect the market power.

IV. Numerical Studies

In order to indicate the usefulness of the proposed approach, a modified thirty-bus IEEE system is taken into account. Three cases are studied to investigate the impact of market structures, rules and regulations on market efficiency.

In Case 1, a uniform mechanism is assumed for market price clearance. Case 2 clears the market based on a pay-as-bid mechanism as well as price caps. Case 3 is associated with a pay-as-bid mechanism but a revenue cap for each Genco.

The impact of the price/ revenue cap is studied on the market performance. Total generation cost is illustrated for different cases in Fig. 2. The represented indices NCI is computed for Case 1 and illustrated in Figs. 3. Moreover, the other proposed indices, TCI and ECI, are derived from Case 1 and exemplified in Figs. 4 and 5 respectively.

According to Fig. 3, the advantages for Gencos 1 and 4 from the network constraints are more than other Gencos. In addition, it is obvious that the extra profit of the two Gencos because of network constraints in hours 10 to 14 is more massive than other hours of the day. Comparing Figs. 3 and 4, it can be observed that the potential of market power because of tacit collusion is more considerable than the one due to network constraints.

Moreover, NCI explains no market power in the time interval of the first 10 hours of the day while TCI represents an enormous potential of market power (particularly for Genco 1) at the same time.

In addition, the wind generation units in those hours have a considerable potential to wield of market power. Employing of Genco 3's elevated ramp rate at the hours of 11 to 15, Genco 3 can extent the benefit of oligopoly behavior much more than the other players. In the time interval of the hours 16 and 22, Gencos 1, 2 and 4 can effectively promote their benefits through raising and pushing the market price up.

Since the wind unit cannot produce efficiently because of the slow speed of wind, Genco 2 can benefit from the other Gencos' tacit collusion only in the time interval of the hours 15 and 22. As it is obvious in Fig. 5, Gencos 3 and 4 face a serious possibility to work in explicit collusion in the time interval of the hours 16 and 22, while the wind speed is slow.

Explicit collusion for wind unit and Genco 2 lead to limiting the market power. Nevertheless, Genco 2 holds the market power in the time interval of hours 19 and 20. In the majority of the hours, Genco 1 takes part in the market with its total capacity due to its market power which is resulted from the power system limitations and tacit collusion.

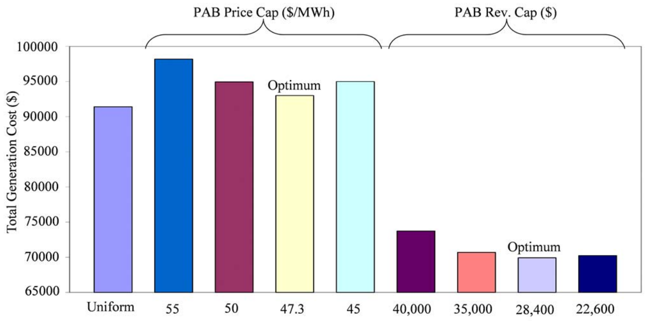

Fig. 2. Total generation cost in different cases.

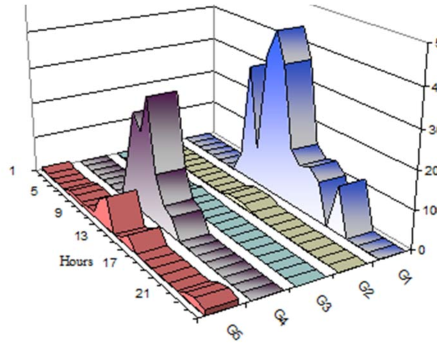

Fig. 3. The proposed NCI for different generation companies in case I.

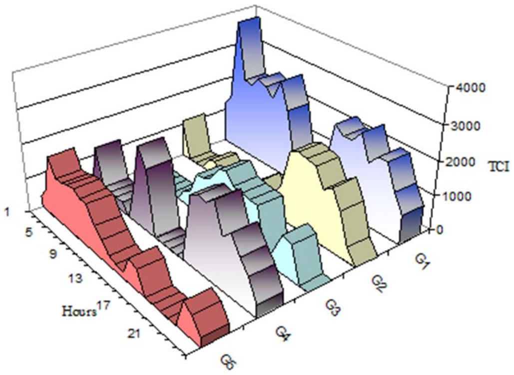

Fig. 4. The proposed TCI for different generation companies in case I.

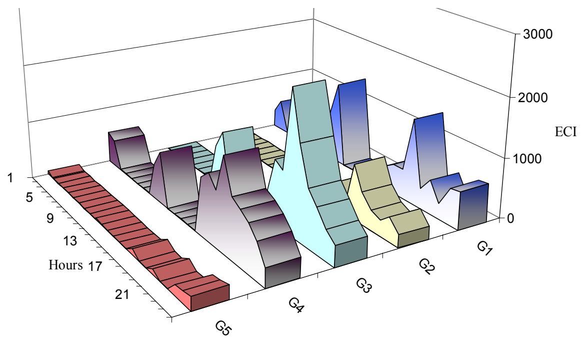

Fig. 5. The proposed ECI for different generation companies in case I.

Moreover, from last features adopted by Genco 1, it can obtain a considerable benefit. As a result, Genco 1 is not very interested in working in explicit collusion. In this sense, the behavior of market participants is simulated through applying the variety of the source of the revenue to analyze and evaluate the impact of the market price and income on the market conditions.

V. CONCLUSIONS

In this work, a new approach powered by multi-agent and game theory was proposed to evaluate the ex-ante market power. In addition, three new market power indexes were introduced to clarify the main reason of market power. These indexes could be implemented for renewable-based Gencos. Also, an electricity market with a clearance of pay-as-bid mechanism could benefit from the new indexes. A comparison with conventional indexes demonstrated that the new indexes could clarify that the market power was arisen from grid limits, the oligopoly behaviors of Gencos, or explicit collusions between them. Several numerical studies showed the effectiveness of the proposed method.

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