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Research on Transaction Mechanism and Game Theory for Energy Management of Virtual Power Plants

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Abstract: In response to the problem of low enthusiasm for energy efficiency transformation of high energy consuming enterprises under the traditional fixed electricity pricing model, a differential pricing mechanism is adopted in the process of power reform to promote energy conservation and emission reduction. Virtual power plants aggregate multiple distributed resources, providing energy-saving equipment transformation for high energy consuming enterprises while also providing power guarantee. This not only alleviates the power supply shortage problem of power supply companies, but also reduces their operating income, This has led to a cooperative and competitive relationship between virtual power plants and power supply companies. This article constructs a two-layer optimization model for this scenario, simulates and analyzes the decision-making game between the virtual power plant and the power supply company, obtains the final optimized results, and compares the user benefits and social comprehensive benefits before and after the user transformation.

Keywords: grid frequency regulation, load-side, cooperative control

1. INTRODUCTION

Under the conditions of a market economy, the marketing behavior of the country implementing different electricity pricing policies for different electricity users' needs in order to achieve energy-saving and emission reduction goals belongs to the differential electricity pricing strategy. For high energy consuming and heavily polluting industries such as electrolytic aluminum, cement, and steel, China mainly divides them into

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allowable, restricted, and eliminated categories, and gradually increases electricity prices[1]. This measure effectively combines price leverage with industrial policies to effectively reduce the excessive development of high energy consuming industries, while reducing unnecessary redundant construction. During this process, production skills are tested, advanced production capacity is further developed, and outdated production capacity will be slowly phased out[2]. These will improve the general technological level and increase energy utilization efficiency, Relieve energy tension. However, there are still many difficulties in the specific implementation process. Therefore, in order to promote the healthy and sustainable development of high energy consuming enterprises and further promote energy conservation and emission reduction work, the trading mechanism and decision-making benefits of virtual power plants are studied on the basis of differential electricity pricing system[3].

2. Virtual Power Plant Trading Mechanism

2.1 Virtual Power Plant Energy Efficiency Transformation Plan

To a certain extent, a virtual power plant can be seen as an energy efficient power plant, and its energy efficiency is reflected in its energy-saving plan and energy efficiency projects. The operation of VPP will further promote users' energy conservation and emission reduction work, and adopt certain drastic measures to encourage users to use more new technologies instead of high energy consuming technologies to improve their own energy utilization efficiency[4].

The core of the planning method for energy efficient power plants is to select the technical transformation measures and industries that have the highest efficiency improvement after transformation, and the core of maximizing efficiency improvement lies in the degree to which each equipment parameter can be modified, the potential for energy conservation, and the maximum load savings. Based on the above analysis, establish a virtual power plant based on distributed energy generation. In the context of national energy conservation and emission reduction, virtual power plants can participate in the electricity market by providing suppliers with new and energy-saving power supply methods[5].

Virtual power plants are composed of government agencies, credit institutions, power grid companies, and high energy consuming enterprises. In this process, the government constructs relevant policy frameworks, and the rules within this framework adopt different differential pricing methods for different high energy consuming enterprises. The power grid company plays a role as an intermediary in this process. The power grid company not only needs to provide feedback to the government on users' information about differential electricity prices, but also needs to bridge the gap between virtual power plants and users, and sometimes even provide considerable technical support to virtual power plants. In differential electricity prices, high energy consuming enterprises are the specific implementers. On the basis of paying according to the existing differential electricity prices, high energy consuming enterprises can upgrade and transform their relevant equipment based on their own implementation experience and the technical transformation plans provided by virtual power plants. In the initial stage of investment and operation, the most important financing and recovery methods for virtual power plants are the form of obtaining the necessary funds for power plant operation, as well as the corresponding capital value recovery method. The corresponding funding sources for virtual power plants are government investment, subsidies, and credit[6].

2.2 Differential electricity price operation mechanism

The distributed energy aggregated in virtual power plants almost covers all distributed energy sources in the current market, including wind power generation, micro gas turbine power generation, fuel cell power generation, etc. In the process of virtual power plant operation mode, there is a government differential electricity price policy. Therefore, high energy consuming enterprises after energy-saving equipment renovation should make corresponding adjustments to their differential electricity prices[7]. The corresponding differential electricity price operation process is shown in Figure 1.

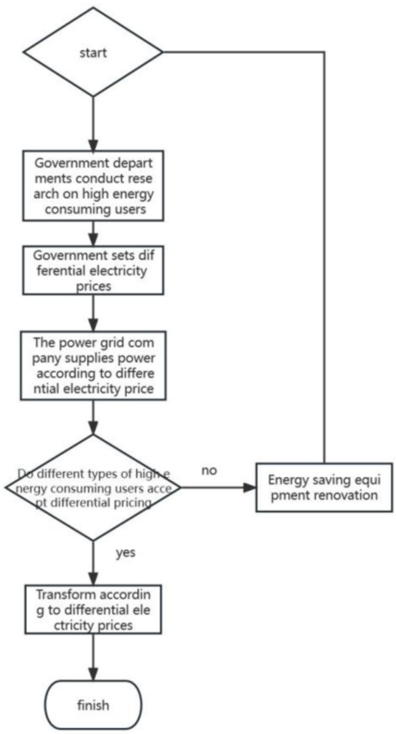

Fig. 1. Differential electricity price operation diagram

According to Figure1, under the existing differential electricity price mechanism, high energy consuming enterprises, on the basis of upgrading and transforming their equipment to improve energy utilization efficiency, accept corresponding differential electricity price revisions from government departments to promote energy conservation and emission reduction work of high energy consuming enterprises. When virtual power plants renovate energy-saving new equipment for high energy consuming enterprises, they will also sign corresponding power supply contracts with high energy consuming enterprises. At the same time, in order to not affect the power supply structure of other power supply companies and power grid companies, there is a upper limit on the power supply volume of the contracts signed between virtual power plants and high energy consuming enterprises. The part of the electricity consumption of high energy consuming enterprises outside the upper limit will be supplied by the power grid company according to differential electricity prices[8].

3. DECISION ANALYSIS OF VIRTUAL POWER PLANT AND POWER SUPPLY COMPANY

Virtual power plants not only provide energy-saving equipment renovation for high energy consuming enterprises, but also provide power guarantee for high energy consuming enterprises. This alleviates the power supply shortage of power supply companies on the side, but also reduces the operating revenue of power supply companies. This inevitably leads to a cooperative and competitive relationship between virtual power plants and power supply companies. How to make effective decisions in this relationship is a problem that must be addressed[9].

3.1 Decision analysis of Virtual Power Plant

In the process of completing energy-saving equipment renovation and technical guidance for high energy consuming enterprises, virtual power plants will receive corresponding power supply contracts; Virtual power plant is a collection group of distributed generation stations, such as photovoltaic power generation, fuel cell power generation, gas turbine power generation and wind power generation. It can conduct two-way power exchange with low-voltage distribution network through tie lines[10]. The power generation costs of each generation set group and each generation unit in a virtual power plant are as follows:

$$\sum_{i=1}^{n} C_{(p_i)} = \sum_{i=1}^{n} \left(\alpha_i P_i^2 + \beta_i P_i + \lambda_i \right)$$

In the formula, n is the number of power generation components in the virtual power plant, αi,βi and λ i are the cost coefficients of power generation components.

$\alpha_i P_i^2 + \beta_i P_i$ are variable costs, and λ_i are fixed costs. The annual fixed investment cost of distributed generation is:

$$\sum_{i=1}^{n} C_{Di} = \sum_{i=1}^{n} \delta_i C'_{Di}$$

In the formula, δ_i represents the average cost coefficient of the ith power source, and C_{Di} represents the fixed investment cost of the ith power source;

Virtual power plants provide energy-saving equipment and new technologies for enterprises, and the energy efficiency benefits obtained within a certain power supply period are:

$$R_{NX} = \sum_{i=1}^{m} \left(C_{Wi} - C_{Ii} \right)$$

In the formula, m is the total number of enterprises participating in energy-saving equipment renovation, CWi is the purchase cost of the equipment required by the enterprise; CIi is the investment cost virtual power plant equipment for the ith enterprise. The income from selling virtual power plants to users is:

$$R_{XS} = \sum_{i=1}^{m} \sum_{t=1}^{T} P_{ti} P_{3ti}$$

In the formula, Pti refers to the unified sales of electricity after optimization; P3ti determine the load capacity of each transformed enterprise user during the power supply period T.

After virtual power plants participate in market operation, their goal of purchasing and selling electricity is to maximize their own profits while ensuring stable operation. Therefore, the objective function is expressed as follows:

$$\max R = R_{NX} + R_{XS} - \sum_{i=1}^{n} C_{Di} - \sum_{i=1}^{n} C_{(p_i)}$$

The constraints include:

1) Power balance constraint: The power generation components in a virtual power plant can ignore network losses, therefore, the power balance constraint in the virtual power plant is shown in the equation:

$$\sum_{i=1}^{n} P_i = \sum_{j=1}^{m} \sum_{t=1}^{T} P_{3tj}$$

2) Output constraints of unit power generation components:

$$P_{\min i} \le P_i \le P_{\max i}$$

In the formula, $P_{\min i}$ and $P_{\max i}$ are the minimum and maximum outputs of the power generation components in the microgrid, respectively.

3) Purchasing power constraint: According to different energy-saving investments and production conditions of users, the amount of electricity purchased varies and has an upper limit.

$$0 \le P_{3i} \le P_{\max i}$$

3.2 decision analysis of Power Supply Company

The power supply company implements the previous differential electricity price policy for enterprises that have undergone energy-saving transformation, and supplies power to enterprises that have not undergone energy-saving transformation according to the new electricity price standard[11-12]. Implementing separate power supply for virtual power plants, the power supply company charges a certain fee for power supply compensation, so the power supply revenue becomes:

$$R_F = \sum_{j=1}^{N}\sum_{t=1}^{T} P_{Ntj}P_{1tj} + \sum_{i=1}^{m}\sum_{t=1}^{T} P_{ti}P_{2ti} + \sigma R - C_{KZD} - \sum_{t=1}^{T}\overline{p}_t P_0$$

Within a certain power supply period T, N is the total number of enterprises that do not participate in energy-saving equipment renovation, P_{Ntj} is the differential electricity price implemented for this part of enterprises, P_{1tj} is the load of this part of users during the power supply period T; P_{1tj} is the user load purchased by each renovation enterprise from the power supply company during the power supply period T; R is the virtual power plant revenue; σ is the power supply compensation fee coefficient collected by the power supply company from the virtual power plant, and meets the requirements $0<\sigma<1$; C_{KZD} is the total cost of interruptible compensation for the enterprise; $\overline{p}_t$ is the average price of electricity purchased by the power supply company from various markets within a certain power supply period T; P_0 is the corresponding purchasing power.

The constraints include:

1) System power balance constraints: do not consider network losses.

$$\sum_{j=1}^{N}\sum_{t=1}^{T} P_{1tj} + \sum_{i=1}^{m}\sum_{t=1}^{T} P_{2ti} = \sum_{t=1}^{T} P_0$$

The unified sales electricity price optimized for users who accept energy-saving equipment renovation should be lower than the previous differential electricity price:

$$P_{tj} < P_{Ntj}$$

Through the analysis of the above decisions, it is found that there is a cooperative relationship between the power supply company and the virtual power plant, as well as a conflict of interest, which is known as a game relationship. Therefore, a two-layer optimization integration model for differential electricity prices is proposed below to achieve a win-win situation.

3.3 Integrated model based on two-layer optimization

In summary, although virtual power plants and power supply companies may adopt non cooperative decisions due to conflicts of their own interests when making decisions, the lower level decision-makers make decisions under the guidance of the upper level decision-makers, and the upper level decision-makers will continuously adjust and optimize their original decisions based on the feedback information of the lower level decision-makers. Therefore, to a certain extent, they reflect a characteristic of mutual gaming. Therefore, a two-level optimization model for dealing with multi-objective decision-making problems will be introduced for hierarchical decision-making modeling[13]. This model is divided into two levels of decision-making: the upper level decision-making is for the benefit of the power supply company, the lower level decision-making is for the benefit of the virtual power plant, and the constraint condition is that the purchase cost of electricity after renovation<the purchase cost of electricity before renovation. The summary is as follows:

$$\begin{cases} R_F = \sum_{j=1}^{N}\sum_{t=1}^{T} P_{Ntj}P_{1tj} + \sum_{i=1}^{m}\sum_{t=1}^{T} P_{ti}P_{2ti} + \sigma R - C_{KZD} - \sum_{t=1}^{T} \overline{p}_t P_o \\ s.t. \sum_{j=1}^{N}\sum_{t=1}^{T} P_{1tj} + \sum_{i=1}^{m}\sum_{t=1}^{T} P_{2ti} = \sum_{t=1}^{T} P_0 \\ P_{tj} < P_{Ntj}, 0 < \sigma < 1 \\ \sum_{j=1}^{m}\sum_{t=1}^{T} P_{2tj} + \sum_{i=1}^{m}\sum_{t=1}^{T} P_{3ti} = E \\ s.t. \sum_{i=1}^{n} P_i = \sum_{j=1}^{m}\sum_{t=1}^{T} P_{3tj} \\ 0 \le \sum_{j=1}^{m}\sum_{t=1}^{T} P_{3ti} \le P_{\max i} \\ P_{\min i} \le P_i \le P_{\max i} \end{cases}$$

On the basis of completing energy-saving transformation and technological improvement, high energy consuming enterprises improve their production plans, and predict new variables that will occur without changing their production capacity. Decision makers at the upper and lower levels analyze the optimal electricity price based on the electricity quantity, quotation, and relevant information of the power supply company of the virtual power plant.

To solve this model, the upper layer adopts a random search method with a search frequency of 20000, while the lower layer adopts a genetic algorithm with a population size of 50, a crossover probability of 0.5, and a mutation probability of 0.03. The iteration frequency is 100. The specific algorithm solving flowchart is shown in Figures 2

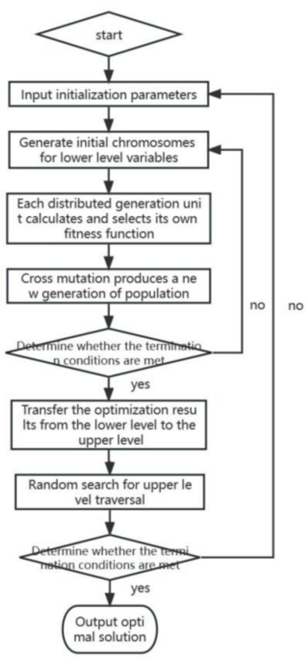

Fig. 2. Flow chart of two-layer optimization model

4. ANALYSIS OF COMPREHENSIVE SOCIAL BENEFITS

In order to verify the feasibility of the above solutions, this chapter will analyze the comprehensive social benefits generated by power supply companies, virtual power plants, and users.

4.1 User benefit analysis

The power supply company and virtual power plant jointly undertake the power consumption of energy-saving transformation enterprises, and set the investment for energy-saving transformation of enterprises as $\sum_{i=1}^{m} C_{Wi}$; At the same time, the government subsidy fee is: $\sum_{i=1}^{m} C_{BTi}$;after the energy-saving transformation, the unit product power consumption of the enterprise decreases, and the unit product pollution discharge cost decreases. Therefore, the output value of the enterprise under the same purchase electricity quantity will increase. The output value of the electricity consumption before the transformation is U, and the output value after the transformation is U′ ; Therefore, the electricity purchase costs for such users before and after energy-saving equipment renovation are:

$$\sum_{i=1}^{m} C_i = \sum_{i=1}^{m} \sum_{t=1}^{T} p_{ti} E$$

$$\sum_{i=1}^{m} C_i' = \sum_{i=1}^{m} \sum_{t=1}^{T} P_{Nti} \left(P_{2ti} + P_{3ti} \right)$$

In the formula, C_i is the original cost of purchasing electricity; C' is the cost of purchasing electricity after renovation; P_{2ti} is the purchase electricity from power supply companies for Class i enterprises; P_{3ti} is the purchase electricity from virtual power plants for the type of enterprise, and ensure that the purchased electricity equals the electricity consumption.

$$\sum_{j=1}^{m} \sum_{t=1}^{T} P_{2tj} + \sum_{i=1}^{m} \sum_{t=1}^{T} P_{3ti} = E = \sum_{i=1}^{m} D_i$$

C_F And C_F' are the other fixed costs, including the cost of purchasing energy-saving equipment, before and after the renovation, excluding electricity bills. When the production and sales ratio is 100%, the profits obtained by the enterprise before and after energy-saving transformation are:

$$\phi = \sum_{i=1}^{m} \left(U - C_i - C_F \right)$$

$$\phi' = \sum_{i=1}^{m} \left(U' + C_{BTi} - C_i' - C_F' \right)$$

In the formula, ϕ and ϕ' are the profits obtained by the enterprise before and after energy-saving transformation.

4.2 Comprehensive Benefit Analysis

The income earned by the power supply company before the renovation of energy-saving equipment is; After the renovation of energy-saving equipment, the income obtained from the above two-level optimization model is, and the income obtained from the virtual power plant is. Therefore, the comprehensive social benefits obtained before and after the renovation are:

$$R_T = R_{F0} + \phi$$

$$R_T' = R_{F1} + \phi' + R_{VPP}$$

R_T and R_T' respectively represent the comprehensive social benefits before and after the renovation. Based on the two-level optimization integration model mentioned above, the comprehensive social benefits of energy-saving equipment renovation can be obtained.

5. Example analysis

The example system built in this article, as shown in the figure, includes four VPP test power generation units. This example is constructed based on the 2018 power grid data of the North China region. The GS related parameters are shown in Table 1. fixed investment cost CD for power supply.

Table 1 Power supply related parameter table

P	A(10^3yuan/kw)	β(10^3yuan/kw)	λ (10^3yuan/kw)	P_{min}(kw)	P_{max}(kw)
1	0.1	0.9	1.2	0	25000
2	0.08	0.8	1.4	0	30000
3	0.12	0.6	1	0	20000
4	0.1	0.8	1.4	0	32000

The initialization parameter of the two-level optimization model is: the coefficient of power supply compensation fees charged by the power supply company from the virtual power plant $\alpha = 0.15$; The total cost of interruptible compensation is L; This example simulates that the energy-saving equipment owned by VPP in the early stage of energy-saving transformation is sold to energy-saving transformation enterprises at a price close to the introduction price, that is, the cost of enterprise energy-saving transformation is approximately equal to the investment cost of VPP's energy-saving equipment; The maximum purchasing power obtained by the energy-saving renovation enterprise from VPP under the constraint conditions is determined by the amount of energy-saving equipment purchased by the enterprise from VPP. The maximum purchasing power Pimax simulated in this example are assumed to be half of all the electricity required by the renovation enterprise. The two-layer optimization model is solved according to the algorithm process, and the optimal sales price of the reconstructed power supply company and virtual power plant that meet various constraints and the optimal output of each distributed generation unit of the virtual power plant are obtained, as shown in Table 2. The production and benefits before and after the transformation of enterprise users are shown in Table 3.

Table 2 Optimized Virtual power plant Output and Optimal Pricing

period	Output of each unit in the VPP (MW·h)				Electricity sold to renovation enterprises / (MW·h)		power price after renovation/ yuan· (MW·h)$^{-1}$	power price before renovation/yuan·(MW·h)$^{-1}$
	PV	WT	GT	FC	Before renovation	After renovation		
peak	346.6	333.5	272.1	567.9	4800	3288.5	319.2	410
flat	328.1	346.9	254.8	562.5	3900	2465.7	298.5	380
valley	289.3	270.3	232.7	557.1	2800	1480.9	280.2	350

Table 3 Production and benefit data before and after enterprise user transformation

period	status	Power price/(yuan·(MW·h)$^{-1}$)	quantity of electricity/ (MW·h)	Power price/10^6yuan	cost/10^6yuan	output value/10^6yuan	benefit /10^6yuan
peak	Before renovation	410	4800	1.968	0.964	4.82	1.888
	After renovation	319.2	4800	1.532	2.438	6.564	2.594
flat	Before renovation	380	3900	1.482	0.741	3.685	1.462
	After renovation	298.5	3900	1.164	2.041	5.292	2.086
valley	Before renovation	350	2800	0.98	0.482	2.358	0.896
	After renovation	280.2	2800	0.785	1.682	3.568	1.102

From the above analysis, it can be seen that the benefits of virtual power plants, high energy consuming enterprises, and social welfare have all increased compared to when VPP was not introduced. At the same time, in order to better implement demand side incentive policies under energy conservation and emission reduction, government agencies will provide certain policy subsidies to power supply companies to avoid boycott behavior taken by power supply companies due to the current decrease in profits. The specific subsidy standards depend on the situation.

6. CONCLUSION

This article aims to explore a new power supply method for high energy consuming enterprises with high energy consumption and pollution restrictions, using the establishment of virtual power plants to optimize high energy consumption. Based on the study of differential electricity prices, the concept of distributed energy generation group virtual power plants is introduced, which is combined with differential electricity prices. The government's differential electricity prices are combined with the operation mode of virtual power plants, Establish a two-layer game optimization model for differential electricity prices under the virtual power plant operation mode, and re optimize and adjust the differential electricity prices. By optimizing and adjusting differential electricity prices, it provides practical reference for government agencies to formulate reasonable electricity pricing policies, and better promotes rapid social development.

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