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A game theory simulator for assessing the performances of competitive electricity markets

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Abstract

In the last years, electricity markets were created all over the world following different basis concepts. Market structure, market rules, demand levels, market concentration and energy sources to produce electricity have a strong influence on market performances. Modifications on these aspects may significantly affect market outcomes. Sensitivity analyses need proper simulation tools. In this paper a medium run electricity market simulator (MREMS) based on game theory is presented. This simulator incorporates two different games, one for the unit commitment of thermal units and one for strategic bidding and hourly market clearing. Either a Forchheimer (one leader) or Bertrand (all player are leaders) or even intermediate model with a whatever number of leaders can be selected, in dependence on the strategic behavior of the producers, allowing for the simulation of markets with different levels of concentration. The simulator was applied to analyse producers' behavior during the first operative year of the Italian power exchange. A comparison between simulation and true market results was carried out in order to test the simulator and validate its simplifying hypotheses. MREMS, yet capable to be used stand-alone, was conceived as the heart of a long-term market simulator (LREMS) allowing to simulate the long-run evolution of the generation park (investments in new plants, refurbishment and dismission of older ones). LREMS is a hierarchic simulator: a long-term "outer" game takes yearly investment decisions based on mid-term price projections provided by MREMS. Although this paper is mainly devoted to describe MREMS, one specific section will provide an overview of the "outer" game implemented by LREMS.

Keywords: Electricity market; Medium run market simulator; Long-run market simulator; Residual demand; Strategic behavior

1. Introduction

In the frame of the ongoing deregulation of electricity markets, competition between private generation companies has replaced monopoly management by vertically integrated state-owned companies in many countries. Since a market design depends on the specificities of the country where it is implemented, electricity markets often show remarkable differences. New markets need to learn the lessons from structural problems arisen in older ones, e.g. California and E&W Pool before restructuring.

Market players and regulators are very interested in foreseeing the behavior of the market for many reasons. The goal of regulators is to monitor the system, test the rules before their implementation and detect market deficiencies, while the goal of players is to operate maximizing their own profit. Simulators can be built to meet the needs of both regulators and market players.

Market simulators can be classified into three categories:

- *Short-run simulators* [1–4], focused on a detailed simulation of each aspect of the bidding process over a short time frame (from 1 h to 1 week). They account mainly for the bidding strategy of the players and their production schedule.
- *Medium run simulators* [5,6], useful to study the market behavior within the time frame of weeks or months. Usually, they pay a particular attention to calculate the optimal hydro production schedule on a monthly basis.
- *Long-run simulators* [7,8], with the time frame of years. They can support regulators in testing new market rules and carrying out scenario analyses on the evolution of the generation

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park and producers in taking strategic decisions regarding investment in production capacity.

In electricity markets, producers interact one with another taking into account that their results are influenced by competitors' decisions. Game theory is well suited for analysing these kinds of situations [9–11]. It has been successfully applied in many fields: information technology [12], transportation industry [13], stock market [14], sociology [15,16] and electricity markets [17–20].

There are comparatively more examples of short-run simulators than of medium and long-term ones. Short-run simulators are easier to create because they don't need to consider many uncertainties that can occur in the long run. Moreover, longer-term simulators are often based on shorter-term ones.

Applying game theory to calculate analytically equilibrium conditions is not easy, especially when a realistic market modelization is required. In fact, taking into account the non-convex and non-differentiable nature of the stepwise aggregated bidding curves, equilibria may not exist or not be unique [20]. On the other hand, if the market player can find the global optimal in each iteration as ensured by the step function of the producer bids and the numerical approach to find the optimal in this paper, we can avoid all the problems relate to local Nash equilibrium [21] as well as the convex and differentiability requirement.

In this paper, we present a new medium run electricity market simulator (MREMS), based on game theory and a very detailed modelization of the generation park. Even if it has been thought for the medium run (e.g. 1 year), it models the day-ahead market with an hourly detail.

Although the Italian electricity market is zonal, the present version of the simulator does not consider market zones. The reason is that MREMS was conceived as a part of a long-run electricity market simulator (LREMS), implemented as a game as well, that hierarchically calls MREMS for performing yearly price projections. As MREMS is called frequently, we wanted the algorithm to be very fast, yet maintaining a detailed description of the market. Thus, as a first level of approximation, price differences between zones were considered not crucial for long-term evaluations and omitted. We are thinking of including zones in future versions of the simulator.

MREMS models in detail the bidding process of the producers and the market clearing using a realistic model of producers' bids, considering the real schedule of hydro energy, and accounting for the unit commitment of the thermal plants. Producers' strategic bidding is modeled in the form of a price mark-up over a minimum price offer that can be chosen according to different criteria (production marginal costs, average costs, etc.) in order to capture different attitudes of the producers in the market.

This paper is composed of the following sections. In Section 2 the structure of MREMS is introduced. The equivalent demand representation used for thermal plants bidding is described in Section 3 while the game approach to the unit commitment of the thermal plants is detailed in Section 4. Section 5 analyses alternative options for the minimum price bids of the thermal plants. The game mechanism for modeling the market clearing is introduced in Sections 6 and 7 presents an application of MREMS to the Italian market and discusses the corresponding results. Section 8 introduces briefly the long-term game implemented by LREMS. Conclusions are drawn in Section 9.

2. The structure of MREMS

The basic structure of the simulator MREMS is represented in Fig. 1. An input data set must be provided in order to characterize demand, power plants features, bilateral contracts, imports and game model. On the basis of these data, bilateral contracts are pre-allocated and excluded from the game (Section 3), the demand curve is pre-processed (Section 4) and a unit commitment of the thermal plants (Section 5) is carried out. The results of these calculations (demand, represented as a duration curve, and a set of thermal units available for bidding) are used by the market clearing game that calculates optimal bids and market clearing. A further module calculates a few market metrics in order to assess market performance.

Input data are defined with reference to arbitrarily defined time intervals (e.g. hour) and periods (e.g. month); demand duration curve is defined over each period while the market is cleared on an interval basis.

3. Bilateral contracts

Concerning the market clearing procedure, bilateral contracts can be considered as pre-assigned.[1] Thus, MREMS does not take them into account in the market clearing game: the portions of generation and load involved in bilateral transactions are excluded from the strategic bidding.

The overall energy allocated by means of bilateral contracts is generally constant along the day. The amount of energy bilaterally contracted by a particular firm is related to its willingness to hedge against price volatility in the power exchange, that depends, in turn, also from its market share: firms having a larger market share, usually prove more confident in market gaming.

Following this principle, MREMS allocates each firm with a share of the overall bilateral contracts proportionally to its market share weighed with a risk aversion parameter that can be estimated on the basis of its past behavior and that may be selected as inversely proportional to the firm market share.

Among the units of a given firm, *those characterized by lower costs are selected to serve bilateral contracts first*. Appendix A shows this is the optimal choice, at least for the case of perfect competition. Thus, the units involved in bilateral contracts are selected in an increasing cost order, up to reach the total bilateral quantity (d_i) considered for each firm. Once the quantities for bilateral contracts are determined, their complement is the quantity to be bid in the power exchange.

[1] In order to guarantee the feasibility of the market solution, also bilateral contracts are taken into account in the clearing procedure, considered as split into a generation bid at price zero and a consumption bid without price indication.