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Optimization Strategy of Multi-agent Integrated Energy System in Campus Considering Thermal and Electrical Demand Response

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Abstract

The integrated energy system of industrial park is composed of multiple micro-grid subjects. When there is energy interaction between subjects, the interest interaction between subjects brings challenges to the operation of the integrated energy system of industrial park. Aiming at the multi-agent integrated energy system with energy sharing, in order to improve the energy supply economy of each agent, this paper studies an optimization strategy of the integrated energy system in the park considering the thermal and electrical demand response. Firstly, this paper takes the subjects composed of different equipment as the research object, and introduces the utility theory to build the demand response models of heat, electricity and gas based on the dynamic electricity and gas prices and the fuzzy degree of human body to temperature. In order to minimize the cost of the comprehensive energy system in the park, a distributed optimization strategy based on demand response and alternate direction multiplier method was proposed to realize the energy sharing among all the subjects in the park and improve the energy supply economy of the comprehensive energy system. Finally, an example is given to verify the effectiveness of the proposed model and method.

Keywords

Integrated energy system, multi-micro-grid agent system, demand response, Alternating direction Multiplier method, distributed optimization

Introduction

In the environment of a large number of new energy connected to the grid, clean and efficient energy supply methods and improving the benefits of micro grid are urgent problems to be solved in the current energy field. One of the most effective ways to solve this problem is the Integrated Energy System (IES), which improves the interests of energy supply and demand subjects and reduces pollution emission through complementation of various energy sources and cascade utilization of energy sources [1-4]. Therefore, IES has become an important part of "building a low-carbon, clean and efficient modern energy system". And it has been applied in all kinds of high energy consumption factories in ecological industrial parks. With the development of IES, some Regional Integrated Energy systems (RIES) are interconnected and form an integrated energy network, especially in the Energy System of the park. Multi-agent integrated energy system in the park (MPIES). It can realize the interaction and collaborative optimization of various energy sources among different subjects, which will effectively improve the flexibility of energy supply, improve the consumption rate of distributed renewable energy, and improve the comprehensive energy efficiency of various energy sources [5-7]. Therefore, the joint scheduling and operation of the multi-agent integrated energy system in the park is one of the key technologies in the future IES research.

Research on cooperative scheduling problem of multi-agent energy system in park. For example, in reference [8], for the coordination and optimization of regional multi-micro grid system, which mainly includes the combined cold, heat and power supply system, an optimal scheduling model considering the power interaction and output coordination among various subjects is established. In reference [9], considering the limitation of transmission power among micro-grid subjects, a multi-micro-network cooperative scheduling model based on cooperative game was constructed. In reference [10], a master-slave game optimization scheduling strategy considering demand response is proposed for the integrated energy system with multi-micro grid electric energy interaction. In reference [11], aiming at the problem of integrated energy system planning centered on power network, a joint planning method of integrated energy system of electricity and gas based on multi-agent game was proposed. Literature [12] has analyzed the computational performance of flexibility balance theory in mining the overall flexibility regulation of source-network-charge-storage.

But most of the study is to wind and light power plant power generation side or separate CHP unit devices such as a research subject, and only model describing energy supply/demand of unilateral energy coupling problem, didn't pay attention to energy supply and demand both sides in the commercial and industrial park can be saved in the integration of system optimization problem, has a large deviation results and the actual.

Based on the above research, this paper puts forward the optimization strategy of multi-agent integrated energy system in the park considering the thermal and electrical demand response. First, in order to make the research fit the reality as best as possible, this paper takes the micro-grid main body composed of a variety of equipment as the research object, and then introduces utility theory on the basis of dynamic electricity and gas pricing mechanism[13-14]. The demand response model of electricity and gas load and the demand response model of heat load are established based on the two models. Secondly, on the basis of single user main body, from the perspective of multi-body in the park, two kinds of energy, heat and electricity, are taken as the object of energy sharing among main bodies at the same time, so as to meet the energy demand of each subject and reduce the energy cost of each subject. Finally, the effectiveness of the proposed method is verified by a practical example.

1. Basic structure of multi-user integrated energy system in the park

This paper consists of three micro network main body of the park more piconets integrated energy system to optimize the configuration, because the distance between the micro network main body in the park is not far, various micro mesh is two interconnected through power and thermal channels, each micro mesh can be purchased from external network and gas each piconets need energy, not to consider selling gas to gas network. The excess power and heat generated during the operation of the micro-grid are sold to other micro-grid entities. The price of electricity/heat energy traded between microgrids is lower than that between microgrids and their superior power distribution networks, and each microgrid belongs to different subjects. Therefore, there is naturally a complex relationship between interest interaction and privacy protection among each microgrid.

Among them, the internal integrated energy system of single user main body mainly includes gas, heat and electricity three kinds of energy loads. Through various energy equipment, the coupling and conversion between energy loads are realized. Energy conversion equipment mainly includes gas boilers, gas turbines, electric heat storage boilers, power to gas equipment and combined heat and power generation units.

In the process of internal optimization scheduling, when the electric energy and heat energy produced by heat generation equipment and power generation equipment (CHP equipment, etc.) meet all the energy demands of their thermal and electrical loads, the excess heat and energy can be used to trade energy with other users to increase their comprehensive interests. The price for the interaction of electricity and heat was agreed in advance to be lower than the price purchased from the main network. The main integrated energy system structure of single micro grid is shown in Fig.1.

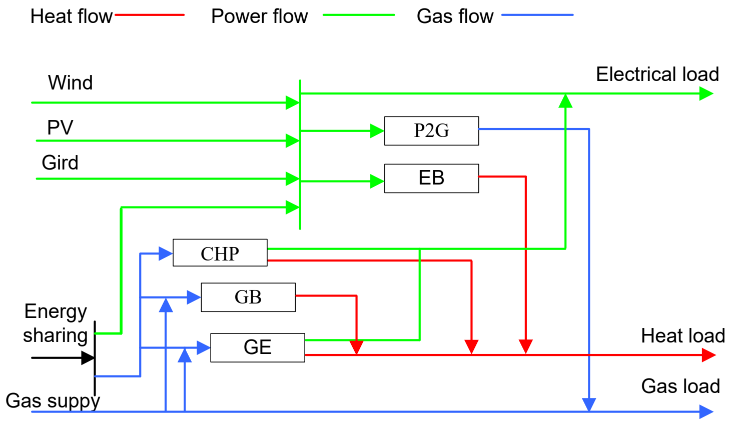

Fig.1. The structure of the main integrated energy system of a single microgrid.

2. Electricity/gas/heat demand response model for a single user subject

The single-user internal multi-energy comprehensive demand response model constructed in this paper optimizes various load demand curves by adjusting users' energy habits, so as to improve the multi-energy utilization rate and the overall interests of users. In this paper, when studying the response behavior of various loads, only the load transfer is considered, and the total load demand before and after the response is unchanged.

2.1 Electrical load demand response model

In this paper, the influence of electricity price on load response is considered when constructing the demand response model of electric load. The guiding effect of dynamic electricity price on users' electricity consumption behavior is studied, so as to reduce the peak-valley difference of electrical load and improve the stability of system operation [15].

The utility theory is introduced to describe the power consumption. The Cobb-Douglas utility function is one of the most famous utility functions widely used by economists in economics. The Cobb-Douglas utility function is adopted to represent the utility forms of two different goods, *i.e*,

$$U(X_1, X_2) = X_1^{\rho} X_2^{1-\rho} \quad 0 \neq \rho < 1 \tag{1}$$

Where U is utility function; X_1, X_2 are two different goods; ρ is an elastic parameter.

According to the utility theory, the demand response functions of peak, flat and valley periods can be obtained.

$$R_p = \frac{R_{f0} + R_{p0} + R_{g0}}{\rho_1(1-\rho)/D_p + \rho/D_f + (1-\rho_1)/D_g} \bullet \frac{(1-\rho)}{\beta} \tag{2}$$

$$R_f = \frac{R_{f0} + R_{p0} + R_{g0}}{\rho_1(1-\rho)/D_p + \rho/D_f + (1-\rho_1)/D_g} \bullet \frac{\rho}{D_f} \tag{3}$$

$$R_g = \frac{R_{p0} + R_{f0} + R_{g0}}{\rho_1(1-\rho)/D_p + \rho/D_f + (1-\rho_1)/D_g} \bullet \frac{(1-\rho)(1-\rho_1)}{D_g} \tag{4}$$

Where: ρ_1 is the elastic parameter when the load is transferred from normal period to grain period, ρ Is the elastic parameter when the load is transferred from the peak period to the normal period and the valley period, R_f, R_p and R_g are the total loads in peak, flat and valley periods, respectively, and are the load consumed in peak hours, normal hours and grain hours, respectively; and are the electricity prices in peak hours, normal hours and grain

In this paper, based on the traditional TOU price and combining with the seasonal characteristics of load, the traditional load forecasting model is used to obtain the load values of the predicted daily peak, flat and valley periods. The electricity price of the dynamic peak, flat and valley periods on the forecast day can be expressed as

$$D_f = D_{f0} R_f / R_{fave} \tag{5}$$

$$D_p = D_{p0} R_p / R_{pave} \tag{6}$$

$$D_g = D_{g0} R_g / R_{gave} \tag{7}$$

Where: D_f, D_p, D_g are respectively the adjusted price of peak, flat and valley hours; R_f, R_p, R_g are the load values of peak, flat and valley periods respectively; R_{fave}, R_{pave}, R_{gave} are the average values of load values in peak, flat and valley periods of the season respectively.

From the overall perspective, the demand response model of electrical load is as follows:

$$R_e(t) = R_{e,0}(t) + \Delta R_e(t) \tag{8}$$

Where: $R_{e,0}(t)$ represents the original electrical load; $R_e(t)$ represents the electrical load after demand response; $\Delta R_e(t)$ denotes the change of electrical load in time period t, According to the optimization of the model proposed in this paper, when the value is greater than zero, the load is transferred in, and when the value is less than zero, the load is transferred out.

2.2 Gas load demand response model

Both natural gas and electric power are important energy resources and have similar market commodity attributes. In this paper, part of the gas load is further regarded as transferable load to participate in demand response. By analogy with transferable electrical load, the mathematical model of transferable gas load is

$$R_{gas}(t) = R_{gas,0}(t) + \Delta R_{gas}(t) \tag{9}$$

Where: $R_{gas,0}(t)$ represents the original gas load; $R_{gas,0}(t)$ represents the gas load after demand response; $\Delta R_{gas}(t)$ Denotes the change of gas load in time period t, according to the optimization of the model proposed in this paper, when the value is greater than zero, the load is transferred in, and when the value is less than zero, the load is transferred out.

2.3 Thermal load demand response model

Since users have a certain degree of ambiguity on temperature comfort, heating load can participate in demand response as a flexible load. Heating load in this paper mainly considers hot water load. Based on this, the heating load in the multi-energy micro grid is involved in the scheduling, and the mathematical model is shown as follows [17].

$$R_{w,0}(t) = \frac{C_w \bullet V(t) \bullet (T_{w,0} - T(t))}{3.6 \times 10^6 \Delta t} \tag{10}$$

$$R_w(t) = \frac{C_w \bullet V(t) \bullet (T_w(t) - T(t))}{3.6 \times 10^6 \Delta t} \tag{11}$$

Where: $R_{w,0}(t)$, $R_w(t)$ respectively represent the thermal load power before and after the demand response in time period t, kW; C_w is the heat capacity per unit volume of water, $4.2\times10^6 J/m^3\,{}^oC$; $V(t)$ Is the hot water consumption in time period t, m^3;$T_{w,0}$ represents the setting temperature of hot water before demand response,50 ${}^oC$; $T(t)$ Is the cold water temperature at time period t,10${}^oC$; $T_w(t)$ represents the hot water temperature at time period t after demand response, ${}^oC$. Equation (12) is rewritten as

$$R_w(t) = R_{w,0}(t) + \Delta R_w(t) \tag{12}$$

$\Delta R_w(t)$ epresents the change of heat load in time period t,Where:

$$\Delta R_w(t) = \frac{C_w \bullet V(t) \bullet (T_w(t) - T_{w,0})}{3.6 \times 10^6 \Delta t} \tag{13}$$

3. A multi-agent decision optimization scheduling model based on user energy interconnection

3.1 The objective function

(1) The optimization operation of multi-subject energy in the park minimizes the sum of operation costs of all subjects through energy management. Therefore, the objective function can be expressed as:

$$\min \sum_{i=1}^{N} \sum_{t \in T} C_t^{mi} = \sum_{i=1}^{N} \sum_{t \in T} (C_{i,e,t}^{in} + C_{i,g,t}^{gas} + C_{i,t}^{op} + C_{i,t}^{flow} + C_{i,t}^{IDR}) \tag{14}$$

Where: N and T are the set of subject and time period respectively, and C_t^{mi} is the operation cost of subject i, including electricity purchase cost $C_{i,e,t}^{in}$, natural gas purchase cost $C_{i,g,t}^{gas}$, energy coupling equipment operation and maintenance cost $C_{i,t}^{op}$,and flowing electric heating load cost $C_{i,t}^{flow}$ purchased from other subjects, comprehensive demand response cost $C_{i,t}^{IDR}$.

(2) Integrated demand response costs

The comprehensive demand response cost includes the transfer compensation cost of transferable electric load, transferable gas load, and transferable heat load, and can be calculated as

$$C_{i,t}^{IDR} = c_{IDR} \sum_{t=1}^{T} (|P_{e,tra}(t)| + |P_{g,tra}(t)| + |P_{h,tra}(t)|) \tag{15}$$

Where: $P_{e,tra}(t)$, $P_{g,tra}(t)$, $P_{h,tra}(t)$ are respectively the transferable electric load, the transferable gas load and the transferable heat load at time t; c_{IDR} is the compensation cost per unit power transfer of transferable load.

3.2 The constraint

3.2.1 Constraints on the system device

(1) CHP unit

$$\begin{cases} P_{CHP,\min} \le P_{CHP}(t) \le P_{CHP,\max} \\ -R_{CHP,down}\Delta t \le P_{CHP}(t) - P_{CHP}(t-1) \le R_{CHP,up}\Delta t \end{cases} \tag{16}$$

Where: $\eta_{H,CHP}$ and $\eta_{P,CHP}$ represent heat and electricity generation efficiency of CHP unit respectively.

(2) Internal combustion engine

$$\begin{cases} H_{GE}(t) = G_{GE}(t)\eta_{H,GE} \\ P_{GE}(t) = G_{GE}(t)\eta_{P,GE} \\ P_{GE,\min} \le P_{GE}(t) \le P_{GE,\max} \\ -R_{GE,down}\Delta t \le P_{GE}(t) - P_{GE}(t-1) \le R_{GE,up}\Delta t \end{cases} \tag{17}$$

Where: $\eta_{H,GE}$ and $\eta_{P,GE}$ represent heat and electricity generation efficiency of internal combustion engine unit respectively;

(3) gas-fired boiler

$$\begin{cases} H_{GFB}(t)=G_{CHP}(t)\eta_{H,CHP} \\ H_{GFB,\min}\le H_{GFB}(t)\le H_{GFB,\max} \\ -R_{GFB,down}\Delta t\le P_{GFB}(t)-P_{GFB}(t-1)\le R_{GFB,up}\Delta t \end{cases} \tag{18}$$

Where: $\eta_{H,CHP}$ is the heat production efficiency of gas boiler;.

(4) P2G devices

$$\begin{cases} G_{P2G}(t)=P_{P2G}(t)\eta_{P2G} \\ G_{P2G,\min}\le G_{P2G}(t)\le G_{P2G,\max} \\ -R_{P2G,down}\Delta t\le G_{P2G}(t)-G_{P2G}(t-1)\le R_{P2G,up}\Delta t \end{cases} \tag{19}$$

Where: η_{P2G} is the gas production efficiency of electric gas conversion equipment;.

(5) Electric boiler

$$\begin{cases} H_{EB}(t)=P_{EB}(t)\eta_{EB} \\ H_{EB,\min}\le H_{EB}(t)\le H_{EB,\max} \\ -R_{EB,down}\Delta t\le H_{EB}(t)-H_{EB}(t-1)\le R_{EB,up}\Delta t \end{cases} \tag{20}$$

Where: η_{EB} is the gas production efficiency of electric boiler.

3.2.2 Load demand response constraints

(1) Electrical load demand response constraint

$$\begin{cases} -P_{put,\max}\le \Delta R_p(t)\Delta t\le P_{in,\max} \\ \sum_{t=1}^{T}\Delta R_p(t)\Delta t=0 \end{cases} \tag{21}$$

(2)Gas load demand response constraints

$$\begin{cases} -G_{put,\max}\le \Delta R_G(t)\Delta t\le G_{in,\max} \\ \sum_{t=1}^{T}\Delta R_G(t)\Delta t=0 \end{cases} \tag{22}$$

(3) Thermal load demand response constraints

$$\sum_{t=1}^{T}R_{W,0}(t)\Delta t=\sum_{t=1}^{T}R_W(t)\Delta t \tag{23}$$

$$\left|T_W(t)-T_{W,0}\right|\le \Delta T \tag{24}$$

Where: T is the maximum allowable deviation of hot water temperature, 5°C.

3.2.3 Constraints on system power balance

(1) Electric power balance constraint

$$P_{i,e}^{chp}+P_{i,e}^{GE}+P_{i,e}^{chp}+P_{i,e}^{in}+P_{i,e}^{flow}=P_{i,e}+P_{i,e}^{EB}+P_{i,e}^{p2g}+\Delta R_e \tag{25}$$

(2) Thermal power balance constraint

$$P_{i,h}^{chp}+P_{i,h}^{GE}+P_{i,h}^{GB}+P_{i,h}^{EB}+P_{i,h}^{in}+P_{i,h}^{flow}=P_{i,h}+\Delta R_h \tag{26}$$

(3) Gas power balance constraint

$$P_{i,g}^{in}+P_{i,g}^{p2g}=P_{i,g}+P_{i,g}^{GB}+\Delta R_g \tag{27}$$

4. Solution

The model built in this paper is a 0-1 mixed integer linear programming model, and is solved by MATLAB combined with Gurobi.

5. Example simulation analysis

5.1 Basic data

In order to verify the effectiveness of the multi-agent integrated energy system optimization strategy of the park proposed in this paper in the optimization operation of RIES, this paper conducted simulation analysis based on the system energy supply and demand data, equipment unit operation parameters, and load data of an industrial park. Internal equipment parameters of RIES are shown in Table 1.

Figure 2 shows TOU price and TOU gas price. Thermal load demand response, the temperature comfort range is $50 \pm 5^{o}C$,

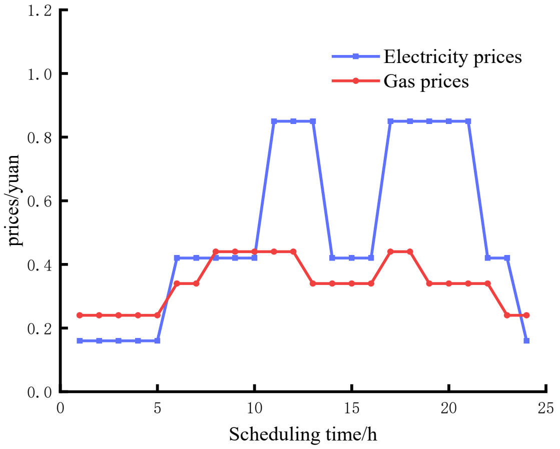

Fig.2. Traditional time-of-use electricity and gas prices.

In this paper, the results before and after the implementation of demand response are compared and analyzed for MPIES composed of three microgrid systems with different energy coupling structures. The distribution of microgrid type energy coupling devices of the three microgrid main systems is shown in the table.

Tab.1. The main components of each microgrid

Equipment	Abbreviations	Subject 1	Subject 2	Subject 3
Gas turbine-1	GT1	√	√	×
Gas turbine-2	GT2	×	×	√
Internal combustion engine - 1	GE1	√	×	×
Internal combustion engine - 2	GE2	×	√	√
Gas boiler	GB	√	√	√
The electric boiler	EB	√	√	√
Electric gas transfer equipment	P2G	×	×	√

Tab.2. Various energy coupling devices and parameters

Equipment	Rated power/kW	Efficiency parameters	Maintenance costs (yuan /(kW•h))	Downhill climbing rate/kW•h	Rate of ascent/kW•h
GT1	2000	$\eta_e^{GT1}=0.24,\eta_h^{GT1}=0.52$	0.059	5	15
GT2	2000	$\eta_e^{GT2}=0.28,\eta_h^{GT2}=0.54$	0.069	6	16
GE1	1400	$\eta_e^{GE1}=0.35,\eta_h^{GE1}=0.44$	0.059	3	13
GE2	2000	$\eta_e^{GE2}=0.36,\eta_h^{GE2}=0.48$	0.079	4	14
GB	2000	$\eta_h^{GB}=0.8$	0026	11	11
EB	1500	$\eta_h^{EB}=0.85$	0.013	12	12
P2G	600	$\eta_h^{EB}=0.85$	0.01	—	—

5.2 Analysis of optimization results

To verify the effectiveness of the model, set operation modes 1-4 and gradually increase the consideration factors, as shown in the table.

Table 3. Considerations for various operating modes

Model	IES	Electric and gas load response	Thermal load response	The thermoelectric Shared
1	√	×	×	×
2	√	√	×	×
3	√	√	√	×
4	√	√	√	√

The sharing power of thermal energy between each subject and other subject after the four optimization methods and the comparison of various system costs before and after the distributed optimization scheduling are shown in Table 4.

Tab.4. Comparison of various system costs before and after optimization

Cost(10^3 yuan)	The total cost	Demand response cost
Model 1	128889.7071	2113.5804
Model 2	123666.4399	2065.7652
Model 3	123606.2476	2038.5671
Model 4	123480.151	2026.7235

Analysis table 4 shows that compared with mode 1 way 2 introduces, electricity and gas load response in dynamic adjustment under the influence of the price of electricity, gas, give full play to the electrical load and gas load demand response function, reduce the purchase cost of electricity, buy gas, and other systems of all kinds of cost, 3 at the same time consider to electricity, gas and heat load of heat electric joint demand response, On the basis of mode 2, the demand response cost and the total operation cost of the park are further reduced by 27198.1 yuan and 60192.3 yuan, respectively. On the basis of mode 3, mode 4 takes into account the sharing of thermal load and electrical load among the main bodies in the park, fully exploiting the trading potential among the main bodies in the park, and further reducing the demand response cost and the total operation cost by 11843.6 yuan and 126096.6 yuan, respectively.

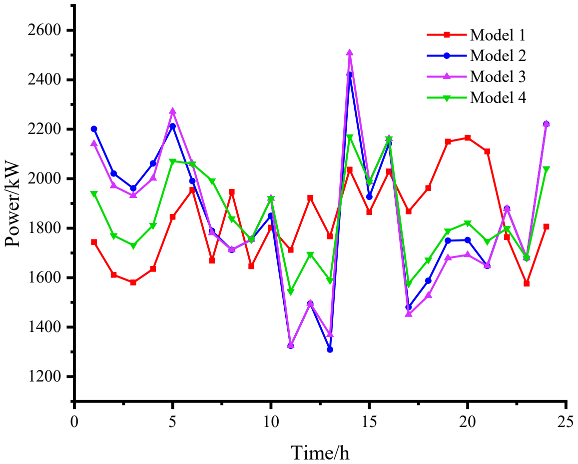

Fig.3. The electrical load curve of model 1 after response under four operation modes.

In Fig.3 electrical load curve, the peak-valley difference from operation mode 2 to operation mode 4 is 1111.231kW, 1183.603kW and 685.787kW, respectively. Compared with mode 2, the peak-valley difference of electrical load after considering heat and electricity energy sharing decreases by 38.29%, 31.12% and 41.92%, respectively. This is due to the effect of electrical load demand response, which transfers the load originally when the electricity price is high to the period when the electricity price is low, so that less electricity can be spent, and the comprehensive operation and maintenance cost and demand response cost of the park can be significantly reduced, thus improving the operation economy of MPIES.

6. Conclusion

This paper contains of different energy conversion equipment user group of integrated energy system, this paper put forward a kind of heat electric energy demand response and Shared park multi-agent integrated energy system optimization strategy, through the example analysis, known to reduce running cost, actively adjust the use of each user behavior, by considering the thermal electric load demand response, It can effectively reduce the peak-valley difference of all kinds of loads, and make the output and load curve of each equipment in MPIES more stable and gentle; At the same time, there is also a thermoelectric interactive sharing feature among users. Each subject trades the surplus energy after meeting its own load demand with other subjects at a low price, and finally achieves the purpose of reducing the cost of power supply and electricity. Compared with the way without considering the sharing of thermoelectric energy, the total cost is reduced by 126096.6 yuan.

At present, the strategy only considers the influence of dynamic electrical price on demand response and the load transfer caused by participating in demand response, but does not consider the influence of thermal inertia and load reduction. Further optimization of the strategy will become the next research direction.

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