Design and Analysis of Simulation Experiment of Bidding Game for Power Suppliers in Electricity Market Teaching

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Abstract

As the most widely used secondary energy source, market-based trading of electricity energy will further improve the formation mechanism of electricity price, realize the optimal allocation of low-carbon electricity resources, and effectively promote the achievement of the carbon peak and carbon neutral goals. In order to make students majoring in electrical engineering understand the electricity market more intuitively, the spot market was taken as an example. The market power of power suppliers was analyzed theoretically, and an electricity spot price discovery method based on the experimental economics of the power suppliers' bidding game was proposed. By using the simulation platform for cyber-physical-social system (Sim-CPSS) of NARI Group Corporation, the experiments were designed for students to participate in a realistic simulation experiment of electricity spot trading, in which a uniform clearing price market settlement method is used to simulate electricity spot trading. The experimental economics simulation will consolidate the students' knowledge on electricity markets and form a feedback learning paradigm through the integration of theoretical study and practical application.

Keywords: *Electricity market teaching; Experimental economics; Bidding game; Simulation experiment; Sim-CPSS*

1 INTRODUCTION

Energy use is the main source of carbon emissions in social activities, and electricity is the most widely used secondary energy source, which is the link between primary and final energy sources [11]. President Xi Jinping stressed the need to build a new electricity system with new energy sources as the mainstay at the Central Finance and Economics Commission's ninth meeting on March 15, 2021, in order to support the achievement of the "double carbon" goal [12]. On November 24, 2021, President Xi Jinping presided over the 22th meeting of the central committee for comprehensively deepening reform, in which the "Guidance on Accelerating the Construction of a National Unified Electricity Market System" was reviewed and passed [14]. Market-based electricity trading provides an effective means for price discovery of electricity. In order to give full play to the supporting role of electricity market in the low-carbon transformation of energy, in addition to promoting the construction of electricity market mechanisms that adapt to the transformation of the energy structure, it is necessary to focus on the cultivation of professional talents related to electricity market trading.

Simulation is an effective means of grasping the interaction of subjects and the behaviour of complex systems. There are currently two main technical branches of electricity market simulation: experimental economics simulation and computational economics simulation [4]. Computational economics simulation is mostly based on game theory equilibrium models or computer agent models. Game equilibrium models are mainly used to study how multiple stakeholders make optimal decisions [10] [20], and computer agent models are generally implemented with the help of heuristic algorithms or intelligent algorithms [7] [8]. Experimental economics explores the intrinsic laws that govern economic

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behaviour in a given social context through experiments involving human participants [1]. It overcomes the problem that the research of market economics and social science can not take into account the influence of finite rational or irrational game behaviour, and provides strong support for mechanism research and decision optimization [21]. Literature [2] applies experimental economics method to electricity market simulation by organizing classroom experiments to investigate simple electricity market bidding strategies.

In order to make students or trainees more intuitive and familiar with spot trading in the electricity market, forming a feedback mechanism for theoretical learning and practical application. Firstly, the influence factors of electricity spot market are analysed. Then, an electricity spot price discovery method based on experimental economics of power suppliers' bidding game is proposed. Finally, a simulation platform for cyber-physical-social system (Sim-CPSS) of NARI Group Corporation (NARI) is used to design an experiment based on experimental economics of electricity spot price trading. By organizing and carrying out the simulation of the bidding game with the actual participation of the trainers, it is possible to simulate the electricity spot trading using the settlement method of uniform clearing price.

2 ELECTRICITY SPOT MARKET

The spot market is an important part of the electricity market and is the main market for electricity generation trading. The spot market in financial markets usually refers to the real-time market for physical delivery of commodities. Due to the physical characteristics of real-time balance of power commodities during delivery, the scope of the electricity spot market often extends beyond the real-time market to the hour-ahead and day-ahead market. The spot clearing price for any future period in a competitive market is uncertain and can only be obtained from the laws of market supply and demand. Factors that determine the distribution of clearing prices include:

(1) Bidding price of power suppliers

(2) The uncertainty of load in future periods

(3) Unit availability (which reflects random variations in unit output)

(4) Trading market rules and settlement mechanisms

The power suppliers' market bid means the optimal combination of its own characteristics, market prospects and various constraints to form its own bidding strategy to achieve certain market goals. Market power generally refers to the ability of a market participant to make the price of its product significantly higher than the price in a perfectly competitive market over a long period of time [18]. Due to the physical, technical, and economic particularity of electric energy, which leads to the electricity market being a typical oligopolistic market, the role of market power of power suppliers is obvious and difficult to control.

The main ways for power suppliers to implement market power are physical retention, which refers to power suppliers intentionally declaring generation capacity below the actual available capacity, and economic retention, which refers to power suppliers bidding exceeds the marginal cost of the units. Although both approaches result in generation capacity retention by the power suppliers themselves, they still have the potential to earn excess profits due to higher market clearing price.

3 SPOT ELECTRICITY PRICE DECISION METHOD BASED ON SIM-CPSS

The essential difference between computational economics simulation and experimental economics simulation is whether the subjective behaviour (people's economic activity or decision) can be accurately described by an objective model. The former believes that it can be accurately described, and there is no human participant involvement in the process of computational economics simulation, and typical simulation applications include MASCEM [13], AMES [3], etc. The latter believes that it can not be accurately described, so that there is human participant in experimental economics simulation, and the links that can be expressed by mathematical models in the experiment will constitute the experimental environment, and the specific game of market participants will be used as the external input of the experimental environment, so that the interactive simulation of human subjective behaviour and the experimental environment model can be carried out, and the representative simulation application is PowerWeb [9].

In response to the problem that general simulation platform is not easy to solve the interaction problem between different time scale dynamics, NARI has independently developed a dynamic simulation platform Sim-CPSS [5] [15] [16] [19]. Sim-CPSS has the functions of supporting multi-domain problem joint simulation, multi-time scale dynamic simulation, multi-role multi-participant dynamic interaction, and flexible and open design architecture. The applications that have been developed based on Sim-CPSS include the study of long-term oscillation mechanism of generation capacity, transmission dynamic blockage management [17], and the impact of emission trading system on power industry [6].

3.1 Bidding and trading module and decision mechanism of power suppliers

The electricity market is an economic system with multi-actors, multi-participants gaming dynamically, and the market participants include power suppliers, power distributors, power users, power grid companies, trade management agencies, regulators, etc., and each type of role may be composed of multiple participants. In the power supplier bidding game simulation, the spot price in the market environment is ultimately determined by the power suppliers' offer strategies due to the certainty of the market rules and settlement mechanism, as well as the predictability of the grid load. While computational economics simulations can not take into account the limited rational or irrational decision-making behaviours of power suppliers, the experimental economics approach explores the intrinsic laws governing economic behaviour through experiments involving human participants, freeing the reliance on models.

Sim-CPSS provides a simulation platform that can accept the participation of human experimental participants, and adds the simulation module of power supplier bidding to the existing simulation module, as shown in Figure 1, so as to support the human-computer interaction between the game behaviours of participants and the mathematical models.

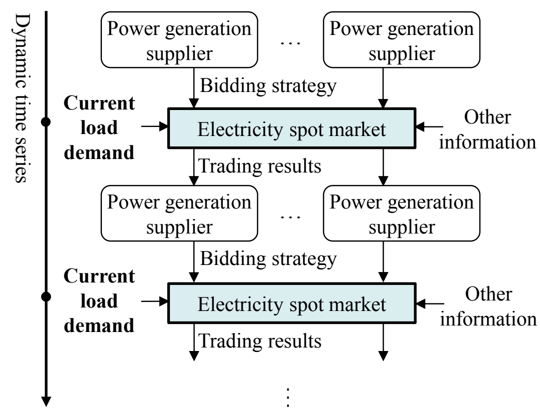


Figure 1: Power supplier bidding module and simulation process.

The human participant in the power supplier bidding game simulation is the power supplier. As the simulation is a unilateral market bidding model, the load here is not a participant, the transaction clearing method is a mathematical model, including the relevant trading algorithm.

The experimental participants form their own bidding strategies based on their judgment of the market situation and market trend, combined with their own characteristics and risk appetite, and interact with the mathematical model through the operational interface provided by the human-machine interface, and form the market spot price of electricity through the price clearing model.

3.2 Power supplier revenue model

The power supplier revenue model is shown in equation (1).

$$M^g(t) = \sum_{i=1}^{N^g} q_i^g(t)\left(c_{mcp}(t) - c_i^g\right) \quad (1)$$

Where: $M^g(t)$ is the profit of the power supplier at time t, N_g is the number of generating units owned by the power supplier, $q_i^g(t)$ is the bid volume of unit i at time t, $c_{mcp}(t)$ is the market clearing price at time t, c_i^g is the marginal cost of unit i.

3.3 Market clearing model

The clearing method of the power spot trading market is shown in Figure 2, in which transactions are made according to the quotation of the generator set from low to high, and the total clearing amount is equal to the load demand. The last closing unit is called the marginal unit in the market, and the clearing price adopts the uniform clearing price (that is, all closing units are settled according to the bidding price of the marginal unit).

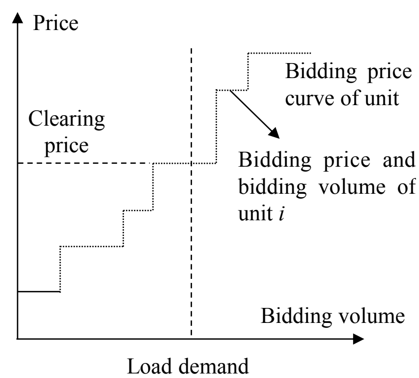


Figure 2: Uniform clearing price model.

3.4 Dynamic time series

Time series is the main feature of dynamic simulation. Unlike physical transient simulation, the time series of economic system dynamic simulation is more complex, and in addition to the basic time steps, there are also logical steps describing the processes of trading and investment. Above the small time scales, there are also larger time scales, forming a situation where dynamic behaviours of multiple time scales coexist.

In the power supplier bidding simulation, the basic time step is set as hourly because the spot market generally bids before hours. In order to realize the simulation of spot quotation and aggregation of each hour, we first configure the time series to generate hourly time steps, and then place a sequential sequence above the hourly time steps to generate several steps such as "bidding assist decision, display biddings, and aggregate and clear". Each step contains the following activities.

a. Bidding assist decision

Based on the unit cost function and the expected profit of the power suppliers, a new round of bidding factors is set for each unit.

b. Display biddings

Sending the formed bidding form to the power suppliers, who can view and adjust the default offer on this offer screen and submit the final offer.

c. Aggregate and clear

After all power suppliers submit their final biddings, the trading center collects the bidding forms from each power supplier, completes the aggregation and clearing, and publishes the clearing results.

4 EXPERIMENTAL PROCESS DESIGN FOR SPOT PRICE DECISION SIMULATION

4.1 Preparation Stage

When the network is unobstructed, the Sim-CPSS Server software on the server is first started by the experiment administrator, and the simulation script of power supplier bidding is loaded after logging in, and the simulation script is in the preparation stage in the form of a simulation project. Then, the participants use the browser software on the client to log into the Sim-CPSS Server and enter the simulation project, as shown in Figure 3.

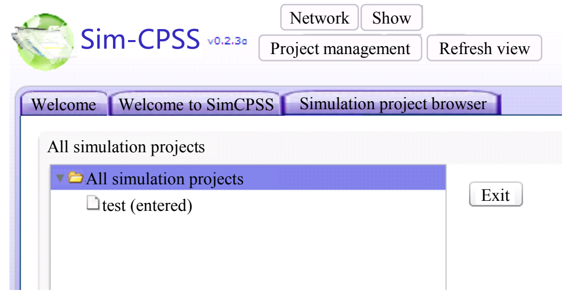


Figure 3: The process of participants joining the simulation project.

When the number of participants reaches the total number of avatars in the project, the experiment administrator initiates the "pairing" process (see Figure 4) and points the avatars to the participants playing it according to the prior agreement. After completing this step, the project enters a "pending" state.

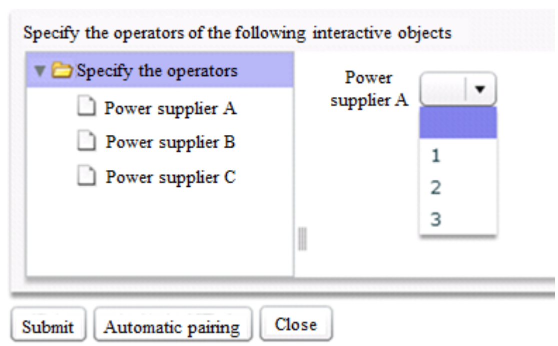
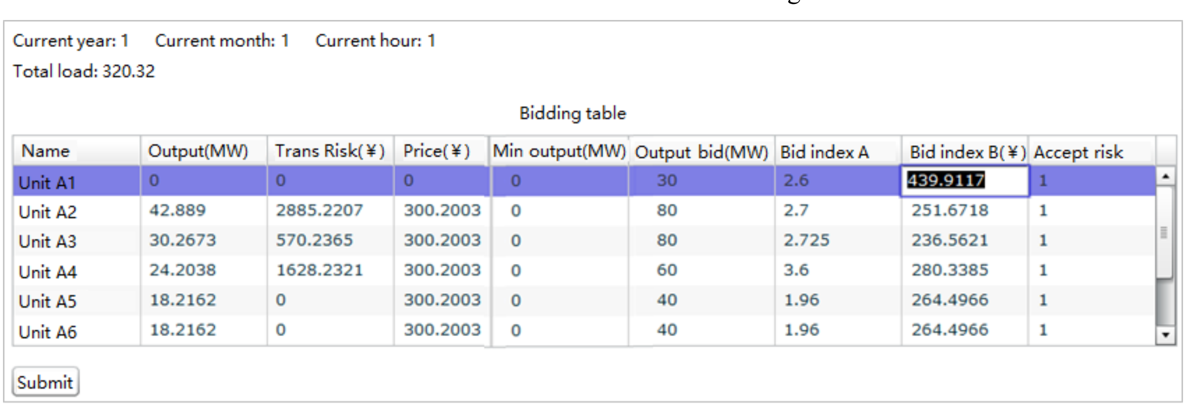


Figure 4: Pairing process of participants and avatars.

4.2 Run Stage

After the simulation project is started, the simulation runs according to the proposed time sequence. The power suppliers draw up their offer strategies (as shown in Figure 5), the market trading module receives the bidding parameters of each unit, and the market trading module clears the market after computing and feeds the results to each power supplier. In multiple rounds of iterative offer, power suppliers can clearly see the trading situation of their units, and then modify their biddings for the next round of bidding simulation.


Current year: 1 Current month: 1 Current hour: 1
Total load: 320.32

Bidding table

Name	Output(MW)	Trans Risk(¥)	Price(¥)	Min output(MW)	Output bid(MW)	Bid index A	Bid index B(¥)	Accept risk
Unit A1	0	0	0	0	30	2.6	439.9117	1
Unit A2	42.889	2885.2207	300.2003	0	80	2.7	251.6718	1
Unit A3	30.2673	570.2365	300.2003	0	80	2.725	236.5621	1
Unit A4	24.2038	1628.2321	300.2003	0	60	3.6	280.3385	1
Unit A5	18.2162	0	300.2003	0	40	1.96	264.4966	1
Unit A6	18.2162	0	300.2003	0	40	1.96	264.4966	1

Submit

Figure 5: Bidding interface of power supplier.

4.3 Results Analysis Stage

After the proposed dynamic time sequence is run, the simulation project enters the "completed" state. In this state, all power suppliers can access the pre-designed analysis functions in the simulation script and mine useful information from the result database.

4.4 Assisted Decision Support

The decision effects of dynamic processes often have time lag characteristics, so decision studies need to go back to historical scenarios. The scenario of a dynamic process is also dynamic, not only the parameters change, but also the relationships between objects.

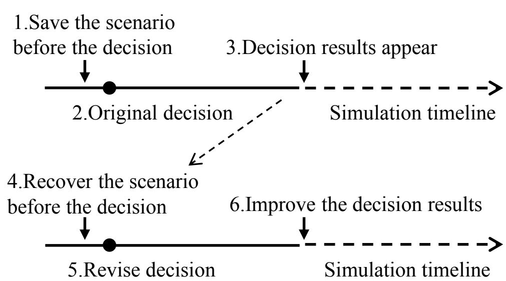


Figure 6: Save simulation scenario.

The simulation script provides the function to save the simulation scenario at any time (as shown in Figure 6). This feature saves an image of the complete scenario at any point in the simulation into a file, from which it can be restored to the scenario when needed, and run down from the scenario, allowing the power supplier to regain control of the original role by "pairing" the process again.

5 SIMULATION CASES OF POWER SUPPLIER BIDDING

In addition to objective factors such as the competitiveness of the units and the power system load (hereafter expressed as load ratio, which is the value of load divided by power system installed capacity) that affect the competition in the market, the bidding objectives of the power suppliers (maximizing profit, maximizing market share, and minimizing the other party's revenue) are issues that need to be considered when submitting a bidding strategy.

5.1 Simulation Setup

There are three power suppliers in the simulation case (the names of their units are listed in Table 1), and the installed capacity and competitiveness of the three power suppliers are basically the same (the parameters of each unit are listed in Table 2), and the total installed capacity of the system is 6000MW.

Table 1: Power suppliers' units.

Power supplier	Owned units
A	A1，A2，A3，A4，A5，A6，A7，A8，A9
B	B1，B2，B3，B4，B5，B6，B7，B8，B9
C	C1，C2，C3，C4，C5，C6，C7，C8，C9

Table 2: Cost parameters of each unit.

Unit	Min output (MW)	Max output (MW)	Marginal cost (￥/MWh)
A1	0	360	161.2
A2	0	330	333.3
A3	0	270	192.3
A4	0	250	250.0
A5	0	220	277.7
A6	0	150	281.6
A7	0	130	357.1
A8	0	110	333.3
A9	0	100	238.0
B1	0	400	158.7
B2	0	320	333.3
B3	0	300	196.0
B4	0	250	250.0
B5	0	220	285.7
B6	0	200	285.7
B7	0	130	350.8
B8	0	100	333.3
B9	0	90	232.5
C1	0	360	163.9
C2	0	340	333.3
C3	0	300	196.0
C4	0	250	243.9
C5	0	220	270.2
C6	0	200	277.7
C7	0	170	363.6
C8	0	130	333.3
C9	0	100	243.9

Table 3: Simulation case settings (power suppliers B and C bid at marginal cost).

Case	Bidding strategy of power supplier A
1	Bids at marginal cost
2	A1 bids 400.0￥/MWh, A3 bids 450.0￥/MWh
3	A4 bids 550.0￥/MWh，A5 bids 577.0 ￥/MWh A6 bids 581.0￥/MWh，A9 bids 538.0 ￥/MWh
4	A2 bids 633.0￥/MWh，A7 bids 657.0 ￥/MWh A8 bids 633.0￥/MWh

5.2 *Results and Analysis*

(1) Case 1 (bid at marginal cost)

The profit of each power supplier under this case is shown in Table 4. The experimental results show that the profits of all three power suppliers are very close to each other when bid at marginal cost under different load ratios, i.e., each power supplier has very close competitiveness in the low, medium and high cost ranges.

Table 4: Power suppliers' profits at each load ratio.

Power supplier	Profits of power suppliers (ten thousand ￥)		
	Load ratio 0.3	Load ratio 0.6	Load ratio 0.9
A	1.4	7.6	15.0
B	1.5	8.3	16.1
C	1.2	7.9	15.8
Clearing price(￥/MWh)	196.0	277.7	333.3

(2) Case 2 (low cost unit bidding high price)

The profit of each power supplier under this case is shown in Table 5. power supplier A increases the bidding price of its two most competitive units to 400.0￥/MWh and 450.0￥/MWh respectively, which is much higher than the clearing price at marginal cost, which obviously results in these two units not being selected and the market clearing price being increased. Since the other two power suppliers still offer at marginal cost, power supplier B and C gain a larger market share and earn more profit than that in case 1.

When the load ratio is very low, the supply in the market is much higher than the demand, and the low-priced units will lose more money by bidding higher prices, which is also confirmed by the comparison of the profit change at different load ratios in case 1 and case 2.

Table 5: Power suppliers' profits at each load ratio.

Power supplier	Profits of power suppliers (ten thousand ￥)		
	Load ratio 0.3	Load ratio 0.6	Load ratio 0.9
A	0.1	1.6	8.6
B	4.9	9.1	22.0
C	4.3	9.0	21.6
Clearing price(￥/MWh)	243.9	285.7	363.6

(3) Case 3 (medium-cost unit bidding high price)

The profit of each power supplier under this case is shown in Table 6. At a load ratio of 0.3, the units are outside the margins, so their higher price will not affect the market clearing. At a load ratio of 0.6, units A4, A5 and A9, which originally won the bidding, enter outside the margin due to the high price bidding, and their market shares are heavily compressed, but since the market clearing price is greatly raised, the profit of power supplier A increases, and the profits of the remaining power suppliers increase significantly with the double increase of electricity price and feed-in power volume. At a load ratio of 0.9, a large number of medium-cost units (more than 10% of the total installed capacity of the system) that raise their biddings inevitably lead to full generation of power suppliers B and C, who bid at marginal cost.

At a load ratio of 0.9, power supplier A bids a high price for unit A9 as the marginal unit, and the high load ratio causes A9 to win the bid even after the bidding is further raised, i.e., the scarcity of power generation leads to a spike in the price of electricity. In the electricity market, some power suppliers tend to take advantage of this and deliberately raise their biddings.

Table 6: Power suppliers' profits at each load ratio.

Power supplier	Profits of power suppliers (ten thousand ￥)		
	Load ratio 0.3	Load ratio 0.6	Load ratio 0.9
A	1.4	10.0	35.3
B	1.5	16.1	57.0
C	1.2	15.8	57.7
Clearing price(￥/MWh)	196.0	333.3	538.0

(4) Case 4 (high cost unit bidding high price)

The profit of each power supplier in this case is shown in Table 7. At the load ratio of 0.3 and 0.6, since these units are marginal units, their raising of price will not affect the market clearing. At the load ratio of 0.9, the units A2 and A8 of power supplier A in case 1 are marginal units. However, due to the high price bidding, its share is replaced by the high-priced units of other power suppliers who bid at marginal cost, and unit C7 of power supplier C becomes the new marginal unit. Since the medium- and low-cost units are bidding at cost and the total capacity of units bidding high prices (440 MW) is less than 10% of the total installed capacity, this part of units fails to become scarce capacity of the system and has limited effect on raising the market clearing price.

Table 7: Power suppliers' profits at each load ratio.

Power supplier	Profits of power suppliers (ten thousand ￥)		
	Load ratio 0.3	Load ratio 0.6	Load ratio 0.9
A	1.4	7.6	19.1
B	1.5	8.3	22.0
C	1.2	7.9	21.6
Clearing price(￥/MWh)	196.0	277.7	363.6

5.3 Summary of Cases

(1) The market adopts a uniform clearing price method, so the units with low generation costs are the most competitive and earn the most substantial profits, which fully illustrates the impact of unit competitiveness on power suppliers' revenue.

(2) The bidding strategies adopted by power suppliers will affect the market clearing price and the revenue of each participant, and the same strategy will have different effects under different load ratios.

(3) The market is not affected if the unit within the margin raises its bidding but does not exceed the marginal price. The market price is raised if the bidding is raised and exceeds the marginal price.

(4) The power suppliers lack the ability and incentive to raise their prices at low load.

(5) Power suppliers' profits are directly proportional to the price and volume of electricity traded, and when they raise their biddings, most of the time their own volume decreases (except when they become scarce), and the change of its profit depends on which one has the larger change.

6 CONCLUSION

The interactive dynamic simulation of participants based on experimental economics can solve the problem that it is difficult to model participants' behaviour, and its decision-making scheme can better reflect the decision-making behaviour of market participants in the real market with the available bidding information. The Sim-CPSS simulation platform is designed to explore the spot price of electricity market by using the decision mechanism of human experimenters bidding and clearing the spot price at a uniform price. By organizing students or trainees to actually participate in the bidding game, the spot price of electricity market can be explored.

The simulation experiment of spot price bidding game with the participation of human experimental participants constructs a feedback mechanism for theoretical learning and practical application. The power supplier bidding is a long-term dynamic process in the electricity spot market trading, and the subsequent experimental case of spot trading with multiple rounds of bidding decision iteration by multiple people will be carried out to deeply analyze the motivation of market participants to implement market force, which helps power suppliers to understand their competitive position and rival strategies, and finally makes the market bidding decision to reach a more stable balance.

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