Financial Engineering and Risk Management (2022)
Clausius Scientific Press, Canada

DOI: 10.23977/ferm.2022.050508
ISSN 2523-2576 Vol. 5 Num. 5

Bidding Strategy of Thermal Power Enterprises Based on Evolutionary Game

Sijia Shen*

Zhejiang Windey Co.,Ltd., Hangzhou, 310012, Zhejiang, China
**Corresponding author*

Keywords: Evolutionary game theory, power generation market, thermal power unit bidding strategy

Abstract: Deepening the reform of the electricity market and increasing the permeability of new energy gradually reduce the generating space of conventional power sources in the electricity market, which requires more flexible regulation functions, and puts forward higher requirements for the bidding strategy of thermal power generation enterprises. It is necessary to formulate countermeasures to adapt to the policy requirements and market competition mechanism of thermal power units with different technical characteristics, to achieve sustainable transformation and sound development. In this paper, a three-group, two-strategy evolutionary game model was constructed for three types of power generation enterprises with typical unit capacity in the current power generation market, and a multi-scenario analysis of strategy simulation was conducted under different new energy permeabilitys based on the data from the East China power market. The research results show that market clearing price, permeability of new energy, and technical characteristics of thermal power units have a greater impact on the bidding income of thermal power enterprises. In order to guide the efficient competition of thermal power units in the power market, the government and regulatory authorities should regulate the relative net payment parameters that best meet the expectations and formulate reasonable trading rules.

1. Introduction

As the electricity market on the power generation side has gradually developed and matured, the initiative of power generation enterprises to participate in the market competition and the market competitiveness can be effectively improved by introducing the bidding mechanism, thus reducing the total cost of social electricity consumption. In the bidding process of power generation enterprises, enterprises seek to maximize economic benefits by formulating reasonable bidding strategies. However, in the process of promoting the realization of the “carbon peaking and carbon neutrality”, the traditional thermal power generating units are oriented towards the green and low-carbon transformation direction of “more efficient, cleaner and reduction”. Therefore, it is necessary to increase the forward-looking research on thermal power generating enterprises and formulate corresponding countermeasures for thermal power units with different technical characteristics.

The main idea of game theory is to build a game model on the basis of clarifying the trading behavior of the participants in the electricity market, and then to find the equilibrium point to obtain the optimal bidding strategy of each participant. The evolutionary game theory based on “bounded rationality” and “limited information” hypothesis is introduced into the research of power market to analyze the increasingly complex power market. At present, some scholars have applied evolutionary game theory to study the dynamic behavior decision of enterprises in the open electricity market. In references [1-2], the competitive co-evolutionary game algorithm is used to model the equilibrium calculation in the electricity market as solving a two-stage stochastic evolutionary game problem, and the behavior of power generation enterprises in the electricity market is simulated and analyzed. In reference [3], the interest coordination mechanism between power grid enterprises and renewable energy power generation enterprises is analyzed, and it is concluded that the interest coordination between power grid enterprises and renewable energy power generation enterprises is a situation of balanced interests formed in the process of dynamic and gradual evolution. In references [4-5], based on the research background of southern China’s regional electricity market, a market equilibrium evolution game model in which electric power companies and power generation enterprises participate in bidding together is established, and the strategic point for the electricity market to finally reach a stable equilibrium is given from the perspective of income distribution. In reference [6], the influence of resource constraints on the operation innovation and strategy choice of different power generation enterprises is discussed, and the dynamic evolution of innovative service of power generation enterprises under resource constraints is emphatically analyzed. In reference [7], a supervision model for the demand-side electricity market is built, and an empirical analysis is made on it. The research results and conclusions obtained have certain guiding significance and reference value for the supervision of the demand-side electricity market. In reference [8], the bidding behavior of power generation companies in the power market on the generation side is simulated and analyzed. In reference [9], the co-evolutionary game algorithm is introduced to model, and then the equilibrium in the electricity market is calculated aiming at the stochastic evolutionary game problem in the competitive electricity market. In reference [10], the dynamic evolution process of power generation enterprises in the electricity market under different behavior decisions is analyzed, and then the Nash equilibrium point of the dynamic model is solved and the stability of the solution is analyzed. In reference [11], a multi-strategy evolutionary game model of power generation enterprises is constructed, and the asymptotic stability conditions of the equilibrium point of multi-group evolutionary game are discussed. In reference [12], the strategy of disclosing quoted price is used in calculating the revenue matrix of each participant in the game pattern, and then the equilibrium point of the bidding matrix game of power generation enterprises is found.

Based on the above analysis and evolutionary game theory, in this paper, a three-group and two-strategy evolutionary game model was built for three types of thermal power enterprises with different technical characteristics in the current power market. By solving the equilibrium solution of the replicated dynamic equation, the evolutionary process and evolutionary stability strategy of the group bidding strategy selection of three types of asymmetric power generation enterprises were systematically investigated, and corresponding suggestions were put forward for bidding strategies of all participants in the power market on the generation side.

2. The Three-Group and Two-Strategy Evolutionary Game Model

2.1. Evolutionary Characteristics

The bidding evolutionary game model of thermal power enterprises has the following evolutionary characteristics:

(1) Power generation enterprises have the goal of maximizing their own profits, and they are all independent individuals.

(2) Because different power generation enterprises have different perceptions of market conditions

and different risk levels that each enterprise is willing to take, each participant has different bidding strategies, and also forms various trading behaviors.

(3) Power generation enterprises compete in the market mainly through electricity price, and can make decision-making optimization by analyzing the market electricity price. How each power generation enterprise quotes directly determines the amount of electricity won and the amount of income, because risking to quote a high-price may lead to failure to win the bid, while quoting a low-price may result in a smaller income.

(4) Power generation enterprises have the ability of autonomous learning. Instead of a single fight between power generation enterprises, they learn and imitate in the process of continuous repeated bidding, and adjust their bidding strategies for a long-term game.

2.2. Thermal Power Enterprise Revenue Function

Since the actual bidding is mainly based on the electricity price, only the variable cost is considered. By applying the regression analysis method to the historical data of the generation capacity and variable cost of conventional thermal power units participating in the bidding, the generation capacity-cost curve is obtained, which is then fitted by the quadratic function. The cost of the power generation enterprises can be expressed by the following quadratic function:

$$C_{i,j,t} = aP_{i,j,t}^2 + bP_{i,j,t} + c \tag{1}$$

The marginal cost of each unit can be expressed as:

$$MC_{i,j,t} = \frac{dC_{i,j,t}}{dP_{i,j,t}} = 2aP_{i,j,t} + b \tag{2}$$

Where, $P_{i,j,t}$ represents the power generation of unit j in generator i at time t; a, b, and c represent fuel cost coefficients related to electric power production of power generation enterprises. Power generation enterprises get a reasonable profit when the marginal revenue is equal to the marginal cost. The actual quotation of power generation enterprises will be adjusted appropriately in the actual game scenario to make the quotation higher or lower than the marginal cost, so the quotation curve function of power generation enterprises can be set as,

$$\lambda_{i,t} = m_{i,t} \sum\nolimits_{j \in J} (2a_i P_{i,j,t} + b) \tag{3}$$

Where,

$\lambda_{i,t}$ =the quotation of power generation enterprise i in t period;

$m_{i,t}$ = the quotation coefficient of the power generation enterprise i in t period.

As the unit cost data of power generation enterprises is confidential, the unit cost parameters of power generation enterprises can be reasonably selected according to the characteristics of cost function. In this paper, the cost coefficient of the cost function was selected according to the following conditions:

(1) a in the quadratic function should generally be negative, that is, the cost function curve is convex, and the actual data part is the rising part of the convex function;

(2) The central axis $x = -\frac{b}{2a}$ of the quadratic function should be slightly larger than the unit capacity, otherwise the negative cost growth may occur in the case of high-load power generation;

(3) A negative constant term in the quadratic function where $c \geq 0$ indicates that the unit has a negative cost when generating electricity, which does not meet the actual conditions;

(4) In order to make the research more practical, the cost coefficient is adjusted based on the above conditions so that the minimum generation cost should be lower than the current electricity price in the market.

Revenue function of power generation enterprises in the market can be expressed as,

$$y = q_{i,j,t}P_{i,j,t} - C(P_{i,j,t}) = (q_{i,j,t} - b)P_{i,j,t} - c - aP_{i,j,t}^2 \tag{4}$$

Where, a, b, c represent the fuel cost coefficients related to the power production of power generation enterprises, $P_{i,j,t}$ is the power generation amount of unit j in generator i in time t, $C(P_{i,j,t})$ is the total cost of power generation enterprises, and $q_{i,j,t}$ is the actual transaction price. The objective function is as follows:

$$y_{\max} = \max(q_{i,j,t}P_{i,j,t} - C(P_{i,j,t})) = \max((q_{i,j,t} - b)P_{i,j,t} - c - ap_{i,j,t}^2) \tag{5}$$

2.3 Strategy Definition

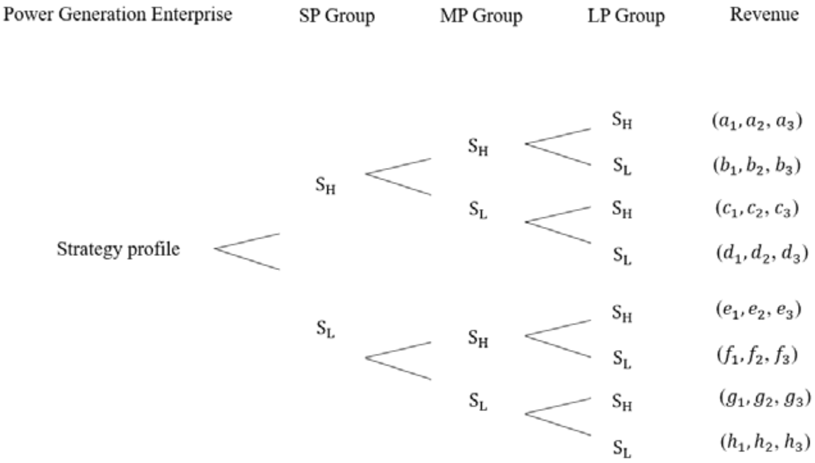


Figure 1: Tree diagram of income of power generation enterprises

The profit of power generation enterprises is mainly determined by their own bidding strategies and competitors' bidding strategies. The bidding process of power generation enterprises can be regarded as a game process of multi-group competition to maximize profits, in which the bidding strategies of power generation enterprises will influence each other, and will be continuously studied, imitated and adjusted in the game pattern. On the basis of evolutionary game theory, the spontaneous evolution process of bidding strategy of power generation enterprises in the bidding process was described in this paper. The power generation enterprises with three typical unit capacities in the current power generation market were selected and set as small (SP), medium (MP) and large (LP) power generation enterprise groups respectively. According to the bounded rationality hypothesis of evolutionary game theory, the power generation enterprise group does not need to be fully aware of the information of the competitors in the game structure, and its own computing power, risk awareness, and analytical reasoning ability are limited. Based on this, it is assumed that each group has only two bidding strategies: high-price strategy (SH) and low-price strategy (SL). The distribution of income payments is shown in Figure1 after the combination of two strategies of three groups of high-priced and low-priced bids.

In the above diagram, $a \sim h$ represents the actual income of various power generation enterprises under different strategy profiles. If the probabilities of SP choosing high-price and low-price strategies are x and 1-x, MP choosing high-price and low-price strategies are y and 1-y, and LP choosing high-price and low-price strategies are z and 1-z, respectively. The expected revenue of group SP adopting high-price strategy S_H is E_{SP1}, that of group MP adopting high-price strategy S_H is E_{MP1}, and that of group LP adopting high-price strategy S_H is E_{LP1}. Accordingly, the expected return of group SP adopting low-price strategy S_L is E_{SP2}, that of group MP adopting low-price strategy S_L is E_{MP2}, that of group LP adopting low-price strategy S_L is E_{LP2}. The average expected returns of group SP, group MP and group LP are $\overline{E_{SP}}$, $\overline{E_{MP}}$, $\overline{E_{LP}}$, respectively. The incomes are expressed as,

$$\begin{cases} E_{SP1} = y\left[za_1 + (1-z)b_1\right] + (1-y)\left[zc_1 + (1-z)d_1\right] \\ E_{SP2} = y\left[ze_1 + (1-z)f_1\right] + (1-y)\left[zg_1 + (1-z)h_1\right] \\ E_{MP1} = z\left[xa_2 + (1-x)e_2\right] + (1-z)\left[xb_2 + (1-x)f_2\right] \\ E_{MP2} = z\left[xc_2 + (1-x)g_2\right] + (1-z)\left[xd_2 + (1-x)h_2\right] \\ E_{LP1} = x\left[ya_3 + (1-y)c_3\right] + (1-x)\left[ye_3 + (1-y)g_3\right] \\ E_{LP2} = x\left[yb_3 + (1-y)d_3\right] + (1-x)\left[yf_3 + (1-y)h_3\right] \end{cases} \tag{6}$$

$$\begin{cases} \overline{E_{SP}} = xE_{SP1} + (1-x)E_{SP2} \\ \overline{E_{MP}} = yE_{MP1} + (1-y)E_{MP2} \\ \overline{E_{LP}} = zE_{LP1} + (1-z)E_{LP2} \end{cases} \tag{7}$$

The replication dynamic equation of the three-group evolutionary game is:

$$\begin{cases} f_{SP}(x) = \dfrac{dx}{dt} = x \cdot (E_{SP1} - \overline{E_{SP}}) = x(1-x) \cdot g_{SP}(y,z) \\ f_{MP}(y) = \dfrac{dy}{dt} = y \cdot (E_{MP1} - \overline{E_{MP}}) = y(1-y) \cdot g_{MP}(x,z) \\ f_{LP}(z) = \dfrac{dz}{dt} = z \cdot (E_{LP1} - \overline{E_{LP}}) = z(1-z) \cdot g_{LP}(x,y) \end{cases} \tag{8}$$

Where,

$$\begin{aligned} g_{SP}(y,z) = {} & (a_1 - b_1 - c_1 + d_1 - e_1 + f_1 + g_1 - h_1)yz + (b_1 - d_1 - f_1 + h_1)y \\ & + (c_1 - d_1 - g_1 + h_1)z + d_1 - h_1 \\ g_{MP}(x,z) = {} & (a_2 - b_2 - c_2 + d_2 - e_2 + f_2 + g_2 - h_2)zx + (e_2 - f_2 - g_2 + h_2)z \\ & + (b_2 - d_2 - f_2 + h_2)x + f_2 - h_2 \\ g_{LP}(x,y) = {} & (a_3 - b_3 - c_3 + d_3 - e_3 + f_3 + g_3 - h_3)xy + (c_3 - d_3 - g_3 + h_3)x \\ & + (e_3 - f_3 - g_3 + h_3)x + g_3 - h_3 \end{aligned}$$

According to equations (7) and (8):

$$\begin{bmatrix} \frac{dx}{dt} \\ \frac{dy}{dt} \\ \frac{dz}{dt} \end{bmatrix} = \begin{bmatrix} x(1-x)g_{SP}(y,z) \\ y(1-y)g_{MP}(x,z) \\ z(1-z)g_{LP}(x,y) \end{bmatrix} \tag{9}$$

The equilibrium point of the system satisfies the equation:

$$\begin{cases} x(1-x)g_{SP}(y,z)=0 \\ y(1-y)g_{MP}(x,z)=0 \\ z(1-z)g_{LP}(x,y)=0 \end{cases} \tag{10}$$

According to Lyapunov's stability theory, the corresponding Jacobian matrix can be obtained by the established replication dynamic equation, and then the stability of the equilibrium point can be discussed according to the characteristic root. According to equation (9), the Jacobian matrix of the three-party evolutionary game is:

$$J=\begin{bmatrix} J_1 & J_2 & J_3 \\ J_4 & J_5 & J_6 \\ J_7 & J_8 & J_9 \end{bmatrix} = \begin{bmatrix} \frac{\partial f_{SP}(x)}{\partial x} & \frac{\partial f_{SP}(x)}{\partial y} & \frac{\partial f_{SP}(x)}{\partial z} \\ \frac{\partial f_{MP}(y)}{\partial x} & \frac{\partial f_{MP}(y)}{\partial y} & \frac{\partial f_{MP}(y)}{\partial z} \\ \frac{\partial f_{LP}(z)}{\partial x} & \frac{\partial f_{LP}(z)}{\partial y} & \frac{\partial f_{LP}(z)}{\partial z} \end{bmatrix} \tag{11}$$

From the equation (10), the solution that makes the equation hold water is the equilibrium point, and only eight equilibrium points (0,0,0), (0,0,1), (0,1,0), (0,1,1), (1,0,0), (1,0,1), (1,1,0) and (1,1,1) can reach a stable evolution stable equilibrium under the condition of satisfying specific income to make it have solutions. In addition, C_1, C_2 and C_3 are the compensation expenses for the introduction of peak shaving auxiliary services, which can be analyzed and calculated according to specific cases to judge the stability of the balance point.

3. Scenario Analysis

In order to verify the effectiveness of the proposed model, three groups of power generating enterprises with sufficient generating units in the East China Power Bidding Market are taken as an example. All individuals in each group are regarded as having the same cost function and unit capacity. The group SP is a power plant with a generating unit capacity of 300MW, the group MP is a power plant with a generating unit capacity of 600MW, and the group LP is a power plant with a generating unit capacity of 1,000 MW. Then the bidding evolutionary game analysis is performed.

Three types of enterprises offer price by capacity segment, with six segments in total. The cost function of power generation enterprises is shown in Table 1. C_{SP}, C_{MP} and C_{LP} refer to the power generation cost of three types of power generation enterprises[13-14]. In this paper, it is assumed that 40% of the rated power of thermal power plants is the minimum stability limit of generating units.

The segmental bidding strategies of power generation enterprises under the two clearing prices are shown in Tables 2 and 3:

Table 1: Cost parameters of three types of power generation enterprises

Power generation enterprises	Rated generating capacity (MW)	Cost function
SP group	300	$C_{SP} = 6700 + 110P - 0.18P^2$
MP group	600	$C_{MP} = 8000 + 91.4P - 0.076P^2$
LP group	1000	$C_{LP} = 53460 + 0.16P - 0.0315P^2$

Table 2: Sectional bidding strategy of power generation enterprises with forecasted clearing price of 333 yuan /MWh (unit: yuan /MWh)

SP group	Bidding capacity segments					
Bidding strategy	[120,150]	[150,180]	[180,210]	[210,240]	[240,270]	[270,300]
Low quotation	144.23	154.23	164.23	174.23	184.23	194.23
High quotation	283	293	303	313	323	333
MP group	Bidding capacity segments					
Bidding strategy	[240,300]	[300,360]	[360,420]	[420,480]	[480,540]	[540,600]
Low quotation	106.49	116.49	126.49	136.49	146.49	156.49
High quotation	283	293	303	313	323	333
LP group	Bidding capacity segments					
Bidding strategy	[120,150]	[150,180]	[180,210]	[210,240]	[240,270]	[270,300]
Low quotation	91.33	101.33	111.33	121.33	131.33	141.33
High quotation	283	293	303	313	323	333

Because there is more than one thermal power enterprise in a perfectly competitive market, all individuals in each group are regarded as having the same cost function and technical characteristics. Here, the competitive behavior of multiple thermal power enterprises is considered to be modeled by the performance of one thermal power enterprise. The setting scenario in this chapter is mainly based on the market clearing price and the new energy permeability in the power generation market as the high-price strategy of power generation enterprises. With reference to the publicity of centralized bidding transactions in Jiangsu Power Trading Center from September 2020 to September 2021, the lowest quoted price for marginal units of power generating enterprises is 333 yuan/MWh (December 2020) and the highest is 391 yuan /MWh (February 2021). These two clearing prices are respectively set as the high-price strategies for the quoted price of power generating enterprises. With the addition of new energy in the power generation market, the power generation space of traditional thermal power units is compressed, and four scenarios of new energy permeabilitys of 10%, 20%, 30%, and

40% are set.

Table 3: Sectional bidding strategy of power generation enterprises with forecasted clearing price of 391 yuan /MWh (unit: yuan /MWh)

SP group	Bidding capacity segments					
Bidding strategy	[120,150]	[150,180]	[180,210]	[210,240]	[240,270]	[270,300]
Low quotation	144.23	154.23	164.23	174.23	184.23	194.23
High quotation	341	351	361	371	381	391
MP group	Bidding capacity segments					
Bidding strategy	[240,300]	[300,360]	[360,420]	[420,480]	[480,540]	[540,600]
Low quotation	106.49	116.49	126.49	136.49	146.49	156.49
High quotation	341	351	361	371	381	391
LP group	Bidding capacity segments					
Bidding strategy	[400,500]	[500,600]	[600,700]	[700,800]	[800,900]	[900,1000]
Low quotation	91.33	101.33	111.33	121.33	131.33	141.33
High quotation	341	351	361	371	381	391

In the following sections, a total of eight scenarios with two clear prices and four new energy permeabilitys are assumed to simulate the bidding strategies of three types of power generation enterprises, and the applicability of the strategies in various scenarios is discussed.

3.1 Scenario 1: New Energy Permeability Is 10%

In scenario I, the strategy evolution law of three types of power generation enterprises was discussed under the scenario that the new energy permeability is 10%, that is, the generating space of thermal power units is 1,710MWh. The bidding quantity of three types of enterprises is shown in Table 4.

Table 4: Bid-winning capacity of three types of enterprises when the new energy permeability is 10%

Equilibrium point	Bid-winning capacity (MWh)	Equilibrium point	Bid-winning capacity (MWh)
(0,0,0)	(110,600,1000)	(1,1,0)	(236.67,473.33,1000)
(0,1,0)	(300,410,1000)	(1,0,1)	(256.15,600,853.85)
(1,0,0)	(110,600,1000)	(0,1,1)	(300,528.75,881.25)
(0,0,1)	(300,600,810)	(1,1,1)	(270,540,900)

Note: Taking the equilibrium point (1, 1, 1) and the bid-winning capacity (270, 540, 900) as an example, it means that when the permeability of new energy is 10%, the SP group, the MP group and the LP group all choose the high-price strategy to bid, and the bid-winning capacity of the group is 270 MWh for the SP group, 540 MWh for the MP group and 900 MWh for the LP group, respectively. The remaining equilibrium points will not be described in detail later.

Table 4 shows that at the equilibrium points (0, 0, 0) and (1, 0, 0), the bid-winning capacity of SP group is 110 MWh, which is 36.67% of the rated capacity. According to the auxiliary service compensation standard, the compensation cost of SP group in this scenario can be calculated as,

$$C_{(0,0,0)} = C_{(1,0,0)} = 500 \times (300 \times 0.6 - 110) = 35000 yuan$$

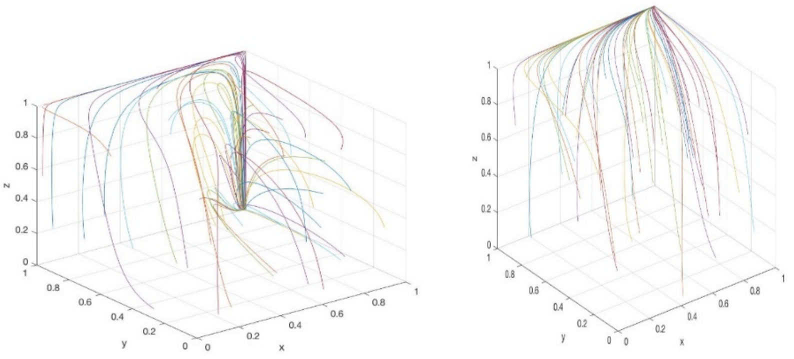
Table 5: Results of stability analysis of equilibrium point under clear price of 333 yuan /MWh with new energy permeability of 10%

Equilibrium point	Eigenvalues	Stationarity
(0,0,0)	$\lambda_1 = 0, \lambda_2 > 0, \lambda_3 > 0$	Unstable
(0,1,0)	$\lambda_1 > 0, \lambda_2 < 0, \lambda_3 = 0$	Unstable
(1,0,0)	$\lambda_1 = 0, \lambda_2 > 0, \lambda_3 > 0$	Unstable
(0,0,1)	$\lambda_1 < 0, \lambda_2 > 0, \lambda_3 < 0$	Unstable
(1,1,0)	$\lambda_1 < 0, \lambda_2 < 0, \lambda_3 < 0$	Stable
(1,0,1)	$\lambda_1 < 0, \lambda_2 > 0, \lambda_3 < 0$	Unstable
(0,1,1)	$\lambda_1 > 0, \lambda_2 < 0, \lambda_3 < 0$	Unstable
(1,1,1)	$\lambda_1 < 0, \lambda_2 < 0, \lambda_3 > 0$	Unstable

Table 6: Results of stability analysis of equilibrium point under clear price of 391 yuan /MWh with new energy permeability of 10%

Equilibrium point	Eigenvalues	Stationarity
(0,1,0)	$\lambda_1 > 0, \lambda_2 < 0, \lambda_3 = 0$	Unstable
(1,0,0)	$\lambda_1 = 0, \lambda_2 > 0, \lambda_3 > 0$	Unstable
(0,0,1)	$\lambda_1 < 0, \lambda_2 > 0, \lambda_3 < 0$	Unstable
(1,1,0)	$\lambda_1 < 0, \lambda_2 < 0, \lambda_3 > 0$	Unstable
(1,0,1)	$\lambda_1 < 0, \lambda_2 > 0, \lambda_3 < 0$	Unstable
(0,1,1)	$\lambda_1 > 0, \lambda_2 < 0, \lambda_3 < 0$	Unstable
(1,1,1)	$\lambda_1 < 0, \lambda_2 < 0, \lambda_3 < 0$	Stable

According to the stability analysis of the equilibrium point, the stability performance of the equilibrium point under two clearing prices is shown in Tables 5 and 6, and the corresponding phase diagram is shown in Figure 2:



(a) (b)

(a) Clearing income matrix with clearing price of 333 yuan /MWh
(b) Clearing income matrix with clearing price of 391 yuan /MWh

Figure 2: Trends of evolution and stability strategies under different clearing conditions when the new energy permeability is 10%

3.2. Scenario 2: New Energy Permeability Is 20%

In scenario II, the strategy evolution law of three types of power generation enterprises was discussed under the scenario that the new energy permeability is 20%, that is, the generating space of thermal power units is 1,520MWh. At the equilibrium point (0, 1, 0), the bid-winning capacity of PP group is 220 MWh, which is 36.67% of the rated capacity. According to the auxiliary service compensation standard, the compensation cost of PP group in this scenario can be calculated as

$$C_{(0,1,1)} = 500 \times (1000 \times 0.6 - 525) = 37500 yuan$$

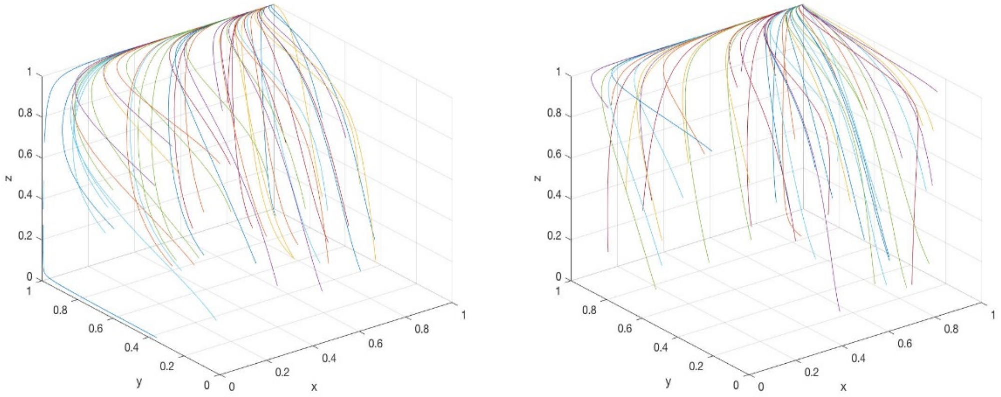
Tables 7 and 8 show the stability of the equilibrium point under two clearing prices, and Figure 3 shows the corresponding phase diagram:

Table 7: Results of stability analysis of equilibrium point under clear price of 333 yuan /MWh with new energy permeability of 20%

Equilibrium point	Eigenvalues	Stationarity
(0,0,0)	$\lambda_1 = 0, \lambda_2 > 0, \lambda_3 > 0$	Unstable
(0,1,0)	$\lambda_1 < 0, \lambda_2 < 0, \lambda_3 = 0$	Stable (critical)
(1,0,0)	$\lambda_1 = 0, \lambda_2 > 0, \lambda_3 > 0$	Unstable
(0,0,1)	$\lambda_1 < 0, \lambda_2 > 0, \lambda_3 < 0$	Unstable
(1,1,0)	$\lambda_1 > 0, \lambda_2 < 0, \lambda_3 > 0$	Unstable
(1,0,1)	$\lambda_1 < 0, \lambda_2 > 0, \lambda_3 < 0$	Unstable
(0,1,1)	$\lambda_1 > 0, \lambda_2 < 0, \lambda_3 < 0$	Unstable
(1,1,1)	$\lambda_1 < 0, \lambda_2 < 0, \lambda_3 < 0$	Stable

Table 8: Results of stability analysis of equilibrium point under clear price of 391 yuan /MWh with new energy permeability of 20%

Equilibrium point	Eigenvalues	Stationarity
(0,0,0)	$\lambda_1 = 0, \lambda_2 > 0, \lambda_3 > 0$	Unstable
(0,1,0)	$\lambda_1 > 0, \lambda_2 < 0, \lambda_3 = 0$	Unstable
(1,0,0)	$\lambda_1 = 0, \lambda_2 > 0, \lambda_3 > 0$	Unstable
(0,0,1)	$\lambda_1 < 0, \lambda_2 > 0, \lambda_3 < 0$	Unstable
(1,1,0)	$\lambda_1 < 0, \lambda_2 < 0, \lambda_3 > 0$	Unstable
(1,0,1)	$\lambda_1 < 0, \lambda_2 > 0, \lambda_3 < 0$	Unstable
(0,1,1)	$\lambda_1 > 0, \lambda_2 < 0, \lambda_3 < 0$	Unstable
(1,1,1)	$\lambda_1 < 0, \lambda_2 < 0, \lambda_3 < 0$	Stable



(a) (b)

(a) Evolution diagram when the clearing price is 333 yuan /MWh

(b) Evolution diagram when the clearing price is 391 yuan /MWh

Figure 3: Trends of evolution and stability strategies under different clearing conditions when the new energy penetration rate is 20%

3.3. Scenario 3: New Energy Permeability Is 30%

In scenario III, the strategy evolution law of three types of power generation enterprises was discussed under the scenario that the new energy permeability is 30%, that is, the generating space of thermal power units is 1,520MWh. At the equilibrium points (0, 0, 0) and (1, 0, 0), the compensation cost of MP group power generation enterprises is,

$$C_{(0,0,0)} = C_{(1,0,0)} = 500 \times (600 \times 0.6 - 330) = 15000 yuan$$

At the equilibrium point (0,1,0), it is lower than the minimum stable load capacity of MP group, so it can’t win the bid;

At the equilibrium point (0,0,1), the compensation cost of LP group is:

$$C_{(0,0,1)} = 500 \times (1000 \times 0.6 - 430) = 85000 yuan$$

At the equilibrium point (1,1,0), it is lower than the minimum stable load capacity of SP and MP groups, so it can’t win the bid;

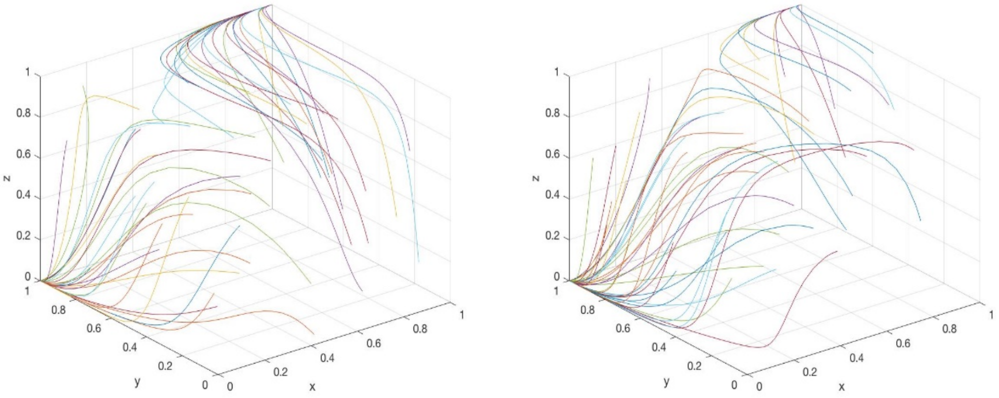
At the equilibrium point (1,0,1), the compensation cost of power generation enterprises of SP group is:

$$C_{(1,0,1)} = 500 \times (300 \times 0.6 - 168.46) = 5770 yuan$$

Table 9 shows the stability of the equilibrium point under two clearing prices, and Figure 4 shows the corresponding phase diagram:

Table 9: Results of equilibrium point stability analysis with new energy permeability of 30%

Equilibrium point	Eigenvalues	Stationarity
(0,0,0)	$\lambda_1 = 0, \lambda_2 = ?, \lambda_3 < 0$	Critical (that depends)
(0,1,0)	$\lambda_1 = ?, \lambda_2 = ?, \lambda_3 = 0$	Critical (that depends)
(1,0,0)	$\lambda_1 = 0, \lambda_2 = ?, \lambda_3 > 0$	Unstable
(0,0,1)	$\lambda_1 < 0, \lambda_2 > 0, \lambda_3 > 0$	Unstable
(1,1,0)	$\lambda_1 = ?, \lambda_2 = ?, \lambda_3 > 0$	Unstable
(1,0,1)	$\lambda_1 > 0, \lambda_2 > 0, \lambda_3 < 0$	Unstable
(0,1,1)	$\lambda_1 > 0, \lambda_2 < 0, \lambda_3 < 0$	Unstable
(1,1,1)	$\lambda_1 < 0, \lambda_2 < 0, \lambda_3 < 0$	Stable



(a) (b)

(a) Evolution diagram when the clearing price is 333 yuan /MWh

(b) Evolution diagram when the clearing price is 391 yuan /MWh

Figure 4: Trends of evolution and stability strategies under different clearing conditions when the new energy penetration rate is 30%

3.4. Scenario 4: New Energy Permeability Is 40%

In scenario IV, the strategy evolution law of three types of power generation enterprises was discussed under the scenario that the new energy permeability is 40%, that is, the generating space of thermal power units is 1,140MWh.

At the equilibrium points (0,1,0), (1,0,1), the compensation cost of power generation enterprises of MP group is:

$$C_{(0,1,0)} = 500 \times (300 \times 0.6 - 140) = 20000 yuan$$

$$C_{(1,0,1)} = 500 \times (300 \times 0.6 - 124.62) = 27690 yuan$$

At the equilibrium point (0,1,1), the compensation cost of power generation enterprises of MP group is:

$$C_{(0,1,1)} = 500 \times (600 \times 0.6 - 315) = 22500 yuan$$

At the equilibrium points (1,0,1), (0,1,1), the compensation cost of power generation enterprises of LP group is:

$$C_{(1,0,1)} = 500 \times (1000 \times 0.6 - 415.38) = 92310 yuan$$

$$C_{(0,1,1)} = 500 \times (1000 \times 0.6 - 525) = 37500 yuan$$

Table 10: Results of equilibrium point stability analysis with new energy permeability of 40% at the clearing price of 333 yuan/MWh

Equilibrium points	Eigenvalues	Stationarity
(0,0,0)	$\lambda_1 = 0, \lambda_2 = ?, \lambda_3 = ?$	Critical (that depends)
(0,1,0)	$\lambda_1 = ?, \lambda_2 = ?, \lambda_3 = 0$	Critical (that depends)
(1,0,0)	$\lambda_1 = 0, \lambda_2 = ?, \lambda_3 < 0$	Critical (that depends)
(0,0,1)	$\lambda_1 < 0, \lambda_2 < 0, \lambda_3 = ?$	Critical (that depends)
(1,1,0)	$\lambda_1 = ?, \lambda_2 = ?, \lambda_3 > 0$	Unstable
(1,0,1)	$\lambda_1 > 0, \lambda_2 > 0, \lambda_3 > 0$	Unstable
(0,1,1)	$\lambda_1 < 0, \lambda_2 > 0, \lambda_3 > 0$	Unstable
(1,1,1)	$\lambda_1 > 0, \lambda_2 < 0, \lambda_3 < 0$	Unstable

Table 11: Results of equilibrium point stability analysis with new energy permeability of 40% at the clearing price of 391 yuan/MWh

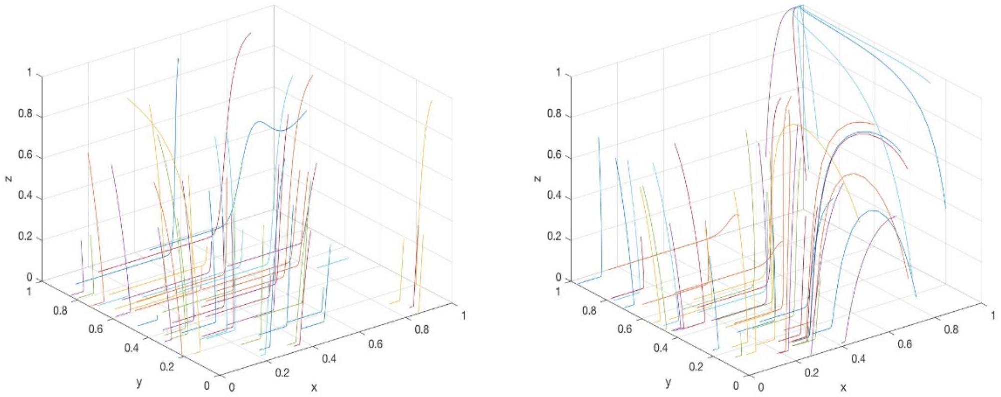
Equilibrium point	Eigenvalue	Stationarity
(0,0,0)	$\lambda_1 = 0, \lambda_2 = ?, \lambda_3 = ?$	Critical (that depends)
(0,1,0)	$\lambda_1 = ?, \lambda_2 = ?, \lambda_3 = 0$	Critical (that depends)
(1,0,0)	$\lambda_1 = 0, \lambda_2 = ?, \lambda_3 < 0$	Critical (that depends)
(0,0,1)	$\lambda_1 < 0, \lambda_2 < 0, \lambda_3 = ?$	Critical (that depends)
(1,1,0)	$\lambda_1 = ?, \lambda_2 = ?, \lambda_3 > 0$	Unstable
(1,0,1)	$\lambda_1 > 0, \lambda_2 > 0, \lambda_3 > 0$	Unstable
(0,1,1)	$\lambda_1 > 0, \lambda_2 > 0, \lambda_3 < 0$	Unstable
(1,1,1)	$\lambda_1 < 0, \lambda_2 < 0, \lambda_3 < 0$	Stable

At the equilibrium point (1,1,0), it is lower than the minimum stable load capacity of SP group, so it can’t win the bid;

At the equilibrium points (0,0,0), (1,0,0) and (1,1,0), it is lower than the minimum stable load capacity of MP group, so it can’t win the bid;

At the equilibrium point (0,0,1), it is lower than the minimum stable load capacity of LP group, so it can’t win the bid;

Tables 10 and 11 show the stability of the equilibrium point under two clearing prices, and Figure 5 shows the corresponding phase diagram:



(a) (b)

(a) Evolution diagram when the clearing price is 333 yuan /MWh

(b) Evolution diagram when the clearing price is 391 yuan /MWh

Figure 5: Trends of evolution and stability strategies under different clearing conditions when the new energy penetration rate is 40%

3.5. Analysis and Summary of Simulation Strategy Scenarios

In the forecast of two kinds of clearing price as the high-price strategy of power generation enterprises and the scenario of four kinds of new energy permeability, the evolution and stability strategies of three kinds of power generation enterprise groups are sorted out as shown in Table 12:

Table 12: Summary of bidding strategies of various power generation enterprises under multi-scenario analysis

New energy permeability	Clearing prices	
	333 yuan/MWh	391 yuan/MWh
10%	(1,1,0)	(1,1,1)
20%	(1,1,1)	(1,1,1)
30%	(1,1,1)+(0,1,0)	(1,1,1,)+(0,1,0)
40%	No + LP groups tend to quote low-prices	(1,1,1)+ LP groups tend to quote low-prices

In this section, under the four kinds of new energy permeability: 10%, 20%, 30% and 40%, the evolutionary stability strategies of three types of power generation enterprise groups were calculated respectively. The results show that when the market clearing price is 333 yuan /MWh as the high-price strategy, the evolution trend of SP group always tends to the high-price strategy when the new energy permeability is 10% - 20%, there are two evolutionary stable strategies when the new energy permeability is 30%, and there is no evolutionary stable strategy when the new energy permeability is 40%. For the LP group, the evolutionary stability strategy changes with the change of new energy permeability. When the new energy permeability is 20%, the evolution tends to the high-price strategy; when the new energy permeability is 10% and exceeds 30%, the evolution tends to the low-price strategy. When the market clearing price of 391 yuan /MWh is regarded as the high-price strategy, the evolutionary trend of the three groups is changed. For SP group, the permeability of new energy increases from 10% to 40%, and the high-price strategy is always the evolutionary stable strategy. When the permeability of new energy is 30%, the low-price strategy is also one of the evolutionary stable strategies. For the MP group, the evolution trend is always stable towards the high-price strategy when the new energy increases from 10% to 20%. For the LP group, the evolution trend is high-price strategy when the new energy permeability is 20%, and both the high-price strategy and the low-price strategy are evolutionary stable strategies when the new energy permeability exceeds 30%.

As the permeability of new energy continues to rise, the space left for thermal power generating units continues to shrink. All three types of power generating enterprises have to choose the high-price strategy from the beginning to choose the low-price strategy later. For different types of generating units, with the increase of market clearing price, the probability of selecting high price strategy will increase. In this way, on the one hand, backward and inefficient generating units can be eliminated; on the other hand, the decrease of marginal clearing price will also promote the adjustment of the functional positioning of different types of thermal power units.

The above strategy simulation analysis verifies that the permeability of new energy, market clearing price and the generation capacity of various types of power generation enterprises have a great impact on the selection of bidding strategies for power generation enterprises.

4. Conclusions and Policy Recommendations

The LP groups of large-capacity generating units hold a large market share and play a leading role in the market price to a certain extent. Therefore, in regions with tight power supply and demand, they may tend to adopt the bidding strategy of limiting production and increasing prices. However, it is necessary to find the quotation point for enterprises to maximize profits under the framework of market supervision, and to increase the quotation in a limited way, instead of exerting the market power recklessly, causing vicious competition. In the long run, the output space of thermal power is gradually reduced. When the 1,000MW unit cannot exert their high load to bring their high performance into full play, it may be considered to retire them naturally without further modification.For the MP group of medium-capacity units, the corresponding peak-shaving compensation can be obtained when the bid-winning quantity is lower than the paid peak-shaving limit under various scenarios. However, such power generation enterprises cannot obtain a reasonable return under the current paid peak shaving compensation mechanism. Thus, it is necessary to revise the paid peak shaving compensation mechanism to stimulate their enthusiasm for participating in peak shaving service. For the SP group with small power generation capacity, when the new energy permeability reaches 30%, they can only follow the market price fluctuations as followers, thus passively becoming the price receivers so that such enterprises can still have certain living space in the market. Under the condition that the permeability of new energy reaches 40%, when the effective power capacity is tight, the small thermal power unit can be regarded as a standby unit, and the revenue obtained can only make up for the cost of electricity, but cannot recover the fixed cost. In order to ensure the safety of peak power consumption, it is necessary to explore a capacity compensation mechanism that can effectively stimulate thermal power units to provide flexibility.

References

[1] Cheng Lefeng, Yang Ru, Liu Guiyun, Wang Jianhui, Chen Yang, Wang Xiaogang, Zhang Jie, Yu Tao. (2020) Multi-population Asymmetric Evolutionary Game Dynamics and Its Applications in Power Demand-side Response in Smart Grid. Proceedings of the CSEE, 40, 1, 20-36.

[2] Cheng Lefeng, Yu Tao. (2018) Typical Scenario Analysis of Equilibrium Stability of Multi-group Asymmetric Evolutionary Games in the Open and Ever-growing Electricity Market. Proceedings of the CSEE, 38, 19, 5687-5703+5926.

[3] Wang Xiaotian, Xue Huifeng, Zhang Qiang. (2012) Evolutionary Game Analysis on the Interest Coordination of Grid-connected Renewable Energy Power Generation. Systems Engineering, 30, 4, :94-99.

[4] Zhang Cheng, Du Songhuai, Su Juan. (2010) Study on Bidding Strategies of Regional Electricity Markets Based on

Evolutionary Game Theory. Modern Electric Power, 27, 2, 87-90.

[5] Huang Xian, Wang Zhanhua. (2009) Simulation and Analysis of Generation Companies' Bidding Strategies Based on Evolutionary Game Theory. Modern Electric Power, 26, 3, 91-94.

[6] Zhang Jingjing. (2016) Dynamic Evolutionary Game Analysis on Innovation Value-added Services of Electricity Sales Enterprise Under The New Power System Reform. Coal Economic Research, 36, 9, 59-65.

[7] Jiang Jinliang, Shen Yanjun. (2012) Analysis on Regulation of Demand Side Management Based on Evolutionary Game. Journal of South China University of Technology (Social Science Edition), 14, 5, 50-56.

[8] Daniele Menniti, Anna Pinnarelli, Nicola Sorrentino. (2008) Simulation of producers behaviour in the electricity market by evolutionary games.Electric Power Systems Research, 78, 3, 475-483

[9] Ahmed Amine Ladjici, Ahmed Tiguercha, Mohamed Boudour. (2012) Equilibrium Calculation in Electricity Market Modeled as a Two-stage Stochastic Game using competitive Coevolutionary Algorithms. IFAC Proceedings Volumes, 45, 21, 524-529

[10] Chen Runying. (2010) Evolutionary Game and Chaos Control of Electricity Market Based on Different Behavioral Decisions. Changsha University of Science and Technology.

[11] Yin, Linfei, Shengyuan Li, and Fang Gao. (2020) "Equilibrium Stability of Asymmetric Evolutionary Games of Multi-Agent Systems With Multiple Groups in Open Electricity Market." IEEE Access, 8, 28970-28978

[12] Krichrra V Ramesh V C .(1997) Intelligent agents for negotiations in market games. I. Model.Application 20th International Conference on Power Industry Computer Applications,Columbus,OHUSA, 388-393,394-39

[13] Wang Yiming. (2014)Research on bidding behavior of power generation companies based on evolutionary game. North China Electric Power University.

[14] Zhang Ye. (2017) Study on Evolutionary Game Model of Thermal Power Regulation in Large-scale Wind Power Grid Integration. North China Electric Power University (Beijing).