Research and implementation of optimal operation method of island integrated energy system

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***Abstract*—In order to improve the economy of island integrated energy system, an optimization model of electric-gas-thermal coupling integrated island energy system operation considering the demand response of building is proposed. The building thermal inertia model including HVAC load and integrated energy system model including gas turbine, diesel generator, wind turbine, electric boiler and gas storage tank are modeled. Considering the coupling property of time-sharing electricity price, gas price and multi energy, the demand side management is carried out through building thermal inertia, and the minimum operating cost of the system is taken as the goal. The yalmip toolbox and cplex solver are used to solve the model and obtain the power of each equipment and load in the scheduling period. The results show that the demand response of the buildings can play a role of peak load reduction and valley filling on the premise of ensuring the user's requirements for indoor temperature comfort, stabilize the fluctuation of wind power, and make the supply and demand more balanced. Through the coordinated interaction of the source, net and load, as well as the multiple energy sources on the supply side support and reserve each other, the efficiency of energy interactive utilization gets improved, and the system operation cost is reduced as well.**

Key words-integrated energy system; demand response; building thermal inertia; optimal operation; electric-gas-thermal coupling

I. INTRODUCTION

In order to further study the optimal operation method of island integrated energy system considering demand response, this paper establishes a building thermal inertia model including HVAC load, using the differential equations in the model for difference treatment. Then the supply side of electric-thermal-gas coupling is optimized to reduce the operating cost of the system.

II. OBJECTIVE FUNCTION

The integrated operating cost of the system includes the cost of purchasing electricity from the power grid, the cost of purchasing coal from the outside world, the cost of natural gas the cost of operation and maintenance.The objective function is:

$$Min.\left\{\sum_{i=1}^{N_i}\left(C_{\mathrm{d}}+C_{g,sum}+C_{gas,sum}+C_{e,sum}\right)+\kappa\sum_{t=1}^{t_{\max}}\left(\left|\overline{\varepsilon}_t\right|+\left|\underline{\varepsilon}_t\right|\right)\right\} \tag{1}$$

In the above function, κ is the penalty parameter.The penalty function terms can be set to κ times the difference between the actual indoor temperature and the set limit temperature at the t time. The relaxation variable in parentheses is that the heating area can violate the user's ability to set the upper and lower limits of comfort. N_t is the number of optimization periods the other day. C_d is the cost of purchasing electricity from the external power grid.

The cost of purchasing coal is calculated through the following calculation:

$$C_{g,sum}=\lambda_t^{\mathrm{g}}*(\phi_{CHP,\ \mathrm{sum}}+P_{CHP,\mathrm{sum}}) \tag{2}$$

In the above function, λ_t^g is the product of the equivalent coal consumption rate after conversion and the unit price of coal.

The cost of natural gas extraction is calculated by the following calculation:

$$C_{gas,sum}=\lambda_{gas}^{GT}\eta_{gas}^{P}P_{GT,t} \tag{3}$$

In the above function, λ_{gas}^{GT} is the converted gas price; η_{gas}^{P} is the micro gas turbine coefficient; $P_{GT,t}$ is the power of micro gas turbine.

The operation and maintenance cost is calculated by the following formula:

$$\begin{aligned}C_{e,sum}=&\sum_{m=1}^{N_{GT}}C_{GT,m}+\sum_{e=1}^{N_{CHP}}C_{CHP,e}+\sum_{b=1}^{N_{\mathrm{r}}}C_{\mathrm{br}}+\sum_{c=1}^{N_{\mathrm{h}}}C_{\mathrm{h,c}}\\&+\sum_{\mathrm{i}=1}^{N_G}C_{G,\mathrm{i}}+\sum_{\mathrm{d}=1}^{G_{\mathrm{w}}}C_{\mathrm{d}G_{\mathrm{w}}}+\sum_{\mathrm{f}=1}^{N_{\mathrm{w}}}C_{\mathrm{w,f}}\end{aligned} \tag{4}$$

In the above function,each is gas turbine, coal-fired cogeneration (CHP) unit, electric boiler, air conditioning, diesel generator, wind turbine and gas storage tank operation and maintenance costs.

The equipment operation and maintenance cost C_{gen} is obtained by multiplying the unit operation and maintenance cost $C_{gen,unit}$ by the equivalent operating power $P_{gen,t}$ of the equipment:

$$C_{gen} = C_{gen,unit} * P_{gen,t} \tag{5}$$

III. CONSTRAINT CONDITION

HVAC (Heating,Ventilation and Air Conditioning) load belongs to the controllable electric to thermal load on the demand side. Its energy demand has great flexibility potential and is one of the main loads of building system. A network model of thermal resistance heat capacity (Resistance-Capacitance,RC) shown in Fig. 1 can be used to describe a single heating area in a typical building to reflect the nature of heat transfer and saving.The mathematical model is:

$$C_{i,j}^{W} \frac{dT_{i,j}^{W}}{dt} = \sum_{j \in N_{i,j}^{W}} \frac{T_j - T_{i,j}^{W}}{R_{i,j}^{W}} + r_{i,j}\alpha_{i,j}A_{i,j}^{W}Q_{i,j}^{rad} \tag{6}$$

$$\begin{aligned} C_i^r \frac{dT_i^r}{dt} &= \sum_{j \in N_i^r} \frac{T_{i,j}^W - T_i^r}{R_{i,j}^W} + \pi_{i,j} \sum_{j \in N_i^r} \frac{T_j - T_i^r}{R_{i,j}^{win}} + \dot{Q}_i^{int} \\ &+ \dot{m}_i^r C_p (T_i^s - T_i^r) + \pi_{i,j}\tau_{i,j}^W A_{i,j}^{win} Q_i^{rad} \end{aligned} \tag{7}$$

Equation (6) is the wall equality constraint between node i and node j, and (7) is the room equality constraint.

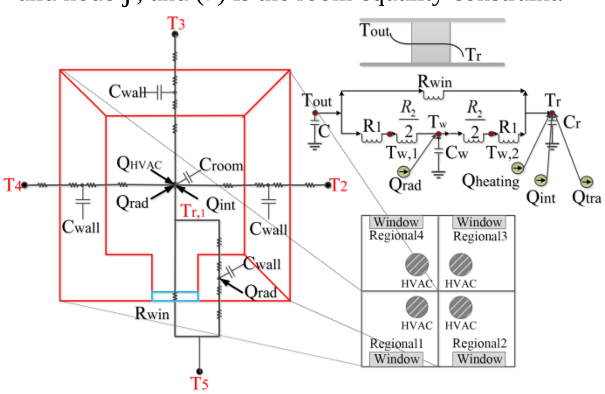

FIGURE 1. TYPICAL BUILDING RC NETWORK MODEL

Taking a heating area as an example, (6) and (7) are written as (8) and (9) respectively.

$$\begin{cases} C_{1,2}^{w} \dfrac{dT_{1,2}^{w}}{dt} = \dfrac{T_1^r - T_{1,2}^W}{R_{1,2}^W} + \dfrac{T_2 - T_{1,2}^W}{R_{1,2}^W} + r_{1,2}\alpha_{1,2}A_{1,2}^{W}Q_{1,2}^{rad} \\ C_{1,3}^{w} \dfrac{dT_{1,3}^{w}}{dt} = \dfrac{T_1^r - T_{1,3}^W}{R_{1,3}^W} + \dfrac{T_3 - T_{1,3}^W}{R_{1,3}^W} + r_{1,3}\alpha_{1,3}A_{1,3}^{W}Q_{1,3}^{rad} \\ C_{1,4}^{w} \dfrac{dT_{1,4}^{w}}{dt} = \dfrac{T_1^r - T_{1,4}^W}{R_{1,4}^W} + \dfrac{T_4 - T_{1,4}^W}{R_{1,4}^W} + r_{1,4}\alpha_{1,4}A_{1,4}^{W}Q_{1,4}^{rad} \\ C_{1,5}^{w} \dfrac{dT_{1,5}^{w}}{dt} = \dfrac{T_1^r - T_{1,5}^W}{R_{1,5}^W} + \dfrac{T_5 - T_{1,5}^W}{R_{1,5}^W} + r_{1,5}\alpha_{1,5}A_{1,5}^{W}Q_{1,5}^{rad} \end{cases} \tag{8}$$

$$\begin{aligned} C_1^r \frac{dT_1^r}{dt} &= \sum_{j=1}^{4} \frac{T_{1,j}^W - T_1^r}{R_{1,j}^W} + \frac{T_5 - T_1^r}{R_{1,5}^{win}} \\ &+ mC_p(T_1^s - T_1^r) + Q_1^{int} + \tau^W A_{1,5}^{win} Q_1^{rad} \end{aligned} \tag{9}$$

Considering the slow dynamic process of building heat dissipation and temperature change, the differential equation can be treated by difference:

$$\begin{cases} C_{1,2}^w R_{1,2}^w T_{1,2}^w(t+1) - \left(C_{1,2}^w R_{1,2}^w - 2\right) * T_{1,2}^w(t) \\ = \Delta t * \left(T_1^r(t) + T_2(t) + r_{1,2}\alpha_{1,2}A_{1,3}^w Q_{1,2}^{rad} * R_{1,2}^w\right) \end{cases} \tag{10}$$

$$\begin{cases} C_{1,3}^w R_{1,3}^w T_{1,3}^w(t+1) - \left(C_{1,3}^w R_{1,3}^w - 2\right) * T_{1,3}^w(t) \\ = \Delta t * \left(T_1^r(t) + T_3(t) + r_{1,3}\alpha_{1,3}A_{1,3}^w Q_{1,3}^{rad} * R_{1,3}^w\right) \end{cases} \tag{11}$$

$$\begin{cases} C_{1,4}^w R_{1,4}^w T_{1,4}^w(t+1) - \left(C_{1,4}^w R_{1,4}^w - 2\right) * T_{1,4}^w(t) \\ = \Delta t * \left(T_1^r(t) + T_4(t) + r_{1,4}\alpha_{1,4}A_{1,4}^w Q_{1,4}^{rad} * R_{1,4}^w\right) \end{cases} \tag{12}$$

$$\begin{cases} C_{1,5}^w R_{1,5}^w T_{1,5}^w(t+1) - \left(C_{1,5}^w R_{1,5}^w - 2\right) * T_{1,5}^w(t) \\ = \Delta t * \left(T_1^r(t) + T_5(t) + r_{1,5}\alpha_{1,5}A_{1,5}^w Q_{1,5}^{rad} * R_{1,5}^w\right) \end{cases} \tag{13}$$

$$\begin{aligned} C_1^r * \left(T_1^r(t+1) - T_1^r(t)\right) &= \Delta t * \Bigg(\sum_{j=1}^{4} \frac{T_{1,j}^w(t) - T_1^r(t)}{R_{1,j}^w} \\ &+ \frac{T_5(t) - T_1^r(t)}{R_{1,5}^{win}} + Q_{R,K} + Q_1^{int} + \tau^w A_{1,5}^{win} Q_1^{rad} \Bigg) \end{aligned} \tag{14}$$

The twenty-fourth hour of the first day and the first hour of the second day should also be satisfied, that is:

$$\begin{cases} C_{1,2}^w R_{1,2}^w T_{1,2}^w(`1') - \left(C_{1,2}^w R_{1,2}^w - 2\right) * T_{1,2}^w(`24') \\ = \Delta t * \left(T_1^r(`24') + T_2(`24') + r_{1,2}\alpha_{1,2}A_{1,2}^w Q_{1,2}^{rad} * R_{1,2}^w\right) \end{cases} \tag{15}$$

$$\begin{cases} C_{1,3}^w R_{1,3}^w T_{1,3}^w(`1') - \left(C_{1,3}^w R_{1,3}^w - 2\right) * T_{1,3}^w(`24') \\ = \Delta t * \left(T_1^r(`24') + T_3(`24') + r_{1,3}\alpha_{1,3}A_{1,3}^w Q_{1,3}^{rad} * R_{1,3}^w\right) \end{cases} \tag{16}$$

$$\begin{cases} C_{1,4}^w R_{1,4}^w T_{1,4}^w(`1') - \left(C_{1,4}^w R_{1,4}^w - 2\right) * T_{1,4}^w(`24') \\ = \Delta t * \left(T_1^r(`24') + T_4(`24') + r_{1,4}\alpha_{1,4}A_{1,4}^w Q_{1,4}^{rad} * R_{1,4}^w\right) \end{cases} \tag{17}$$

$$\begin{cases} C_{1,5}^w R_{1,5}^w T_{1,5}^w(`1') - \left(C_{1,5}^w R_{1,5}^w - 2\right) * T_{1,5}^w(`24') \\ = \Delta t * \left(T_1^r(`24') + T_5(`24') + r_{1,5}\alpha_{1,5}A_{1,5}^w Q_{1,5}^{rad} * R_{1,5}^w\right) \end{cases} \tag{18}$$

$$\begin{aligned} C_1^r * \left(T_1^r(`1') - T_1^r(`24')\right) &= \Delta t * \Bigg(\sum_{j=1}^{4} \frac{T_{1,j}^w(`24') - T_1^r(`24')}{R_{1,j}^w} \\ &+ \frac{T_5(`24') - T_1^r(`24')}{R_{1,5}^{win}} + Q_{R,K} + Q_1^{int} + \tau^w A_5^{win} Q_1^{rad} \Bigg) \end{aligned} \tag{19}$$

IV. THE EXAMPLE ANALYSIS

A. *The initial data*

As shown in Fig. 2, the network diagram of the system is shown. In this paper, the power system of IEEE30 node is coupled with the natural gas distribution system of 20 nodes and the regional thermal system of 6 nodes.

B. *Optimization results*

The buildings set in this paper are connected to random nodes. In Fig. 2, node 1 of the power system is connected to 70 buildings, and node 7 is connected to 30 buildings. The comfortable temperature range set by users is 19 ℃ ~ 23 ℃.Each building has 20 same heating areas, all of which have HVAC system to maintain the same comfort requirements of users.The average output of diesel generator and gas turbine is shown in Fig. 3.

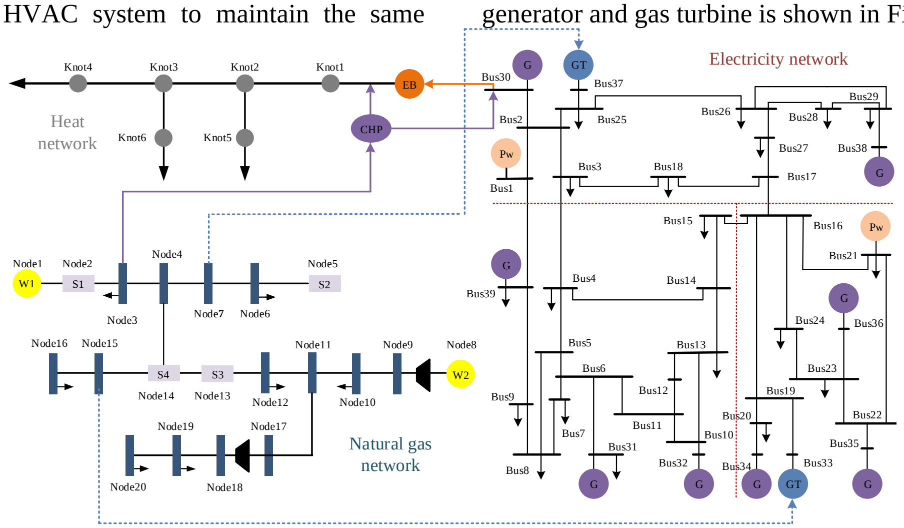

FIGURE 2. SCHEMATIC DIAGRAM OF ISLAND INTEGRATED ENERGY SYSTEM NETWORK

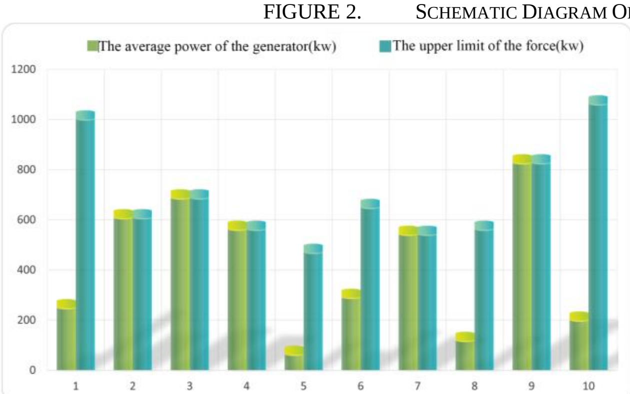

FIGURE 3. AVERAGE OUTPUT OF DIESEL GENERATOR AND GAS TURBINE

There is no coal-fired boiler in the system. Electric boiler and HVAC are used to meet the thermal demand of users. Fig. 3 has been shown, in which the gas turbine number 4 is always full, which effectively uses the natural gas resources on the island.

As shown in Fig. 4, the HVAC load effectively realizes the demand response of electricity pricing type responsible. By changing the supply air temperature, the indoor temperature is also ensured to be within the user's comfort range. Using the thermal inertia of the building, by adjusting the supply air temperature of the HVAC system, under the condition of meeting the indoor temperature comfort range set by the user, the coordinated interaction between the source and load is realized, and the cutting peak and filling valley. In the future, the influence of energy interaction on other energy source networks will be explored.

In order to compare the peak and valley difference of the power grid before and after adding the demand response, the data before and after optimization of the power of the total load of the integrated energy system are placed in the same histogram, as shown in Fig. 5.Compared with the system electric load before and after the optimization of the demand response of the building cluster in Fig. 6, it can be seen that the demand response of the load realizes the peak cutting and filling of the power grid. The maximum load in peak period is reduced from 6383 kW to 6292 kW, the minimum load in valley period is increased from 3296 kW to 3374 kW, and the peak-valley difference is reduced from 3087 to 2918 kW. The peak-valley difference of power grid is reduced from 3087 to 2918 The optimized system electric load curve is flatter than before.

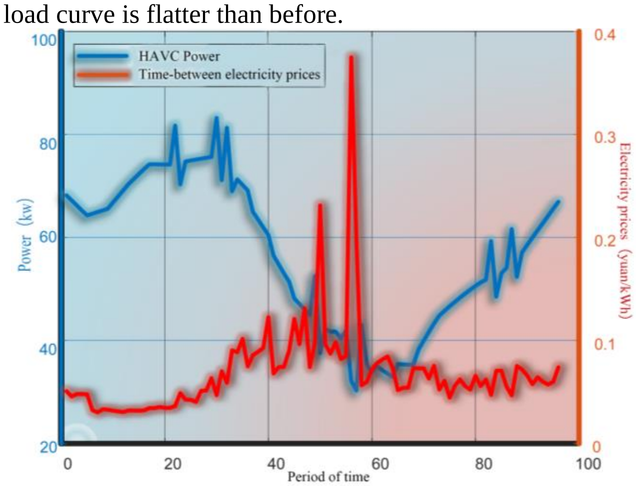

FIGURE 4. OPTIMIZED POWER OF HVAC LOAD AND TIME-SHARING ELECTRICITY PRICE CURVE

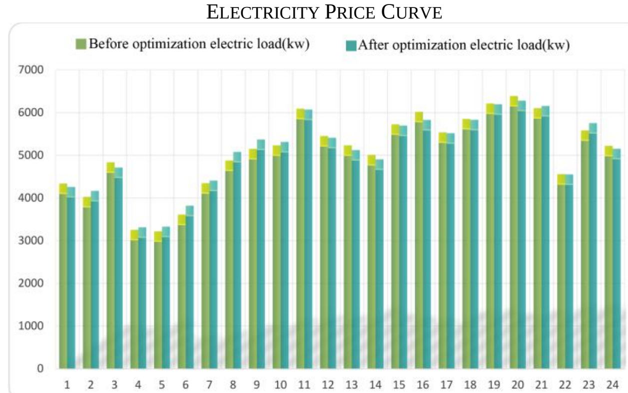

FIGURE 5. SYSTEM ELECTRICAL LOADS BEFORE AND AFTER CONSIDERING DEMAND RESPONSE

In an electricity-gas-thermal coupling island integrated energy system, each energy network is interrelated and energy interacts, and the demand response of HVAC load has a significant impact on the operation state of the thermal network. Fig. 6 shows the thermal power of a typical diurnal thermoelectric unit. It can be seen that the heat storage devices configured by CHP unit, electric boiler and heat recovery system alternately produce power and serve as backups for each other. For example, the electric load of the system is very low in valley period, and the electricity purchase price of the external grid is low, but there is still a fixed heat load in the system to be met. In this case, the thermal power emitted by the CHP unit is not enough to meet the fixed heat load of the system, and the electric boiler and heat storage device will provide the power. During the peak period, the electrical load of the system becomes higher, and the CHP unit has a large output and high thermal power. The electric boiler for heating no longer consumes electric energy to heat, and the excess heat is stored through the heat storage device. This characteristic significantly improves the flexibility and economy of the system operation.

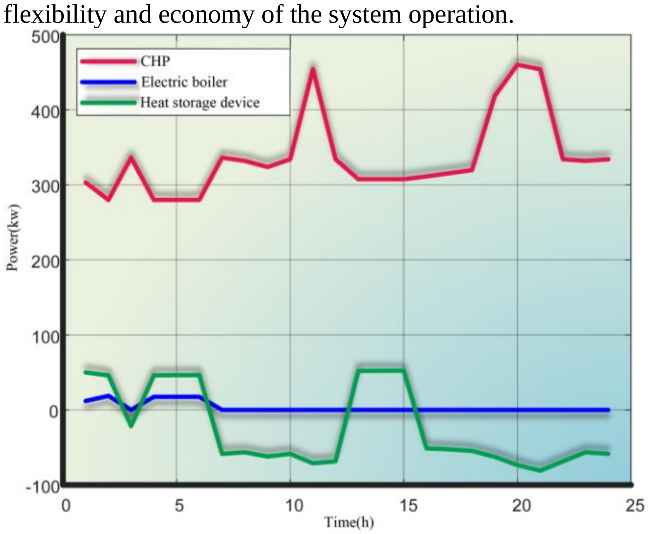

FIGURE 6. THERMAL POWER CURVE OF UNIT

It can also be seen from Fig. 5 and Fig.6 that, on the premise of satisfying different constraints of each system, the operating states of power grids and heat grids change with the optimization of demand response of building clusters, which indicates that in the operation of an integrated energy system, the operating states of one energy network will affect the operating states of another network, and there are coupling characteristics between different energy networks.

Demand response of load and complementary utilization of energy can effectively reduce the operating cost of the system.The power purchase price in valley period of time(0:00-7:00) is low, lower than natural gas power generation costs, random normal distribution of uncontrolled electrical load is less, the power through the supply air temperature to improve the HVAC system, reduces the power of CHP unit, through the heat storage device to a certain thermal power meet the heat load of system is fixed, even at 2, 4, 5, and 6 CHP is not a power unit. During the peak period of time(10:00-15:00), the electricity purchase price is high and the uncontrollable electrical load with random normal distribution is large. At this time, the power of HVAC system is reduced through the air supply temperature and the power of CHP unit is increased. Generally speaking, the heat storage device stores thermal power during this period. In the typical day selected in this paper, the total cost of system operation is 9732.72 yuan before optimization, and 9544.37 yuan after optimization.

V. CONCLUSION

Under the constraints of source, net and load, this paper optimizes and adjusts the transfer of HVAC load and the complementary utilization of energy, the optimization model of island integrated energy system which aims at minimum operating cost in the system scheduling cycle is transformed into a standard mixed integer linear programming model. This model considers the electric-thermal-gas coupling system on the supply side and individual constraint, and analyzes the constraints of demand side HVAC load participation in scheduling. It can realize the operation optimization of electric-thermal-gas multi-energy coupling system with supply side and demand side as a whole.Demand side scheduling makes the supply and demand more balanced, increases the elasticity of demand side, and initially realizes the joint optimization of production capacity base and user interests.Building HVAC system in this paper not only has a good energy saving effect on the premise of ensuring the user's requirement of indoor temperature comfort, but also plays the role of cutting peak and filling valley to the power grid and reducing the peak and valley difference of the system.Complementary use of multiple sources of energy is achieved through coordinated interaction of sources, networks and charges.Under the condition of satisfying individual constraints and the balance of supply and demand of each part, the mutual support and reserve of various energy sources on the supply side are of great significance to ensure the safe and reliable operation of the island integrated energy system.It also optimizes the spare capacity of the unit, improves the efficiency of energy interaction and reduces the operating cost of the system.

REFERENCES

[1] Wang Yongzhen, Zhang Ning, Guan Yonggang, Zhao Wei, Gao Feng and Kang Chongqing. Inheriting and Expansion of Current Research Topics on Energy Internet and Smart Grid [J]. Automation of Electric Power Systems, 2020,44 (04): 1-8.

[2] Chen Houhe, Zhang Ting, Zhang Hannan, Zhang Rufeng, Wang Pengyu and Li Ling. Robust Intersection Optimal Scheduling of Electro-thermal Integrated Energy System Considering Transmission Delay of Heat Network [J]. Guangdong Electric Power, 2019,32 (10): 2-11.

[3] Chen Houhe, Li Wenming, Zhang Rufeng and Qian Yeniu. A Dayahead Optimal Scheduling Model for Integrated Energy System of Industrial Park Considering Energy Storage Characteristics of Building Cooling Area [J]. Electric Power Construction, 2019,40 (08): 43-50.

[4] Li Z, Wu W and Wang J, et al. Transmission-Constrained Unit Commitment Considering Combined Electricity and District Heating Networks[J]. IEEE Transactions on Sustainable Energy, 2016, 7(2): 480-492.

[5] Li Yonggang, Wang Yue and Liu Fengrui, et al. Combined Model of Short-term Wind Speed Prediction Based on Stacking Fusion [J]. Power System Technology, 2020, 44(08): 2875-2882.