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Optimal bidding strategy in a competitive electricity market based on agent-based approach and numerical sensitivity analysis

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ABSTRACT

The objective of this study is to present a new method for determination of the optimal bidding strategies among generating companies (GenCo) in the electricity markets using agent-based approach and numerical sensitivity analysis (NSA). While agent-based approach provides for decision making, NSA can help with identifying the critical control points that lead to proper decisions to be taken by GenCos. To achieve the objective, the pricing mechanism used for settling the electricity market and determining the GenCos rewards is locational marginal pricing (LMP) and the sensitivity of each GenCo reward with respect to its bid is analyzed, then, the optimal strategy is determined. An example and a case study are used to illustrate the efficiency of the proposed method. The LMPs and allocated generations of GenCos show that the proposed method leads GenCos to learn a strategic manner and, as a result, increase prices and maximize their rewards. To validate the proposed method, the results from this study are compared with those available in the literature. The comparison of results shows an improved simulation time by 8.16 percent and total reward of market by 2.46 percent.

1. Introduction

In competitive electricity markets, a generating company (GenCo) is considered responsible for maximizing its reward. With this purpose, GenCos establish economic goals in the long and short terms that involve adjustment of their technical output or self-scheduling. Bidding strategies are composed of sets of price–production pairs designed to accomplish these goals in the short term [1].

GenCos in the electricity market industry are looking for policy guidance on how to determine an appropriate electricity pricing system. A price change in the wholesale electricity market occurs due to several socio-economic and engineering factors including a) an imperfect market structure, b) a possible existence of a market power (market power is defined as the ability of a seller to maintain prices above competitive levels for a significant period of time [2]), c) an occurrence of congestion in transmission, d) different speculation views among traders, e) imperfect information on electricity transmission, f) different bidding approaches among traders, g) a system failure and a maintenance problem and h) a price change of fuel. Thus, the wholesale electricity market can be considered as a complex system [3].

The above noted complexities have caused a shift from rational behavior and equilibrium toward heterogeneity and adaptivity for economic analysis. At the same time, the tremendous availability of computational resources has made it possible to set up large-scale and detailed computational models that allow a high degree of design flexibility. As mentioned above, electricity markets are complex systems and can benefit from decision-making models such as agent-based approach. Agent-based models offer the possibility of not only describing relationships in complex systems, but also allowing them to grow in an artificial environment and dealing with large-scale computations [4].

In the literature, the agent-based approach is used to study various complex systems. The applicability of the approach is found in computer sciences and decision making in operations research. For example, Samuelson [5] discusses how to apply agent-based approach to various social systems for optimization purposes.

Sueyoshi and Tadiparthi [3,6] apply agent-based approach in an electricity market study. In modeling various types of agents the noted studies incorporate several adaptive learning capabilities based upon reinforcement learning.

2. Previous research on power trading is examined based on the following classifications

2.1. Behavioral analysis

This classification argues about the GenCos bidding strategies and their behavior in the electricity markets. It provides an

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Nomenclature

A. Variables

F_l	Power flow on line *l*.
$k^1_{i,t,j}$, $k^2_{i,t,j}$	Mark-up ratios for GenCo *i* at period *t* and iteration *j*.
$\mathrm{LMP}_{i,t,j}$	Locational marginal price at node *i* for period *t* and iteration *j*.
$\mathrm{MC}_{i,t}$	Marginal cost of each GenCo.
$P_{i,t,j}$	Generation amount allocated to GenCo *i* at period *t* and iteration *j*.
$P_{i,n}$	Bidding quantity for block *n* of GenCo *i*
$R_{i,t,j}$	Reward of GenCo *i* for period *t* and iteration *j*.
$\rho_{i,n}$	Bidding price for block *n* of GenCo *i*
$\mathrm{status}_{i,t,j}$	$= \begin{cases} 1 & \text{if GenCo } i \text{ generates at period } t \text{ and iteration } j \\ 0 & \text{if GenCo } i \text{ dos not generate at period } t \text{ and iteration } j \end{cases}$
sena, senb	Sensitivities of reward w.r.t. MC coefficients
$\Delta k_{i,t,j}$	Difference between 2 consecutive bids.
$\Delta R_{i,t,j}$	Difference between 2 consecutive rewards obtained from 2 random bids.

B. Constants

a_i,b_i,c_i	Cost function coefficients for GenCo *i*.
block_i	Number of blocks for GenCo *i*.
d_t	Demand for period *t*.
$F_{\min,l}$,$F_{\max,l}$	Lower and upper flow limits on line.
L	Number of lines in the network.
N	Number of GenCos ($i = 1,\ldots, N$).
$P_{\min,i,n}$,$P_{\max,i,n}$	Lower and upper bounds of block *n* of GenCo *i*
T	Number of periods ($t = 1,\ldots, T$).

C. Indices

i	Index for GenCos.
j	Increment index of the DG process.
l	Index for lines.
m	Increment index of the RB process.
n	Index for blocks.
t	Time index

D. Matrixes and vectors

B	Susceptance matrix of network.
P_D	Constant vector of bus loads.
P_G	Vector of bus generation, with P_i as an element.
SENA	Sensitivity of reward w.r.t. k^1 with condition$\Delta R \geq 0$.
SENB	Sensitivity of reward w.r.t. k^2 with condition$\Delta R \geq 0$.
SEN_A	Sensitivity of reward w.r.t. k^1
SEN_B	Sensitivity of reward w.r.t. k^2
Δk^1, Δk^2	Difference between 2 consecutive bids with condition$\Delta R \geq 0$.
θ	Vector of bus voltage angles.

analytical rationale regarding how wholesale electricity market price affected by market power. Behavioral analysis is methodologically limited to price predictability [6].

2.2. Numerical analysis

Artificial intelligence techniques such as artificial neural networks (ANN) and genetic algorithms (GA) are used in this classification. Numerical analysis is used to predict price changes under the dynamic fluctuations of other factors such as weather that influences the electricity demand. However, there is no theoretical rationale about the estimation reliability of ANNs. The GA method is useful when electricity markets are not volatile [6].

2.3. Agent-based analysis

Multi-agent adaptive systems are used in this classification for dynamic bidding processes in the electricity markets, where bidding decisions are affected by several uncontrollable factors. A new type of numerical analysis is introduced by this classification to deal with business complexity on power trading [6,7].

The agent-based approach roughly consists of three elements [8]:

- A set of agents.
- A set of agent relationships.
- A framework for simulating agent behaviors and interactions.

In a multi-agent environment each agent attempts to optimize its cost function that is strongly influenced by price and as mentioned previously, the market price is affected by different factors. The agent-based approach includes these factors in modeling of relationships between agents. It must be noted that incorporating these factors in a closed form analytical cost function equation is not possible. When the agents cost function is obtained from agent-based modeling, sensitivity analysis is used (as a reinforcement learning for agents) to identify the most important factors of risk and to develop strategies for risk mitigation and obtain an optimal bidding strategy.

Sensitivity analysis has been identified as one of the principal quantitative techniques used for risk management in the United Kingdom. It also can be used in decision making for examining robustness of model results [9]. Sensitivity analysis methods are applied in various fields including complex engineering systems, economics, physics, social sciences, medical decision making, and others.

In electricity markets, GenCos can use information on sensitivity of reward to bids and determine the optimal bids by taking into account both maximum individual profit and system security. Further, if GenCos can make coalition with others units (or companies) belonging to the same company or with other rivals, sensitivity of reward to bids will be important. From this point of view, sensitivity analysis is also useful for the market regulator to investigate the potential coalition or market power [10].

He et al. [10] present the first-order derivatives of nodal prices, generation outputs, unit profits and transmission line power with respect to each GenCos bids. The bids sensitivities are derived based on the interior-point optimal power flow model that is used for an individual GenCo to generate its optimal bids in the electricity market. However, they did not consider learning capability for players. Also, in that study, the GenCos game alternatively, not simultaneously, and agent-based approach is not used. Oh and Thomas [11] and Cain and Alvarado [12] explored a mathematical method for detecting groups of GenCos, in an electricity market, that have the potential to benefit from exercising market power. The revenue and dispatch to bid sensitivity matrices are developed and used to identify load pockets and exercising of market power. Conejo et al. [13] provided a simple analytical expression to