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Research on Industrial Economic Development and Electricity Price Adjustment Strategy Based on Multi-Agent Game

Qianhui Cai[1,2], Xue Han[1,2], Wei Wang[1,2,*]

[1]*NARI School of Electrical and Automation Engineering, Nanjing Normal University, Nanjing, China*

[2]*Jiangsu International Joint Laboratory of Integrated Energy Equipment and Integration, Nanjing, China*

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ABSTRACT

With the deepening of the electricity market reform and the accelerating transformation of the new power system, the number of new electricity customers in the market with local development characteristics has increased. The local industrial and economic development have been affected by the ability to guide electricity prices. In this paper, using the multi-agent game based on exploring the impact of electricity price on the industrial economy, the specific optimization scheme of electricity price adjustment is proposed with the aim of improving the overall efficiency of the power grid and reducing the cost of electricity for industrial users. After the game, the overall efficiency of the electricity supplier will be increased by about 3.06 percent, and the cost of electricity used by various special industries will be reduced by about 6.86 percent to 4.48 percent. The win-win situation of the electricity suppliers' income and the featured industries' development can be achieved by the optimization results. As well as the cost of electricity consumption in featured industries can be reduced, and the comprehensive benefits of electricity suppliers can be improved by using the electricity price adjustment scheme after game interaction, which promotes the rational use of energy and meets the current social requirements for the green and sustainable development of the electricity industry.

*Corresponding Author
Email: wangw_seu@163.com
Tel: +(86) 15251868102

1. Introduction

In the context of the transformation of the new power system, the adjustment of electricity price affects industrial electricity behavior and economic development, and a variety of trends have emerged in the electricity behavior of domestic industrial users in China [1], including focusing on environmental protection and energy saving, electricity safety and reliability, and optimizing the cost of electricity to achieve the improvement of the quality and efficiency of electricity consumption.

Taking the featured industries as an example, the second featured industries, i.e. users in the computer and other electronic installation manufacturing industry, the metal product industry, the electrical machinery and the equipment manufacturing industry, with the development of the new electric power system transformation, their electricity consumption behaviors are mainly embodied in the wide application of intelligent equipment, diversification of electricity consumption and the promotion of clean energy.

Users in the tertiary featured industries, i.e. the software and information technology services industry and the water conservancy, environment and public facilities management industry, with the development of the new power system transformation, their electricity consumption behavior is mainly reflected in the aspects of energy refinement and management, intelligent control and clean energy use.

There is a direct impact on the energy costs of enterprises caused by electricity prices, and high electricity price may increase their production costs and reduce their competitiveness. The adjustment and transformation of the industrial structure can be guided by the setting of electricity prices, as well as the transformation of the energy structure and the development of renewable energy.

Along with the construction of the new power system, there will be more and more new energy access to the power system in the future, at this time the electricity price [2] also needs to be considered in how to promote the consumption of new energy, and at the same time to avoid or reduce the rise in electricity price brought about by the construction of the new power system. Therefore, the future of electricity prices needs to be optimized in the aspects of the electricity price structure, electricity price mechanism innovation and other factors.

Current research on gaming behavior in electricity markets focuses on electricity retailers' price decisions and customers' power purchase strategies. Literature [3] based on master-slave game considers the relationship between electricity retailers and customers, and designs multi-market retail packages and power purchase strategies for electricity retailers according to different situations, which improves the profit of electricity retailers. Literature [4] developed a retail pricing model based on master-slave game for electricity retailers in the day-ahead stage, where pricing takes into account the interactive behavior of supply and demand.

The Stackelberg master-slave game in this study focuses on decision sequencing and is an important model for analyzing price-setting problems involving sequential decision-making [5, 6]. Literature [7] studied the shared energy storage time-sharing electricity price strategy based on master-slave game and utilized a two-layer planning model. Literature [8] proposed a multi-energy supplier pricing strategy using a two-layer planning model based on the Stackelberg game, which achieves a win-win situation for the interests of energy suppliers and residential customers. Literature [9] proposes a price-volume optimization model for energy trading in parks based on Stackelberg's two-layer game theory to solve the pricing and quantitative optimization problems in energy trading between energy suppliers and users in parks.

This paper selects typical scenarios based on exploring the bidirectional relationship between industrial economic development and electricity price adjustment strategy, taking the electricity market game theory as the method, dynamically exploring the change of electricity price and the adjustment of the industrial system, researching the electricity price adjustment scheme adapted to the industrial development, and the results of the research can provide a new way of thinking for the formulation of electricity price scheme.

2. Situation

For example, in a province in eastern China, the industrial structure generally shows a trend of a shrinking share of the metal products industry and an expanding share of the software and information technology services industry, as well as of the water conservancy, environment and public facilities management, the computer and other electronic installation manufacturing industry, which is a strong manifestation of industrialization and modernization. Five featured industries have been investigated in this paper:

i. Industry 1: the software and information technology services industry;

ii. Industry 2: the water conservancy, environment and public facilities management;

iii. Industry 3: the metal product industry;

iv. Industry 4: the computer and other electronic installation manufacturing industry;

v. Industry 5: the electrical machinery and the equipment manufacturing industry.

As is shown in Table **1**, the proportion of the industry 4 has risen nearly 7 percent between 2016 and 2022, mainly due to the acceleration of the urbanization process in China in recent years. The shares of the industry 4 in the GDP have risen due to the high elasticity of demand for its products, which, in terms of total demand, increases accordingly with the improvement of the living standards. The shares of the industry 3 and industry 5 have remained at around 50 percent in recent years, showing a relatively stable trend with only slight fluctuations in the middle. In addition to the industry 1 and industry 2, as the main forces to promote the development of the tertiary service industry in the province, also account for a relatively high proportion of its output value, and the proportion of output value has been on the rise in the past five years. The proportion of the industry 1 and industry 2, on the other hand, has risen significantly by nearly three percent.

Table 1: Featured industrial structure of a province in eastern China.

Years	Industry 1/billion	Industry 2/billion	Industry 3/billion	Industry 4/billion	Industry 5/billion
2016	7171	3183	13574	24651	11138
2017	8159	5133	16843	25173	12101
2018	9168	6104	16743	26163	13104
2019	10193	6130	17681	26917	14111
2020	10156	6165	17685	27884	15110
2021	12716	7861	18213	28767	15716
2022	9430	8136	18710	29179	16831

In recent years, all kinds of industries have been developing rapidly. Their development and electricity prices have a close connection, and electricity price is an essential factor in restricting industries' electricity consumption and cost of electricity consumption. The electricity cost of featured industries is part of their production cost, so the electricity tariff will directly affect the production and operation of enterprises. If electricity price continues to rise, the cost of electricity consumption of enterprises will increase, resulting in higher production costs and lower competitiveness of enterprises. As the industry develops, its electricity consumption will also increase in the future, which requires an ample supply of electricity. If electricity price is too low, they may increase energy consumption, which will have a negative impact on energy allocation and sustainability. At the same time, electricity is usually derived from non-renewable energy sources such as fossil fuels, which makes the production of electricity likely to discharge a large amount of carbon dioxide and other pollutant emissions, and it is difficult to settle and control the environmental problems in electricity production under the circumstances that electricity price is too low. Therefore, the adjustment of electricity prices is necessary according to the promotion of industrial development and sustainable energy consumption. This paper chooses the multi-agent game theory.

Through the game of electricity suppliers and industrial users, the conclusions will achieve a win-win situation of promoting industrial development and reasonable adjustment of electricity prices, in order to provide better ideas for the sustainable development of the electricity market.

3. Methodology

3.1. Game and Strategies

The current domestic electricity price scheme has room for improvement in guiding customers to change their electricity consumption behavior, improving the overall efficiency of electricity suppliers and promoting the sustainable development of the electricity market. Therefore, this paper adopts the master-slave game model [10] to explore the relationship between the electricity price of electricity suppliers and the demands of industrial users. Electricity suppliers expect to maximize their revenues based on higher demands, while industrial users expect lower electricity prices. According to the above objectives to adjust the electricity strategy, the equilibrium solution obtained by the game [11, 12] is only one.

The objective functions of the two sides of the game are as follows, and the objective function of the electricity suppliers as the leader is the comprehensive benefit function [13, 14]:

$$R_{Ni}(p) = D_{Ni}(p)p_{Ni} + M_{Ni}P_{Ni} - p_{Oi}d_{Oi}(p) - [D_{Ni}(p) + M_{Ni}]C_{Ni} - C_{trans} \tag{1}$$

$$C_{trans,t} = \left[a_{trans}(l_{trans,t,j})^2 + b_{trans}l_{trans,t} \right] | t - j | \tag{2}$$

$$C_{trans} = \sum_{t=1}^{T} C_{trans,t} \tag{3}$$

As is shown in the functions, $C_{trans,t}$ is the transfer load satisfaction cost of industrial users in period t; $l_{trans,t,j}$ is the electricity consumption from time period t to time period j, j is the transfer time period; a_{trans} and b_{trans} are the transfer load satisfaction cost coefficients, with $a_{trans} > 0$ and $b_{trans} < 0$.

Industrial users are followers whose objective function is the cost function of electricity consumption:

$$U_{Mi}(p) = p_{Ni}d_{Mi}(p) - p_{Ri}d_{Ri}(p) \tag{4}$$

As is shown in the functions, p_{Ri} is the distributed photovoltaic energy storage feed-in electricity price for industrial users; $d_{Ri}(P)$ is the distributed photovoltaic energy storage feed-in electricity for industrial users. The featured industries and electricity suppliers are closely connected in real-time through electricity demand and electricity price, and this paper uses a non-cooperative dynamic game under incomplete information and a cooperative dynamic game under complete information.

3.2. The Process of Gaming

The Stackelberg master-slave game between electricity suppliers and industrial users is a reasonable method for real-time electricity price calculation. Also, the computer’s fast optimization search method can quickly obtain the electricity price at the latest time point based on the results of the previous round of the Stackelberg game and the new industrial users' electricity consumption to satisfy the real-time requirements [15].

The electricity suppliers and industrial users first carry out individual optimization solutions for their respective optimization objectives, but there is a mutual influence between the optimization variables of the electricity suppliers and industrial users, so the next step needs to use an iterative algorithm to solve the overall optimization functions.

The solving steps are as follows:

i. Input initial data and parameters;

ii. The electricity suppliers determine the optimal electricity price scheme based on the industrial users' energy use information, and solve to obtain the energy selling price with the goal of maximizing the comprehensive benefits;

iii. The electricity suppliers will feedback on the electricity price that satisfies the maximization of comprehensive benefits to the industrial users. After that, the industrial users will receive the electricity price, considering the minimization of energy costs as the objective. The users will determine the amount of energy consumption and report it to the electricity suppliers;

iv. If the strategies of electricity suppliers and industrial users are conflicting, update the energy consumption of industrial users and return to step ii.. If the strategies of the two adjacent games are the same, the result is the equilibrium solution of the game.

4. Results

4.1. Time-sharing Transmission and Distribution Electricity Price Optimization Program

The current time-sharing transmission and distribution electricity price sales price in a province in eastern China is shown in Table **2** below, and the data in the table is substituted into the model as the initial data of the game to participate in the game. The leader of the game is the electricity suppliers in the province, and the followers are the five types of featured industries in the province, the leader's objective function is the comprehensive benefit function, which requires maximization, and the follower's objective function is the electricity cost function, which requires minimization. When the game reaches equilibrium, the optimal time-sharing transmission and distribution electricity price scheme is obtained as shown in Tables **3**-**4** and Figs. (**1**-**3**).

Table 2: Time-sharing transmission and distribution electricity price sales electricity price table for industrial electricity in a province.

Classification of Electricity Consumption	Voltage Level	Time-sharing Electricity Degree Electricity Price (RMB/kWh)			The Electricity Degree Electricity Price (RMB/kWh)	Demand Electricity Price (RMB /kW-Month)	Capacity Electricity Price (RMB /kVA-Month)
		Peak Hours	Usual Hours	Valley Hours			
Two-part electricity price	1-10(20) kV	1.1267	0.6552	0.2742	0.6552	51.2	32
	35 kV	1.0837	0.6302	0.2637	0.6302	48	30
	110 kV	1.0407	0.6052	0.2633	0.6052	44.8	28
	220 kV and above	0.9960	0.5792	0.2424	0.5792	41.6	26
Single electricity price	Less than 1 kV	1.2688	0.7589	0.3429	0.7589	/	/
	1-10(20) kV	1.2253	0.7329	0.3311	0.7329	/	/
	35 kV	1.1835	0.7079	0.3198	0.7079	/	/

The optimal time-sharing transmission and distribution electricity price scheme obtained at game equilibrium has an increase in the peak of the electricity degree electricity price and a decrease in the valley of the electricity degree electricity price. Higher electricity degree electricity price, higher demand electricity price and lower capacity electricity price at lower voltage levels; lower electricity degree electricity prices, lower demand electricity prices and higher capacity electricity prices at medium and high voltage levels. The electricity consumption of customers in featured industries at high voltage levels is higher and their electricity demand has a significant impact on the revenues of electricity suppliers [16, 17]. As a result, industrial users adjust the electricity price available to their strategy through a game between them and electricity suppliers in both directions, thus reducing their own cost of electricity.

Table 3: Adjusted time-sharing transmission and distribution electricity price sales electricity price table for industrial electricity in a province (part 1).

Classification of Electricity Consumption	Voltage Level	Time-sharing Electricity Degree Electricity Price (RMB/kWh)			The Electricity Degree Electricity Price (RMB/kWh)
		Peak Hours	Usual Hours	Valley Hours	
Two-part electricity price	1-10(20) kV	1.1214	0.6891	0.2816	0.6891
	35 kV	1.0782	0.6555	0.2712	0.6555
	110 kV	1.0211	0.5823	0.2687	0.5823
	220 kV and above	0.9807	0.5532	0.2483	0.5532
Single electricity price	Less than 1 kV	1.2601	0.7624	0.3496	0.7641
	1-10(20) kV	1.2197	0.7392	0.3342	0.7482
	35 kV	1.1816	0.7106	0.3247	0.7113

Table 4: Adjusted time-sharing transmission and distribution electricity price sales electricity price table for industrial electricity in a province (part 2).

Classification of Electricity Consumption	Demand Electricity Price(RMB /kW-Month)	Change Percentage (%)	Capacity Electricity Price (RMB /kVA-Month)	Change Percentage (%)
Two-part electricity price	52.7	1.5	31.2	-0.8
	49.2	1.2	29.3	-0.7
	43.2	-1.6	28.6	0.6
	40.5	-1.1	26.7	0.7

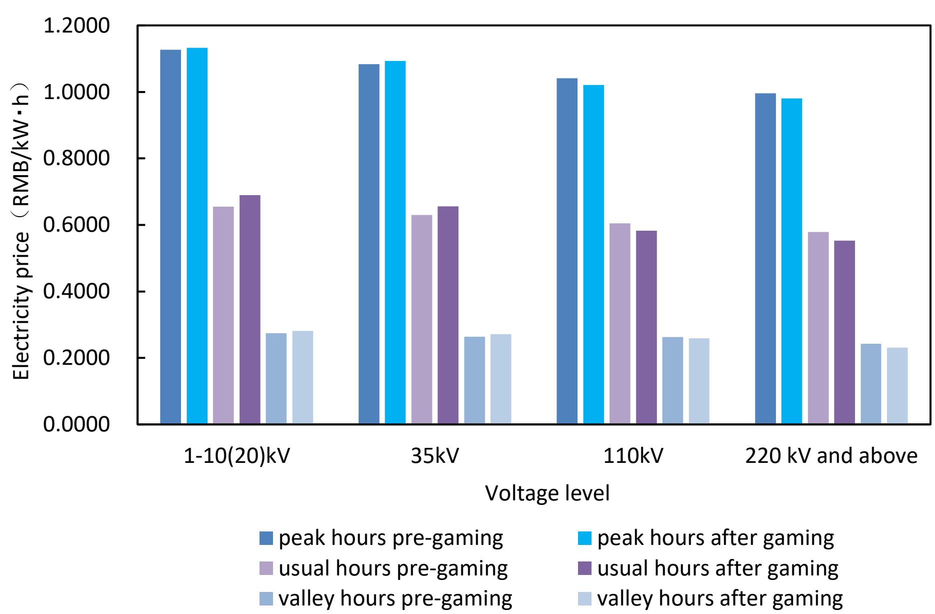

Figure 1: Comparison of two-part time-sharing transmission and distribution electricity price gaming.

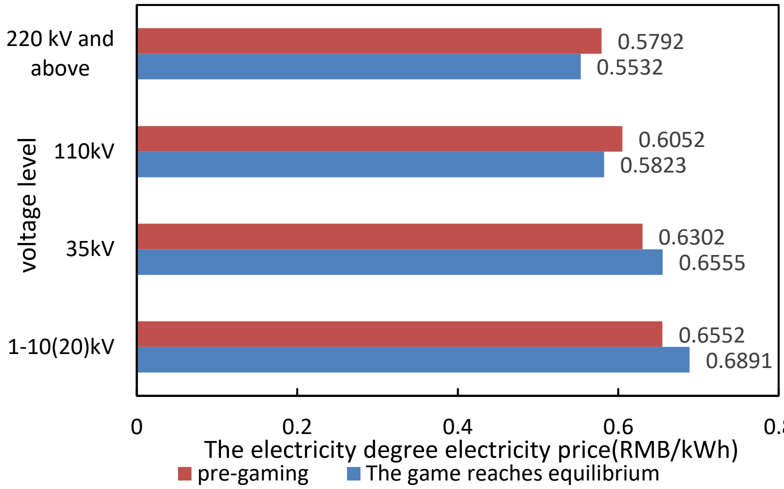

Figure 2: Comparison of electricity degree electricity price gaming.

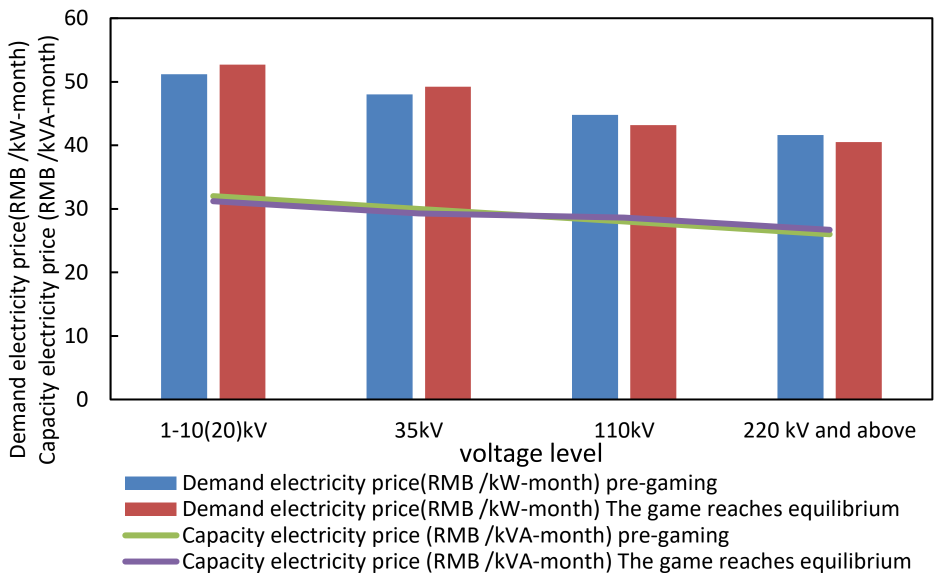

Figure 3: Comparison of demand (capacity) electricity price game.

The peak electricity price at 220 kV and above is 0.9807 RMB/kWh, the usual electricity price is 0.5532 RMB/kWh, the valley electricity price is 0.2483 RMB/kWh, the electricity degree electricity price is 0.5832 RMB/kWh, the demand electricity price is 40.5 RMB/kW-month, and the capacity electricity price is 26.7 RMB /kVA-month.

4.2. Analysis of Game Interaction Behavior

As can be seen in Table **5**, with the increase in the number of iterations, electricity suppliers' comprehensive benefit gradually increases, while the cost of electricity consumption in each industry gradually decreases. At the 36th iteration, the two sides reached the game equilibrium. The comprehensive benefit of electricity suppliers was 503.25 billion yuan this moment, while the cost of electricity consumption in featured industries also reached the minimum. These data prove that the game interaction can indeed maximize the benefits of both sides.

The comprehensive benefit after gaming is 149.3 billion higher than before, indicating that electricity suppliers have achieved evident results in optimizing the time-sharing transmission and distribution of electricity prices and electricity consumption for customers in all industries. The costs of each industry have decreased, and industry 1, industry 2 and industry 3 have the higher degree of decline. Generally, the gaming scheme can effectively decline the cost of electricity consumption on the industry side. The adjustment strategy proposed in this paper can effectively improve the comprehensive efficiency of electricity suppliers while reducing the cost of electricity consumption in each industry.

Table 5: Comprehensive efficiency data of electricity suppliers in a province and cost data of electricity consumption in featured industries.

Number of Iterations	Comprehensive Benefits of Electricity Suppliers/Billion Dollars	Economic Benefits to Electricity Suppliers/ Billion Dollars	Cost of Electricity Consumption/Billion				
			Industry 1	Industry 2	Industry 3	Industry 4	Industry 5
10	4883.2	5012.6	133.6	66.3	323.4	194.7	261.4
22	4919.7	5154.3	131.37	63.82	314.92	193.53	258.6
36	5032.5	5266.7	126.49	62.13	301.23	185.9	249.7
50	5032.5	5266.7	126.49	62.13	301.23	185.9	249.7

Industrial users act as followers. The variable of the game is electricity consumption, which varies in response to the price of electricity. Industrial users adjust their electricity consumption continuously to reduce the cost of electricity according to the changes in electricity prices. Industries that are the main consumers of electricity usually reduce the cost of electricity by conserving electricity and improving energy efficiency. These solutions can make contributions to counteract higher electricity prices. Electricity producers, on the other hand, optimize the quality and reliability of the electricity they provide with the aim of improving the reasonableness and competitiveness of electricity prices [18].

In the dynamic game, the leader electricity suppliers continue to adjust the electricity price policy according to the industrial users' electricity consumption to maximize the comprehensive benefits, and the new electricity price policy will make the industrial users adjust their electricity consumption with the goal of minimizing the cost of electricity as a follower. Both the leader and the follower can only make changes based on historical data and the current situation. This process is repeated until the variables involved in the game reach a stable value, indicating that the game results in a Nash equilibrium. At the equilibrium of the game, the calculation of electricity cost needs to consider the time-sharing transmission and distribution electricity price and electricity consumption. When the game obtains the optimal time-sharing transmission and distribution electricity price scheme, the final electricity consumption of each industrial user in different quarters is obtained as shown in Fig. (**4**).

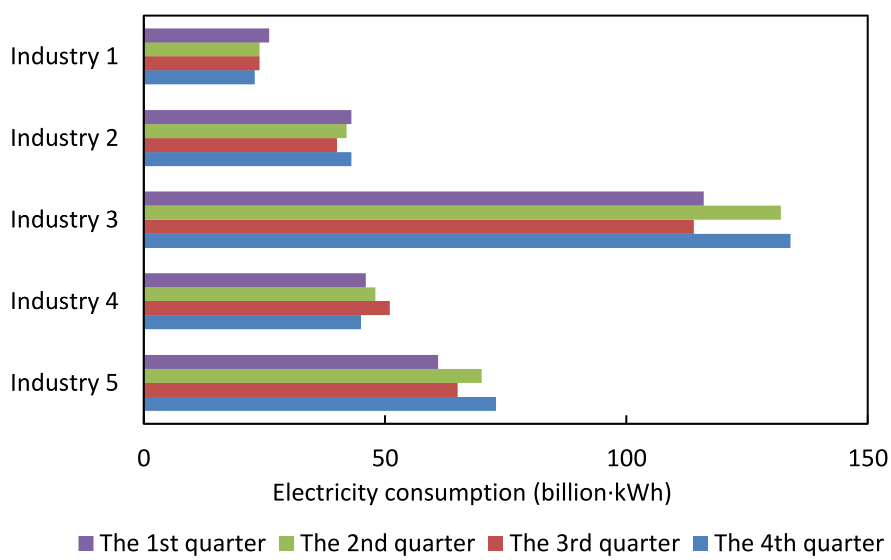

Figure 4: Electricity consumption curves by industrial users.

As can be seen from the figure, the electricity consumption curve of each industrial user in the optimal time-sharing transmission and distribution electricity price scheme before and after optimization has changed evidently. By comparison, it can be seen that the game has a positive impact on the electricity consumption of each industrial user, which enables them to adjust their electricity consumption according to the changes in time-sharing transmission and distribution electricity price [19]. This interaction indeed helps decline the cost of electricity consumption.

As shown in Fig. (**5**), the interactive approach proposed in this paper maintains the shape of the original electricity consumption curve as much as possible. This approach aims to avoid bringing too much adjustment to the electricity consumption plan for each industrial user, thus reducing the energy cost. In general, the method has high practical value and wide application prospects.

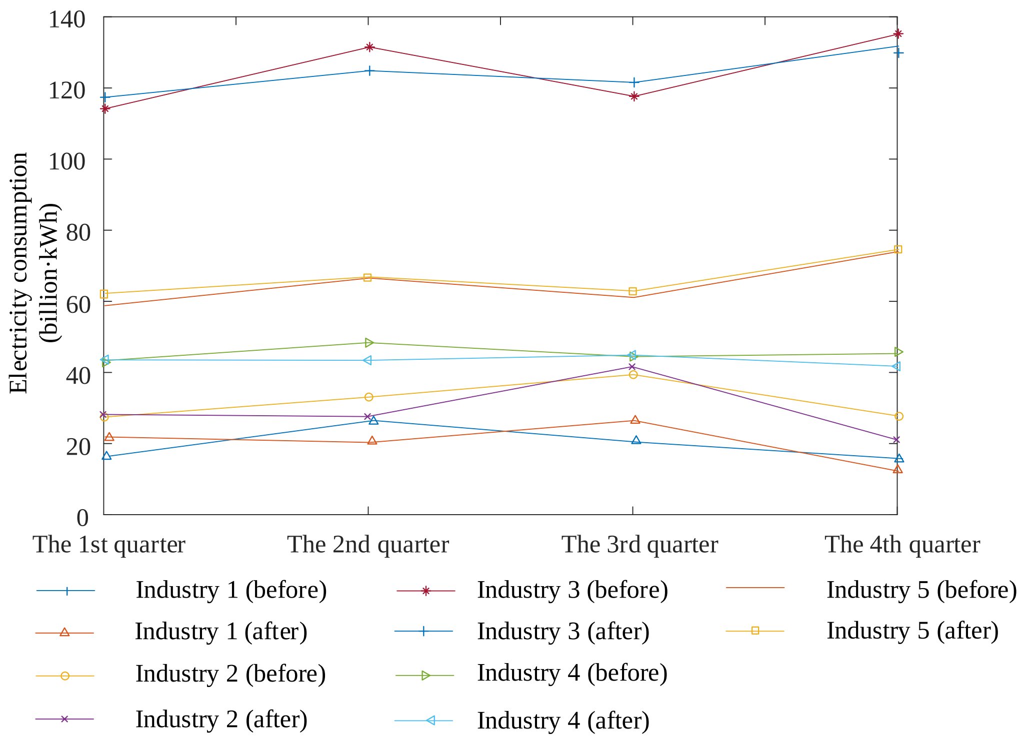

Figure 5: Electricity consumption curve of each industry before and after optimization.

Through two-way synergy, stable operation of the electricity market and sustainable energy development can be realized, while satisfying consumers' electricity demand and providing electricity suppliers benefits. This two-way win-win game process helps build a healthy and sustainable electricity market ecosystem.

5. Conclusion

Based on analyzing the influence of industrial structure and electricity consumption on electricity price policy, this paper introduces the game theory of the electricity market to establish a two-way interaction mechanism between industrial development and electricity price adjustment. Providing guidance and theoretical references for the two-way adjustment of electricity price policy and industrial development through the model is the purpose of the study in this paper.

Through the implementation of this scheme, the peak electricity price of the time-sharing electricity degree electricity price has been increased and the trough electricity price has been reduced, while ensuring that the economic returns of the electricity suppliers remain basically unchanged. The electricity degree electricity price increased, the demand electricity price increased and the capacity electricity price decreased in the low-voltage voltage level; the electricity degree electricity price decreased, the demand electricity price decreased and the capacity electricity price increased in the medium- and high-voltage voltage level. The overall efficiency of electricity suppliers has increased by 5.06 percent, a significant improvement largely due to more effective management of electricity resources and guidance on electricity consumption behavior. In addition, Industry 1~5 have adjusted their electricity consumption accordingly in the light of the changes in electricity prices, and their electricity costs have been reduced by 5.53 percent, 6.28 percent, 6.86 percent, 4.52 percent and 4.47 percent respectively. These reductions in electricity costs have brought tangible economic benefits to these industries.

The adjusted electricity price scheme can help electricity suppliers clarify the orientation of electricity price adjustment. Additionally, the electricity price of different voltage levels and the time-sharing electricity price for different industries can be rationally adjusted by the scheme, which is of great significance to further optimize the domestic electricity price adjustment and the development of featured industries.

The shortcoming of this study is that the obtained electricity price scheme is only a theoretical estimation, and the actual electricity price changes are affected by a variety of factors, such as the relationship between energy supply and demand, market competition, weather conditions, policy regulations, and other factors, therefore, when the actual consideration of the electricity price changes, it is necessary to carry out a comprehensive analysis and assessment in order to draw accurate and comprehensive conclusions. More influencing factors can be considered in future research to obtain the actual optimal electricity price application program.

Conflict of Interest

The authors declare no conflict of interest.

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