Mathematical Approach to Wholesale Power and Capacity Market Regulation

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Abstract
This paper article analyses the application of mathematical approach (represented by the game theory) in the competitive sector of the wholesale power and capacity market on the day-ahead market. We propose the mathematical algorithm for
selecting the best generating company strategy that allows us to take into account the possible effects of regulators responses. We show that the daily profit of the generating company constitutes a criterion for selecting the best game strategy.

**Keywords:** wholesale power and capacity market, day-ahead energy market, strategies of generating companies, power market regulation, game theory

1 Introduction

Since the late 1990s, there has been a plethora of research papers devoted to the problem of strategy formation in electricity markets. The majority of authors employed game theory, statistics, genetic algorithms, and Markov chains in their studies [1; 2; 4; 5; 7; 12; 17; 19]. The topic also gained lots of attention in amongst the mathematicians and energy economists in Russian Federation [7; 8; 13].

It can be shown that when generating companies choose a particular strategy, they do not know how their competitors will react [6; 10; 11]. Therefore, choosing the optimal strategy should take into account the divergence of interests of generating companies and their possible behaviour, as far as the outcome of the situation in this case will depend on the mutual influence of participants’ interests [18; 20].

As far as the wholesale power and capacity market (WPCM) is concerned, game theory can be used as a tool for selecting the best strategy of a generating company in conditions of complete uncertainty, i.e., complete lack of information on the impacts of the external environment.

One key assumption which plays a key role in game theory is that all players of the game demonstrate rational behaviour [2; 3; 6]. This assumption means that each player selecting their behaviour is guided by some algorithm steps, allowing maximization of individual utility functions. Nor less important is the fact of generally known rationality of players. The relationship between sellers of electricity can be described on the basis of two main areas of game theory: non-cooperative and cooperative. Non-cooperative theory is strategically oriented. It examines what we expect the players to do in the game. Cooperative theory, on the other hand, examines the outcomes that one can predict [5; 6; 9; 14; 16].

If there are only two participants of the game, there are also antagonistic and non-antagonistic games. When the interests of the players are opposite, the game goes to pair antagonistic game (i.e. a matrix). If the conflict is more general, and the participants have different, but not necessarily directly opposite interests, the game is non-antagonistic.
2 Game Theory and its Application to Modeling the Wholesale Power Market

Suppose that the demand for electricity is inelastic and therefore price bids of buyers can be neglected during price offer formation. By that “game” we mean the order of price bids selection by Trading System Administrator.

Generating companies are forced to make decisions in terms of countering the other side, which may pursue the opposite or other purposes. And this counteraction to the opposite side can be passive or active. In the case of the wholesale power market we can’t say that the generating companies, pursuing their own goals, consciously counteract the goals of each other due to the fact that on the electricity market is used a marginal price formation. On the other hand, uncertain environment factors may act against the generating company. They are called "nature" in the game theory - a non-active side, which obviously does not counteract the achievement of the generating company goals. In this case the generating company makes the decision and "nature" does not provide it a conscious aggressive reaction, but its real behaviour is unknown.

On WPCM all game participants (in this case, generating companies) can be divided into two groups: A Generation (researched company or group of companies) and B Generation (other companies). In this case, on the wholesale power market, the following game models are possible [20].

The situation between the parties when there is no “antagonism” can be represented as a game we further call “nature game” or “nature”. On the wholesale power market this “nature” game without any aggressive reaction may be one of the following: demand fluctuations, the uncertainty of weather conditions, stations repair modes, seasonality, regulation of the Government, the Federal Antimonopoly Service (FAS), or System and Commercial operators, the competitive environment, etc.

Dependence of Generation A wins on the degree control can be represented by the matrix of elements of which Generation A wins $\alpha_{ij}$, corresponding to the $i_{th}$ strategy at the $j_{th}$ state of “nature” game.

By “nature” game we can also consider the actions of competitors, taking the assumption that while choosing a strategy, they don't think about the behaviour of other players.

The choice of the optimal “nature” game strategy can be made using the following classical criteria:

1. The criterion of Wald's extreme pessimism focuses the player (generating company) on the worst possible conditions of „nature“ game and, therefore, cautious behaviour when choosing a strategy. This criterion is acceptable in those cases, when the player doesn't want to lose more than wants to win.
2. The maximum criterion, acting in the opposite sense to Wald's criterion, is the criterion of extreme optimism, because it focuses the player (generating company) on the best conditions of «nature». 
3. Other criteria (Hurwitz, Savage, Laplace, and others).

The payoff function of A Generation in the absence of regulated contracts (RC) and free bilateral contracts (FBC) can be represented as follows:

\[ L = \sum_{i=1}^{g} \sum_{j=0}^{23} (P_{mj} - P_{ij}) W_{ij}, \forall (P_{mj} - P_{ij}) \geq 0 \]  

(1)

Where:

- \( L \) - daily profit;
- \( P_{mj} \) - equilibrium price for the \( j_{th} \) hour of the day;
- \( P_{ij}, V_{ij} \) - corresponding values of price and volume of price bid in respect to the generating equipment \( i \) of considered generating company to the corresponding \( j_{th} \) hour of the day;
- \( g \) - the number of units of equipment of this company.

For bi-matrix games based on players’ matrices one can construct a general matrix of size \( 4 \times 4 \), the elements of which will be pairs of numbers: the first player win \( \alpha_{ij} \) and the second player win \( b_{ij} \).

Players' wins at the same time correspond to their applicable strategies.

The payoff function of B Generation in the absence of RC and FBC can be written as follows:

\[ L = \sum_{k=1}^{r} \sum_{i=1}^{g} \sum_{j=0}^{23} (P_{mj} - P_{ijk}) W_{ijk}, \forall (P_{mj} - P_{ijk}) \geq 0 \]  

(2)

Where:

- \( P_{ijk}, V_{ijk} \) - corresponding values of price and volume of price bid in respect to the generating equipment \( i \) of the generating company \( k \) for the corresponding \( j_{th} \) hour of the day;
- \( g \) - the number of player \( k \) units of equipment,
- \( r \) - the number of generation companies as part of B generation.

We distinguish two approaches to solving bi-matrix games:

1. Search for the equilibrium situations - conditions are searched, when the game is in some equilibrium, which is disadvantageous to be violated by any of the players individually.

Bi-matrix game always has at least one point of the Nash equilibrium. Thus one has the following options:

   a) the unique Nash equilibrium in pure strategies
b) the unique Nash equilibrium in mixed strategies;

c) three Nash equilibria - two in pure, and one in mixed strategies;

d) two Nash equilibria in pure strategies;

e) a continuum of Nash equilibria in mixed strategies.

2. Searching optimal Pareto situations – searching the conditions under which players can't increase the gain of one player, without decreasing in gain of another.

It can be shown that it might be possible to find a solution of bi-matrix games by using Lemke-Howson algorithm [11; 12].

3 Algorithm of Generating Company Strategy Selection Considering the Restrictions on the Day-Ahead Power Market

It is necessary to consider restrictions on the use of strategies that can be limited by the existing laws and regulations of trade on the Day-Ahead Power Market (DAPM), imposed by the different regulators. Currently, at the legislative level the actions of generating companies may entail both administrative and criminal liability.

Application of the strategy of physical withdrawal is limited by the requirement of System Operator (SO) to submit price bids for participation in the selection procedure of electric generating equipment (SPEGE) and DAPM by the amount of the maximum capacity corresponding to the operational available capacity of the equipment. The value of the operational available capacity is defined as the difference between the set and unused capacity. Unused capacity is determined by the insufficiency or deficiency of energy resource: a reduction in water consumption in the river, lack of fuel; by change of size, mode and load parameters; the deterioration in the quality of operation: reduction in the initial parameters of feed temperature and steam pressure and so on. Thus, at the same time the possibility of using the unused capacity as a local repair reserve is detected for each station. The value of working capacity is defined as the total power of the system generator minus capacity of generators in the repairs [5; 7; 18].

4 The Choice of Generating Company Strategy on the Example of the United Power System of Southern Russia

The United Power System of Southern Russia (UES of South) belongs to the European part of Russia and occupies the territory of the Southern and North Caucasus federal districts. According to SO UES the area of the operational zone of the South UES is 589.2 thousand square kilometres and occupies 3.4% of the territory of Russia, the population is 22.9 million. According to the Russian Federal State Statistics Service (Rosstat), the population of the South and North
Caucasus Federal districts is 23.3 million, or 16.3% of the total population according to the census of 2010. Moreover, considered districts as the Central Federal District, are the only regions where the population growth between 1989 and 2002 was recorded.

A total of 116 power plants with a total capacity of 18.6 thousand MW (according to SO UES, 01.01.2013), 1120 electrical substations 110-500 kV and 1448 110-800 kV transmission lines with a total length of 52166.7 km form the energy complex.

As of 2013 WPCM of South UES is presented by the following major companies: WGC-2, WGC-5, Lukoil - Ekoenergo (until 2010 TGC-8), RUSHYDRO and ROSATOM.

Consider the game with the “nature” game for the company WGC-2, where regulation by FAS will be considered as the prerequisite for our “nature” game. FAS is engaged in antitrust regulation and detection of market abuse to economic status. Manipulation with prices for electricity may occur through the execution of economically and (or) a technologically unjustified actions, including the use of exclusive (including temporary) position on the wholesale power market (separate wholesale market price zones) by the parties, which leads to a significant change in prices for electricity.

Typically, the manipulation is expressed in filing overstated (understated) prices within the price bids or withdrawal of capacity from the market and creating artificial scarcity.

Currently, FAS carries out inspections of compliance of price bids for the sale of electricity (capacity) and economic justification requirement. Antitrust law also suggests preventing abuse of dominant position. In accordance with Federal Law 35-FL “On electric power industry” recognizes the dominant position of an economic entity (group of persons), if at least one of the following conditions is satisfied:

1) The share of the installed capacity of the generating equipment or its share of generation of electricity within the area of free flow exceeds 20 percent;
2) the share of purchased or consumed electric energy and (or) capacity within the boundaries of the free flow respective zone exceeds 20 percent.
3) The amount of revenue is determined in accordance with Article 248 - 249, 271 of the Tax Code of the Russian Federation.

In accordance with Article 3.5 of the Administrative Code of the Russian Federation, the size of the fine is determined as a multiple value to the amount of income of the violator from selling goods (services) on the market where the administrative violation, for the calendar year preceding the year in which an administrative offense was revealed, either preceding the date of detection of an administrative violations of the calendar year in which an administrative offense was revealed if the offender is not involved in the sale of goods (services) in the preceding calendar year, but may not exceed 4%.
Playing with the “nature” for WGC-2 is presented in the Table 1 below, where Strategy 1 indicates margin strategy; strategy 2 indicates financial withdrawal, strategy 3 depicts physical withdrawal, and strategy 4 means joint physical and financial withdrawal [13, 14].

As one can observe, the regulation by the FAS is expressed in the form of lower profits as a result of imposition of sanctions for manipulation of prices as a result of joint action. Moreover, the amount of the penalty varies from 500 thousand Roubles to 1 million Roubles. Daily profit calculation of was made on the assumption that all other companies follow margin strategy.

**Table 1:** Daily profit of WGC-2 when playing the "nature" game (in millions of Roubles)

<table>
<thead>
<tr>
<th>Players</th>
<th>Strategies</th>
<th>Low level of regulation</th>
<th>Average degree of regulation</th>
<th>High level of regulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>WGC-2</td>
<td>Strategy 1</td>
<td>10.7</td>
<td>10.7</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td>Strategy 2</td>
<td>10.7</td>
<td>10.7</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td>Strategy 4</td>
<td>11.12</td>
<td>10.42</td>
<td>10.12</td>
</tr>
</tbody>
</table>

**Source:** own results

As one can see, under regulated conditions in the case of applying the criterion of extreme pessimism (Wald’s criterion) the best strategy for generating company should be marginal strategy, and in the case of applying the criterion of extreme optimism the best strategy should be physical withdrawal.

**5 Conclusions**

Our paper provides analysis of the potential application of game theory in the competitive sector of the wholesale market of electricity and capacity for the development of the algorithm for selecting the best generating company strategy, allowing taking into account the possible effects of regulators’ response. It appears that company’s daily profit is the best criterion for the efficiency of the best strategy selection of the generating company.

Furthermore, we consider the application of the "nature" game for the generation company which carries out its economic activity on the territory of the operational zone of South UES (where regulation by the FAS is studied as a "nature" game). We demonstrate that FAS carries out inspections of compliance of price bids for the sale of electricity (capacity) and economic justification requirements.

Our results show that in the case of applying the criterion of extreme pessimism (Wald’s criterion), the best strategy should be a strategy of margin formation of a price offer, and in the case of applying the criterion of extreme...
optimism, the best generating company strategy will be the strategy of physical withdrawal of part of cheap electricity (capacity).

Our findings might allow generating companies to better assess the potential impact of the implementation of financial and physical withdrawal considering possible regulatory responses to their actions.

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