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Nash equilibria in competitive electric energy markets

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Abstract

Several countries have modified the structure of their Electric Energy Markets (EEM) by the introduction of various levels of competence in the generation, transmission and distribution areas, which allows the generators to sell their production at a short-term market price (or spot price). The fundamental premise of the regulation is that the global efficiency can be improved through a strong competence in a market structure governed by explicit rules. The Game Theory is the study of mathematical models of conflict and cooperation between intelligent rational decision-makers. In this paper, the Game Theory is proposed to analyze the economic behavior of the generators to make their offers to the short-term EEM. The IEEE 9-bus system is used to illustrate the main features of the proposed method. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Electric energy markets; Economic dispatch; Game theory

1. Introduction

In the last decade, the Electric Industry in Argentine, has changed from a vertically integrated structure of EEM, to a vertically and horizontally segmented one. The introduction of competence by means of the vertical and horizontal disintegration of the Electric Industry requires different forms of regulation compared with the ones traditionally applied in the sector. This approach puts emphasis both in the design of the EEM structure, and the set of rules that regulates, it where their 'kindness' is measured by the way in which they establish incentives for those behaviors that would contribute to the global efficiency [1]. The general spirit of the regulation in Argentine incorporates these innovative elements in orders to control the regulated companies through the verification of the fulfillment of obligations, subject to penalties and incentives. This EEM, includes different commercial and financial agreements, by means of contracts of different type and duration, shared risks, short-term transactions, among others. The nucleus of these agreements is the spot market in which the electric energy is valued and commercialized. This task is carried out by CAMMESA, the Argentine Independent System Operator (ISO) [2]. The programming of the economic dispatch (ED) is carried out using models of optimization and simulation of the operation, where the objective is to minimize the cost of operation plus failure of the generating units. The prize of the energy reflects the cost of the next MW of load to be supplied subject to the restrictions associated to the transport and maintenance of the level of quality of the service and security established. From the results obtained in the daily unit commitment, CAMMESA determines the prevision of prices of the energy for each hour.

In this paper, a methodology based on the noncooperative Game Theory [3–5] is used to analyze the economic behavior of the generating companies. The paper is organized as follows: First the application of the game theory on EEMs is reviewed, then the wholesale competitive spot market is described. Finally, the proposed method is presented.

2. Game theory

The Game Theory can be defined as the study of mathematical models of conflict and cooperation be-

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tween decision-makers. The Game Theory is a mathematical technique that analyzes situations in which two or more individuals make decisions that influence one another's welfare. The modem Game Theory was introduced in 1944 by Von Neumann and Morgenstern [6]. Others had anticipated some ideas, Zermelo (1913), Borel (1921) and even Von Neumann (1928). Important developments in this field took place during the period 1950–1960. The Game Theory gain additional relevance in 1994 when the Nobel Prize of Economy was awarded to John Harsanyi, John Nash and Richard Selten for their contributions to the analysis of the equilibrium in noncooperative games. In theory, a game refers to any social situation, which involves two or more players. Two basic hypotheses exist that are made about the players: they are rational and intelligent. Each of these adjectives is employed in a technical sense. A player is rational if he makes consistent decisions with the achievement of his own objectives. It is supposed that the aim of each player is to maximize the expected value of its own payment, which is measured in some scale of utility. A player is intelligent if he knows everything that is relative to the game and can make inferences concerning the situations, which can take place. A first classification of the games, regarding the movements that each player makes and the information he has, is presented in Table 1.

Von Neumann and Morgenstern investigated two different approaches. One is the strategic or noncooperative approach. This requires a very detailed specification of the rules of the game, so that the strategies available to the players could be known in detail. The objective is to find an adequate group of strategies of equilibrium, which will be called the solution of the game. What is best for a player depends on what the other players think to do and this in turn depends on what they think the first player will do. Von Neumann and Morgenstem solved this problem in the particular case of games with two players whose interests are diametrically opposed. These games are called strictly competitive or of zero-sum because any player's gain is always exactly balanced with a loss corresponding to the other player. The solution of games of non zero-sum, those in which the gain of a player is not the same as the loss of others, was first formulated by John Nash [7]. Several applications to EEM of noncooperative Game Theory has been suggested: in [8], the competitive behavior of the generators and the eventual coalitions' that could be formed in order to exploit the situations of imperfect competence is discussed. The analysis is made resorting to the criterion max–min (or characteristic function) to make decisions based on the use of pure strategies. The next step in the analysis of the problem of generator's information is treated in [9], the competence is modeled like a noncooperative game with incomplete information and is solved calculating the Bayesian Nash equilibrium. In both articles the authors deal with static games and the study cases correspond to situations with two or three players where the computational aspects of the resolution of the game are not relevant. The application of the games with complete information is presented in [10]. Three types of competitive behavior between generators are examined: perfect competence, imperfect competence and monopoly based on the use of pure strategies, analyzing the impact of the network on the market power. Reference [11] examines the competitive behavior between generators using mixed strategies, analyzing the impact of the congestion of the transmission network on the market power. The application of the games with incomplete information is presented in [12], where the unit commitment is modeled with restrictions in the transmission and requirements of spinning reserve. It is supposed that each generator only knows its own payment function and uses a Bayesian approach to deal with the information relative to the other generators.

Table 1
Games type

Game	Characteristic
Static	The players perform their actions (strategies) simultaneously and receive payoffs that depend on the combination of previously executed actions
Dynamic	The players perform their actions sequentially and receive payoffs, which depend on the combination of previously executed actions
Complete Information	Each player's payoff function is common knowledge among all the players
Incomplete information	At least one player is uncertain about another player's payoff function
Perfect information	In each movement the player that moves knows the complete story of the game
Imperfect information	In each movement the player who does not know the complete story of the game

The second approach is the coalitional or cooperative, which adopts a less rigid attitude [13–18]. It deals with situations in which the players can negotiate on how to develop the game before starting it. Besides, it is supposed that these negotiations can finish by the signing of a bonding agreement, which obliges them. In these conditions the concrete strategies which are available in the game are not too important in front of the structure of preferences of the game since it determines which contracts are feasible. The cooperative approach can be applied to assignation problems and the different solutions proposed can be interpreted as alternative solutions to a problem of assignation or distribution.