Optimal Dispatching of Integrated Energy System Based on Multi-Energy Complementation

Jiawei Xing*, Shumin Sun, Yan Cheng, Yiyuan Liu, Peng Yu, Yuejiao Wang, Shibai Wang, Xingyou Zhang, Guangqi Zhou, Nan Wang, Yifei Guan,
State Grid Shandong Electric Power Research Institute, Shandong Jinan 250002, China
*573602466@qq.com

Abstract—To raise the energy cascade use ratio and economic benefit, the multi-energy complementation-based integrated energy system (IES) has been considerably developed in recent years, so studying its internal optimal dispatching strategies will be of great importance. In this study, an optimal dispatching strategy applicable to the operation of typical IES was put forward. First, the classical IES architecture and the operating characteristics of each piece of equipment in it were explored. Second, a mixed-integer programming model with uncertainties was constructed for three energy systems—cooling, heating and power—and each equipment in these systems. In the end, the demonstration park of a major project in China was analyzed using the proposed strategy. The effectiveness of this strategy was verified by the simulation results.

1. Introduction

Given the limitation of all kinds of energy sources themselves and the diversity of human energy demands, it is hard for any energy source to undertake the heavy burden of energy transformation independently, so it is necessary to take full advantage of different technical, economic and environmental characteristics of various energy sources to realize their complementation within different temporal and spatial scales and continuously optimize the energy structure. Therefore, an integrated energy system (IES) came into being in response to the proper time and conditions [1]. The optimal dispatching of IES has been investigated a lot, mainly including specific optimal dispatching strategies and uncertain optimal dispatching strategies. In literature [2], an efficient-variable heat and power cogeneration model was proposed, which improved the operating performance of heat and power cogeneration and elevated the multi-energy coupling use ratio. In literature [3], the original algorithm was improved, and an integrated energy multi-agent interest balancing and optimal dispatching method based on the improved nondominated sorting genetic algorithm-II (NSGA-II) was proposed, which realized the multi-agent interest balance in the park. In literature [4], a distributed optimization strategy based on a master-slave game was put forward, and the uniqueness of Stackelberg's balance of this strategy was proved. This method effectively increased the revenues at the power supply side and power use side. In literature [5], a combined bidding and clearing strategy based on three agents—the superior power grid, operator and user group—in an IES was proposed, and the simulation results revealed that this strategy could effectively guide the three agents to keep well-functioning under competitive market environment. In literature [6], a multi-objective optimal dispatching strategy was proposed to minimize the economic and environmental dispatching goal of the system, thus coordinating and optimizing power-heating energy sources. However, uncertain
factors were not introduced into the strategies of the abovementioned literature. As new energy sources continuously infiltrate systems, uncertain factors should be introduced into models to implement feasible and practical optimal dispatching strategies. In literature [7], a long-term programming method considering wind, power and load uncertainties was proposed to solve the capacity configuration problem in an IES. In literature [8], stochastic optimization models under the independent operation mode and the cooperative operation mode were constructed based on the uncertainties of clean energy considering three major agents: external backup system, user and park IES. The effectiveness of the models was verified by the simulation result. In literature [9], an optimal equipment configuration method for an IES considering the uncertainties of comprehensive demand response was put forward, and it was proven that this model showed stronger risk resistance. The literature [10] introduced the carbon trading mechanism, and a two-stage robustness optimization model was established based on the uncertainties of power load, heating load, and power-heating transferable load. The results revealed that this model could enhance the low-carbon quality and economic efficiency of the system. In literature [11], a mixed time-scale economic dispatch model considering characteristic energy difference was constructed, and the electricity and gas with a certain confidence level were set for standby application to cope with the uncertainties of new energy output. The results showed that this model was of great importance for dispatching IESs.

Based on the above background, certain and uncertain factors in the IES were simultaneously considered in this study to put forward a multi-energy complementation-based optimal dispatching strategy. First, the framework of typical IES was established, and each equipment therein and its characteristics were expounded. Second, the optimization model of IES was established, including objective functions and the constraint conditions for each equipment and the system. In the end, an integrated energy demonstration park in a major domestic project was analyzed, and the effectiveness of this strategy was verified.

2. Integrated Energy System (IES)

A typical IES consists of combined cooling, heating and power (CCHP) set, energy storage equipment, electrical refrigeration equipment and external power distribution network to which gas-fired boilers are connected. The concrete structure is as shown in Figure 1:

![Figure 1: Typical IES structure](image_url)

Where the black, red and blue solid lines with arrows represent the electric power transfer directions, the heat energy transfer directions, and the cold energy transfer directions, respectively. The yellow, green and purple boxes represent the equipment in the IES, load and external power distribution network, respectively.
2.1 CCHP set
Combined cooling, heating and power (CCHP) set, the power supply in an IES, is composed of gas power generating equipment, waste heat recovery plant and absorption refrigeration equipment. The gas power generating equipment (including the combustion gas turbine generator, the internal combustion turbine generator, the micro-gas turbine generator, etc.) can simultaneously generate electric energy and heat energy. Namely, it can be regarded as both a power source and a heat source. The electric energy emitted by the gas power plant can be directly supplied to electricity users, and the waste heat exhausted after the power generation can be treated by the waste heat recovery plants. The high-grade heat energy is directly supplied to heating loads after being treated by waste heat recovery plants (including the waste heat boiler, the heat exchanger and the waste heat direct-fired machine). In contrast, low-grade heat energy is supplied to cooling loads via absorption refrigeration equipment (e.g., the lithium bromide machine set) after being treated by the waste heat recovery plants.

2.2 Energy storage equipment
The energy storage equipment consists of electric energy storage, heat energy storage and cold storage plants. The electric energy storage plant, which is operated in the form of charging and discharging, can mitigate the uncertainties brought by the new energy output and enhance the stability of the power grid. Similarly, the heat storage and cold storage plants also operate in the form of storing and releasing cold and heat energy, i.e., storing energy in case of excess energy in the system and releasing energy in the event of insufficient energy. The energy storage equipment can be regarded as a load and power source in the system when storing and releasing energy, respectively.

2.3 Electrical refrigeration equipment
Just as absorption refrigeration equipment, electrical refrigeration equipment is a cold source in the IES. The difference lies in that the energy emitted by the electrical refrigeration equipment is converted from electric energy, while that of absorption refrigeration equipment is converted from the low-grade heat energy of the waste heat recovery plant.

2.4 Gas-fired boiler
The gas-fired boiler, the heat source in the IES, can directly supply heat energy to users. Compared with other boilers, it has better economic efficiency, so it has been widely applied to IESs.

3. Optimization Model

3.1 Objective function
To reduce the total cost of planning, investigation, design and construction in the electric power system and the expenses consumed in the service life cycle [12], and facilitate the dispatch department to coordinate the operation subjects in the IES, the minimum energy use cost of the whole system was taken as the objective function, as seen in Equation (1):

$$\min C = C_d + C_r + C_l$$

(1)

Where $C_d$, $C_r$ and $C_l$ denote the power use cost, heat use cost and cold use cost of the whole system, respectively, which are calculated through the following equations:

$$C_d = \sum_{t=1}^{24} \sum_{j=1}^{24} \left[ C_{CCHP,d}(t)P_{CCHP,d}(t) + C_{p}(t)P_p(t) + C_{cd}(t)P_{cd}(t) \right]$$

(2)

$$C_r = \sum_{t=1}^{24} \sum_{j=1}^{24} \left[ C_{CCHP,r}(t)P_{CCHP,r}(t) + C_{gl}(t)P_{gl}(t) + C_{cr}(t)P_{cr}(t) \right]$$

(3)
When electric energy, heat energy and cold energy are generated by the electrical refrigeration equipment at time $t$, $C_{d}(t)$ stands for the charging/discharging power of electric energy storage at time $t$; positive power denotes charging and negative power represents discharging. $C_{r}(t)$ and $P_{r}(t)$ represent the heat release cost and heat release rate of the gas-fired boiler at time $t$, respectively. $C_{cr}(t)$ denotes the heat storage cost at time $t$. $P_{cr}(t)$ is the heat stored and released by the heat storage device at time $t$; positive power represents heat energy storage, and negative power indicates heat energy release. $C_{d}(t)$ is the operating cost of electrical refrigeration equipment at time $t$, and $P_{d}(t)$ stands for the cold energy generated by the electrical refrigeration equipment at time $t$. $C_{d}(t)$ denotes the operating cost of the cold storage device at time $t$. $P_{d}(t)$ stands for the cold energy stored and released by the cold storage device; positive power indicates cold energy storage, and negative power represents cold energy release.

### 3.2 Constraint conditions

#### (1) CCHP operating constraints

The operating constraints of the CCHP set include power constraint, ramp constraint and thermoelectric coupling constraint, as seen in Equation (5):

$$
0.4P_{CCCHP}^{N}(t) \leq P_{CCCHP}(t) \leq P_{CCCHP}^{N}(t)
$$

$$
-\Delta P_{CCCHP}^{X} \leq P_{CCCHP}(t+1) - P_{CCCHP}^{i}(t) \leq \Delta P_{CCCHP}^{S}
$$

$$
P_{CCCHP}(t) = G_{dr}(P_{CCCHP}^{i}(t) + P_{CCCHP}^{j}(t))
$$

Where $P_{CCCHP}^{N}$ denotes the rated operating power of the CCHP set, $S_{CCCHP}(t)$ represents the operating state $(S_{CCCHP}(t) \in \{0,1\})$ of the set. $P_{CCCHP}(t)$ stands for the power of set $i$. $\Delta P_{CCCHP}^{X}$ and $\Delta P_{CCCHP}^{S}$ represent the lower limit and upper limit of ramp rate of the set, respectively. $G_{dr}$ is the conversion coefficient of electrothermal power. $P_{CCCHP}^{i}(t)$ stands for the heat release power of set $i$. $P_{CCCHP}^{j}(t)$ is the refrigeration power of set $i$ at time $t$.

#### (2) Energy storage constraint

The energy storage constraint includes energy storage and release constraint, ramp constraint, SOC constraint and energy balance constraint, as seen in Equation (6)-(8).

1) Energy storage

$$
\begin{align*}
P_{d}^{\text{out}} & \leq P_{d}(t) \leq P_{d}^{\text{in}} \\
\Delta P_{d}^{\text{out}} & \leq P_{d}(t+1) - P_{d}(t) \leq \Delta P_{d}^{\text{in}} \\
0.05 & \leq S_{soc,d}(t) \leq 0.95 \\
\sum_{t=1}^{24} P_{d}(t) & = 0
\end{align*}
$$

2) Heat storage
\[
\begin{align*}
P_{r}^{\text{out}} & \leq P_{r}(t) \leq P_{r}^{\text{in}} \\
\Delta P_{r}^{\text{out}} & \leq P_{r}(t+1) - P_{r}(t) \leq \Delta P_{r}^{\text{in}} \\
0.05 & \leq S_{\text{soc},r}(t) \leq 0.95 \\
\sum_{t=1}^{24} P_{r}(t) & = 0
\end{align*}
\]
(7)

3) Cold storage
\[
\begin{align*}
P_{l}^{\text{out}} & \leq P_{l}(t) \leq P_{l}^{\text{in}} \\
\Delta P_{l}^{\text{out}} & \leq P_{l}(t+1) - P_{l}(t) \leq \Delta P_{l}^{\text{in}} \\
0.05 & \leq S_{\text{soc},l}(t) \leq 0.95 \\
\sum_{t=1}^{24} P_{l}(t) & = 0
\end{align*}
\]
(8)

Taking electric energy storage as an example, \(P_{d}^{\text{out}}, P_{d}^{\text{in}}, \Delta P_{d}^{\text{out}}, \Delta P_{d}^{\text{in}},\) and \(S_{\text{soc},d}(t)\) represent the maximum charging power, maximum charging power, maximum discharging ramp power, maximum charging ramp power and energy storage SOC at time \(t\), respectively. The lower limit and upper limit of energy storage SOC are 5% and 95%, respectively. \(P_{d}(t)\) is the energy storage power at time \(t\). The sum is taken as 0 within 24 h to realize the charging/discharging balance.

(3) Electrical refrigeration equipment constraint

The constraint of electrical refrigeration equipment includes power constraint and energy balance constraint, as seen in Equation (9):
\[
\begin{align*}
0 & \leq P_{d,zl}(t) \leq P_{d,zl}^{N} \\
P_{d,zl}(t) & = K_{\text{COP}} \cdot P_{d,zl}(t)
\end{align*}
\]
(9)

Where \(P_{d,zl}^{N}\) is the maximum power output of the electrical refrigerating machine set. \(K_{\text{COP}}\) is the electrical refrigeration performance coefficient, and a higher coefficient indicates better refrigeration performance. \(P_{d}(t)\) represents one part of electric energy emitted by the CCHP set at time \(t\).

(4) Gas-fired boiler constraint

The gas-fired boiler constraint includes power constraint and ramp constraint, as seen in Equation (10):
\[
\begin{align*}
0 & \leq P_{gl}(t) \leq P_{gl}^{N} \\
\Delta P_{gl}^{X} & \leq P_{gl}(t+1) - P_{gl}(t) \leq \Delta P_{gl}^{Z}
\end{align*}
\]
(10)

Where \(P_{gl}^{N}, \Delta P_{gl}^{X}, \Delta P_{gl}^{Z}\) represent the maximum power output of the gas-fired boiler, the lower limit and upper limit of the ramp power of CCHP set \(i\), respectively.

(5) System constraint

The system constraint includes the equation of cold and heat power equilibrium expressed by Equation (11):
\[
\begin{align*}
P_{\text{CHP},d}(t) + P_{r}(t) + P_{cd}(t) & = P_{r}(t) \\
P_{\text{CHP},l}(t) + P_{l}(t) + P_{cr}(t) & = P_{l}(t) \\
P_{\text{CHP},l}(t) + P_{dl}(t) + P_{dl}(t) & = P_{l}(t)
\end{align*}
\]
(11)
Where $P_{s,d}(t)$, $P_{s,r}(t)$ and $P_{s,l}(t)$ represent the power load, heating load and cooling load at time $t$, respectively.

4. Analysis of Calculated Example

4.1 Basic data  
The cold and heating loads in the park of a major project were analyzed, which were the typical loads in this park in summer. The load curves, which referred to the literature [13], are as shown in Figure 2:

![Fig. 2: Load curve of the park](image_url)

In this park, the unit prices (time-of-use electricity price) of cold energy and heat energy were taken as RMB 0.587/kWh and RMB 0.563/kWh, respectively. The concrete time division and the corresponding prices are presented in Table 1:

| Time frame       | 1     | 2       |
|------------------|-------|---------|
| Time frame       | 22:00-6:00 | 6:00-22:00 |
| Price            | 0.517 | 1.071   |

There were two CCHP sets in this park. The gas-heat conversion coefficient of the waste heat boiler was taken as 4, the conversion efficiency of the lithium bromide machine set as 0.8, and the purchasing price of natural gas for CCHP sets as RMB 4.03/m$^3$. The operating characteristics of CCHP sets are shown in the following figure, and their energy use costs are displayed in Figure 3 and Figure 4, which directly came from the literature [14] and were acquired through the experimental data of CCHP units under standard operating conditions.

![Figure 3: Thermoelectric Operating Curve of CCHP Set](image_url)
The parameters of the other machine sets in the park were described as follows: The coefficient of performance (COP) and the maximum power of electrical refrigeration equipment were set as 4.2 and 50 MW, respectively. The purchasing price of natural gas for a gas-fired boiler was RMB 3.03/m³. The correlation coefficient between the cost and power of the gas-fired boiler was taken as 6.4. As for electric energy storage, the capacity, maximum charging power and maximum discharging power were set as 35 MWh, 5 MW and 5 MW, respectively. In terms of heat energy storage, the capacity, maximum heat storage power and maximum heat release power were taken as 20 MWh, 5 MW and 5 MW, respectively. In the cold storage part, the capacity, maximum cold storage power and maximum cold energy release power were selected as 40 MWh, 10 MW and 10 MW, respectively. In addition, there was also a photovoltaic power station in this park, with a maximum power of 8 MW. The typical power output curve of this photovoltaic power station is displayed in Figure 5:

**Figure 4: Energy Cost of CCHP**

**Figure 5: Power Output Curve of Photovoltaic Power Station**

### 4.2 Simulation results

The simulation was performed by invoking yalmip optimization toolbox and using MATLABR2019a on a computer with the processor of intel (R) Core ™ i7-10170U CPU@ 1.10 GHz 1.61 GHz. The program was implemented through mixed-integer linear programming (MILP). The dispatch results are presented in Figure 6, Figure 7 and Figure 8.
Cooling system dispatch result

Time/h

Power/MW

Electrical refrigeration
Lithium bromide
Cold storage
Cooling load

Figure 6: Cold Energy Dispatch Result

Heating system dispatch result

Time/h

Power/MW

CCHP
Gas-fired boiler
Heat storage
Heating load

Figure 7: Heat Energy Dispatch Result
The above dispatch results could be analyzed from two angles: system and equipment.

### 4.3 System-side analysis

#### (1) Cooling system

The electrical refrigeration equipment, which was the main power source of the cooling system, balanced most of the cooling loads nearly in all time frames. The power it provided was 656.5549 MW, accounting for 78.48% of total power. The power provided by the lithium bromide machine set in the CCHP set was 107.8651 MW, accounting for 12.89% of total power. The power stored and released by the cold storage equipment was 72.1872 MW and 72.1871 MW, respectively, i.e., the power it absorbed as a load was 72.1872 MW, and the power it provided as a cold source was 72.1871 MW, accounting for 8.63% of the total load. The output power of electrical refrigeration equipment + output power of lithium bromide + output power of cold storage equipment = power absorbed by cold storage equipment + cooling load, which released the cooling power balance of the IES.

#### (2) Heating system

Unlike the function exerted in the cooling system, the CCHP set was the primary heat source of this system, and the power it provided was 174.4999 MW, accounting for 86.60% of total power. For the heat storage equipment, the power absorbed by it as a load was 27.0025 MW and the power released by it as a power source was 27.0026 MW, accounting for 13.40% of total power. The total power provided by the gas-fired boiler was 0 MW, and the heating load was 174.5 MW. The output power of CCHP + output power of heat storage equipment + output power of gas-fired boiler= power absorbed by heat storage equipment+ heating load, which achieved the heat power balance in the IES.

#### (3) Electric system

The electric power provided by the CCHP set was 96.7672 MW, accounting for 47.54% of total power, and that provided by the photovoltaic power station was 69.0988 MW (33.95%). Both discharging power and the charging power of electric energy storage were 27.6049 MW (13.56%). The power purchased by the IES from the power distribution network was 10.08 MW (4.95%), and that provided by it to the power distribution network was 6.2612 MW. The electric power output by
CCHP + electric power output by photovoltaic power station + output power of electric energy storage + power provided to power distribution network = power absorbed by electric energy storage + power load + power provided by the power distribution network, which contributed to the electric power balance in the IES. It was noteworthy that the electric power provided by the power distribution network to this park accounted for a small proportion of the total load; namely, the power loads in the park were supplied with power mainly by the machine sets in the park. In case of a serious fault of the power distribution network, the park could be directly disconnected from the power distribution network to realize the island operation.

4.4 Equipment-side analysis

(1) CCHP set

The CCHP sets were the sole equipment that could simultaneously provide cold, heat and electric energy in the park. It could be known from the dispatch results that the two CCHP sets supported nearly all the heating loads and nearly half of the power loads in the park, as well as a small number of cooling loads. The reason was that the thermoelectric coupling operation mode of the CCHP units substantially improved the energy supply efficiency, being able to supply electric energy and heat energy simultaneously by consuming the same amount of energy, which reduced the energy cost. The operating cost of electrical refrigerating units (maximum unit price: RMB 1.071) was much lower than the refrigeration cost (unit price: RMB 4.03) of CCHP sets, and the cold energy provided by the CCHP sets was restricted by the heat energy. To maximize the revenue, the electrical refrigeration equipment was required to provide as much cold energy as possible. In addition, the CCHP sets operated mainly from 7:00 to 22:00, during which the electricity price was higher, i.e., the revenue of the CCHP sets was higher.

(2) Energy storage equipment

It could be discovered by comparing the energy storage curves in the above three figures that the charging power was small in all three forms of energy storage, with the proportion occupied in the total load not exceeding 14%. The operating cost of energy storage in the park was high, and the storage capacity was not large, so the energy stored in the park mainly served as standby energy, which was put into use when the other equipment failed normal operation or the capacity reached the limiting value.

(3) Electrical refrigeration equipment

This equipment was one of the two cold sources in the park. Since its operating cost was lower than the lithium bromide machine set in CCHP, it undertook the cooling loads in the park within most of the time frames. It could be seen from the dispatch results that from 10:00 to 18:00, the electrical refrigeration equipment realized full-power operation due to the large cooling loads.

(4) Gas-fired boiler

The equipment was one of the heat supply equipment in the park. Given that the gas purchasing price (RMB 3.03) of this equipment was lower than that (RMB 4.03) of CCHP sets, it should have served as the main heat source in the park. However, it could be seen from the operating results that the output power of the gas-fired boiler was always 0 MW; that is to say, it did not participate in the practical heating system dispatching. This can be explained by the following two reasons: first, the capacity of CCHP sets was enough to support the heating loads in the park; second, although the operating cost of CCHP sets was high, it could simultaneously provide electric energy and heat energy and generate revenues in two systems, so its net revenue was much greater than that of the gas-fired boiler. The gas-fired boiler was not needed to participate in the dispatching, given that the CCHP units were capable of sufficiently supporting the heating loads in the park.

5. Conclusions

A multi-energy complementation-based IES optimal dispatching strategy was proposed in this study to realize the cooling, heating and power balance. The following conclusions were drawn by combining the concrete simulation results:
1) CCHP sets are the primary power supply and heat supply equipment in the system, with their energy supply efficiency and economic efficiency higher than other equipment.

2) The electrical refrigeration equipment, as the leading cold supply equipment in the system, can balance the cooling loads in most time frames.

3) Gas-fired boiler and energy storage equipment service serve as standby equipment in consideration of their lower net profit than the other equipment, and they will be put into use in case of energy shortage.

4) The multi-energy complementation operation mode substantially improves the energy utilization ratio and enhances the economic benefits.

Acknowledgments
This work was financially supported by the State Grid Corporation Science and Technology Project (5206002000D9).

References
[1] Li P, Wu D F, Li Y W, Yin Y X, Fang Q, Chen B. Multi-objective combined optimal configuration of a multi-microgrid integrated energy system based on negotiation game [J/OL]. Power System Technology: 1-10 [2020-07-22].
[2] Cui Y, Yan S, Zhong W Z, Wang Z, Zhang P, Zhao Y T. Optimal thermoelectric dispatching of a regionally integrated energy system containing power-to-gas device [J/OL]. Power System Technology: 1-12[2020-07-23].
[3] Wang Y C, Zeng C Y, Xun J J, Tan X Y, Yu M Z. Multi-agent interest balancing and optimal dispatching of an integrated energy system based on improved NSGA-II [J]. Electric Power Automation Equipment, 2020, 40
[4] Wang H Y, Li K, Zheng C H, Ma X. Distributed collaborative optimal operating strategy of a community-integrated energy system based on master-slave game [J/OL]. Proceedings of the CSEE: 1-11 [2020-23].
[5] Cui Y, Yan S, Wang Z, Wang M C, Zhao Y T. Day-ahead iterative clearing strategy of integrated energy system considering three-agent bidding [J/OL]. Power System Technology: 1-11[2020-07-23].
[6] Zheng C M, Huang B N, Wang Z X et al. Multi-objective optimization dispatch for integrated electro-heating systems including network transmission losses [J]. Power System Technology, 2020, 44 (1).
[7] Zhao J, Yong J, Xun J J et al. Stochastic programming of park integrated energy system based on long time scale [J]. Electric Power Automation Equipment, 2020 (3): 10.
[8] Yang X B, Tan Z F, Lin H Y, Degeryzhv, Zhou F A. Stochastic optimization of park integrated energy system and revenue distribution model considering cooperation alliance [J/OL]. Automation of Electric Power Systems: 1-18 [2020-07-23].
[9] Liu W X, Li Z Z, Yang Y et al. Collaborative optimal configuration for integrated energy system considering uncertainties of demand response [J]. Automation of Electric Power Systems, 2020, 44 (10): 41-49.
[10] Zhang X H, Liu X Y, Zhong J Q. Integrated energy system planning considering a reward and punishment ladder-type carbon trading and electric-thermal transfer load uncertainty [J/OL]. Proceedings of the CSEE: 1-13 [2020-07-23].
[11] Li R, Sun F, Liu H L, Ding X, Han Y, Yan J R. Mixed time-scale economic dispatch of user-level integrated energy system considering characteristic energy difference [J/OL]. Power System Technology: 1-10 [2020-07-23].
[12] Gu H F, Yu J, Li Y et al. Double-layer combined optimal economic dispatch of new towns containing multifunctional parks under environmental constraint [J]. Proceedings of the CSEE, 2020 (8): 2441-2452.
[13] Zhang J H, Huang W. Microgrid operational control and protection technology [M]. China Electric Power Press, 2010.
[14] Hao R, Ai Q, Jiang Z Q. Bi-level game strategy for multi-agent with incomplete information in regionally integrated energy system [J]. Automation of Electric Power Systems, 2018, 42 (004): 194-201.