Distributed Optimal Scheduling of Multi-region Integrated Energy Systems Considering Regional Heating Network

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***Abstract*—This paper focuses on the joint optimization scheduling of multi-region integrated energy systems (IES) and the influence of regional heating networks on joint scheduling. The IES model is firstly established, including the heating network model and the internal equipment model. Then, in order to ensure the independence of each IES, a bi-level model of multi-region IESs joint scheduling considering regional heating network is established, which is solved by distributed algorithm - analysis target cascading method (ATC). Finally, the simulation results show that the proposed model can effectively optimize the energy scheduling between IESs while ensuring the independence of each IES. The regional heating network can be used as heat storage equipment to participate in the joint scheduling, and absorbs the excess heat energy in IES that cannot be transferred to other IESs.**

***Index Terms*-- integrated energy system; heating network; distributed optimal scheduling; distributed algorithm**

I. INTRODUCTION

At present, there are many researches on the optimal scheduling of single IES [1-6]. In the network modeling, the dynamic characteristics of the electricity/heat/gas network are mainly considered. In the demand response, the thermal energy storage characteristics of the house, the excitation control of interruptible load, and the direct load control are well applied. In the optimization scheduling, the operation cost, the ability to absorb renewable energy and the robust characteristics of the system are usually considered. For multi-region IESs joint scheduling, in [7], the energy hub is used to establish an electricity-gas integrated power system. The distributed algorithm ADMM is used to solve the problem, but the influence of the delay characteristic of heating network between the IES and the users is not considered. In [8], a mixed integer linear programming model of multi-region IESs with heating network is established, but it does not consider the independent autonomy of each IES, and the model is complex.

In summary, for the optimal scheduling of multi-region IESs, many studies focus on the distributed algorithm and the decoupling of energy between regions, but seldom study the influence of regional heating network on joint scheduling. Considering the heating network in IES and ensuring the independence of each IES, this paper establishes a bi-level model of multi-region IESs joint optimization scheduling, which is solved by the ATC algorithm. The upper layer is the energy coordination center (ECC), and the lower layer is the multi-region IESs. Through the simulation results of the case, the influence of heating network on joint scheduling is analyzed. The results show that the model proposed is correct and effective, and the optimization results of the proposed model are consistent with those of the centralized model. By analyzing the influence of heating network on scheduling, the heating network provides a way for multi-region IESs to absorb excess energy, and can reduce the influence of large fluctuation of heat load on IES.

II. MODELING OF IES

Internal equipment in IES includes gas turbine (GT), gas boiler (GB), waste-heat boiler (WH) and heat exchanger (HX). The heating network connects users and IES. Fig.1 shows the typical structure of IES.

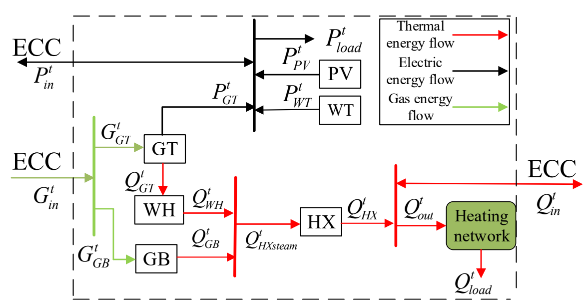

Figure 1. Typical structure of IES.

GT and GB are the main energy supply devices in IES. WH and HX are used as energy conversion devices to recover and transfer energy. Photovoltaic (PV) and wind turbine (WT) provide renewable energy for IES.

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A. Heating Network Model

In this paper, hot water is used as the medium to transfer heat energy [9], and the quality regulation is adopted, that is, the working fluid flow rate in pipeline is fixed value, and the heat energy transmitted to the user is changed by adjusting the temperature [2]. To simplify the model, only the heating network structure between IES and users is considered.

The heating network has been proposed and modeled in many studies. Detailed model of heating network refers to [2]. Here this paper focuses on the delay characteristic of heating network. According to the Sukhov's cooling formula [8], the relationship between the temperature at the beginning and end of the pipeline is:

$$T_{P,end}^{t+\tau_P^t} = \left(T_{P,start}^t - T_{env}^t\right)\theta + T_{env}^t \tag{1}$$

where T_{env}^t is the ambient temperature around the pipeline P; $T_{P,start}^t$ is the temperature at the beginning of the pipeline P; $T_{P,end}^{t+\tau_P^t}$ is the temperature at the end of the pipeline P; τ_P^t is the delay time of the pipeline P; θ is the correlation coefficient of the pipeline P. Due to quality regulation, θ is a fixed value.

(1) shows that the change of the temperature at the beginning of the pipeline needs to be reflected to the end after a certain time delay. Because of the certain delay in the transmission of thermal energy in the pipeline, the heat output of IES cannot be balanced with the heat demand of the users at all times. This kind of imbalance will have an influence on the scheduling of the IES itself, and will also affect the scheduling between IESs. Therefore, this paper focuses on the effects of delay characteristic in the heating network structure on multi-region IESs electro-thermal joint scheduling.

B. Internal Equipment Model

GT burns natural gas to produce electricity and flue gas. It is the main energy supply equipment in the IES.

$$P_{GT}^t = \eta_{GT}^t G_{GT}^t \tag{2}$$

$$Q_{GT}^t = (1-\eta_{GT}^t)\left(1-\sigma_{GT}\right)G_{GT}^t \tag{3}$$

where P_{GT}^t and Q_{GT}^t are the electricity and heat output of GT at time t respectively, kW; G_{GT}^t is the gas consumed by GT at time t, kW; η_{GT}^t is the efficiency of GT; σ_{GT} is the energy loss constant, which is 0.3.

The gas consumption of GB is related to the heat energy and boiler efficiency.

$$Q_{GB}^t = \eta_{GB}^t G_{GB}^t \tag{4}$$

where Q_{GB}^t is the heat output of GB at time t, kW; G_{GB}^t is the gas consumed by GB, kW; η_{GB}^t is conversion efficiency.

The WH absorbs the flue gas generated by the GT and generates high-temperature steam

$$Q_{WH}^t = \eta_{WH}^t Q_{GT}^t \tag{5}$$

where Q_{WH}^t is the heat output of WH at time t, kW; η_{WH}^t is conversion efficiency.

The HX heats the return water through heat exchange.

$$Q_{HX}^t = \eta_{HX}^t Q_{HXsteam}^t \tag{6}$$

where $Q_{HXsteam}^t$ and Q_{HX}^t are the heat input and output of HX respectively, kW; η_{HX}^t is conversion efficiency.

III. OPTIMIZATION SCHEDULING MODEL OF MULTI-REGION IESS

IES purchases electricity from the distribution network and gas from the gas company for generating the energy required by users. The excess energy of one IES can be transferred to other IESs, and gain benefits. For multi-region IESs joint scheduling, the centralized optimization scheduling model has the problems of inconsistent interest demand, easy information exposure and excessive decision variables in the case of multi-agents, which cannot guarantee the independence of each IES. Therefore, this paper abstracts the joint scheduling of multi-region IESs into a bi-level optimization model with the ECC as the upper layer and each IES as the lower layer, which is solved by ATC algorithm. The joint scheduling framework is shown in Fig.2.

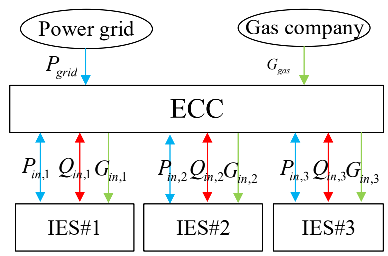

Figure 2. Joint scheduling framework of Multi-region IESs.

According to the dispatch results reported by each IES, the ECC uniformly purchases electric energy and gas energy from the distribution network and the gas company, and then distributes the energy to the corresponding IES. When an IES has excess energy, the information is reported to the ECC. The ECC purchases excess energy at the market transaction price and sells it to other IESs that cannot supply enough energy for users at the same price. Due to distributed model, each IES independently solves its own optimal scheduling model relative to the centralized model. The energy interaction between IESs is completed by the energy coordination of ECC. ECC ensures the independence of each IES.

A. Optimization Model of IES$_i$

For IES$_i$, the objective function is to minimize its own operation cost, including energy purchase cost and operation and maintenance costs of internal equipment.

$$\begin{aligned}\min\ f_i = &\sum_{t=1}^{T}\left(K_E^t P_{in,i}^t + K_G^t G_{in,i}^t + K_Q^t Q_{in,i}^t\right) + \\ &\sum_{t=1}^{T} k_{GT} P_{GT,i}^t + \sum_{t=1}^{T} k_{GB} Q_{GB,i}^t + \sum_{t=1}^{T} k_{WH} Q_{WH,i}^t + \sum_{t=1}^{T} k_{HX} Q_{HX,i}^t\end{aligned} \tag{7}$$

where $P_{in,i}^t$ and $Q_{in,i}^t$ are the electricity and heat interacting with the ECC respectively, kW; $P_{in,i}^t > 0$ means IES$_i$ get electricity from ECC. $P_{in,i}^t < 0$ means IES$_i$ transmits electricity to ECC; $Q_{in,i}^t$ is the same as $P_{in,i}^t$; $G_{in,i}^t$ is the gas obtained by IES$_i$ from ECC, kW; K_E^t , K_G^t and K_Q^t are the price of electricity/gas/heat; k_{GT} , k_{GB} , k_{WH} and k_{HX} are the operation and maintenance cost coefficient of each equipment, they are all 0.05$ in this paper; T is the scheduling cycle, 24h.

(8)-(14) are the constraints of IES$_i$, in which (8)-(11) represents the internal energy balance. (12) represents the climbing rate constraint of internal equipment; (13) represents the upper and lower limits of the operating power of internal equipment; (14) represents the energy constraint of electricity /heat/gas interacting with the ECC respectively. (15) is the heat constraint of pipeline in heating network considering transmission delay. Other general constraints of heating network refer to [2];

$$P_{in,i}^t + P_{PV,i}^t + P_{WT,i}^t + P_{GT,i}^t = P_{load,i}^t \tag{8}$$

$$G_{in,i}^t = G_{GT,i}^t + G_{GB,i}^t \tag{9}$$

$$Q_{WH,i}^t + Q_{GB,i}^t = Q_{HXsteam,i}^t \tag{10}$$

$$Q_{HX,i}^t + Q_{in,i}^t = Q_{out,i}^t \tag{11}$$

$$\begin{cases} \Delta P_{Y,\min} \le P_{Y,i}^t - P_{Y,i}^{t-1} \le \Delta P_{Y,\max} \\ \Delta Q_{Y,\min} \le Q_{Y,i}^t - Q_{Y,i}^{t-1} \le \Delta Q_{Y,\max} \end{cases} \tag{12}$$

$$\begin{cases} P_{Y,i,\min} < P_{Y,i}^t < P_{Y,i,\max} \\ Q_{Y,i,\min} < Q_{Y,i}^t < Q_{Y,i,\max} \end{cases} \tag{13}$$

$$\begin{cases} P_{in,i}^{\min} \le P_{in,i}^t \le P_{in,i}^{\max} \\ Q_{in,i}^{\min} \le Q_{in,i}^t \le Q_{in,i}^{\max} \\ G_{in,i}^{\min} \le G_{in,i}^t \le G_{in,i}^{\max} \end{cases} \tag{14}$$

$$Q_{P,end}^{t+\tau_P^t} = Q_{P,start}^t - c(T_{P,start}^t - T_{P,end}^{t+\tau_P^t}) F_{P,s}^t \big/ \psi \tag{15}$$

where $P_{PV,i}^t$ and $P_{WT,i}^t$ are the electricity output of PV and WT; $\Delta P_{Y,\min}$, $\Delta P_{Y,\max}$, $\Delta Q_{Y,\min}$ and $\Delta Q_{Y,\max}$ are upper and lower limits of equipment operation power climbing rate; $P_{Y,i,\min}$, $P_{Y,i,\max}$, $Q_{Y,i,\min}$ and $Q_{Y,i,\max}$ are the upper and lower limits of equipment operating power, respectively; Index Y refers to the name of equipment; $Q_{P,end}^{t+\tau_P^t}$ is heat output of pipeline P at time $t+\tau_P^t$; $Q_{P,start}^t$ is heat input of pipeline P at time t; c is the specific heat capacity of water; $F_{P,s}^t$ is the flow of pipelie P; ψ is the conversion coefficient.

B. Optimization Model of ECC

The objective function of ECC is to minimize the cost of energy purchase, which consists of two parts: the cost of purchasing electricity from the distribution network and the cost of purchasing gas from the gas company.

$$\min \quad F = \sum_{t=1}^{T} k_E^t P_{grid}^t + \sum_{t=1}^{T} k_G^t G_{gas}^t \tag{16}$$

where P_{grid}^t is the electricity purchased from the distribution network, kW; G_{gas}^t is the gas purchased from the gas company, kW.

The constraints of ECC are (16)-(18).

$$P_{grid}^{\min} \le P_{grid}^t \le P_{grid}^{\max} \tag{17}$$

$$G_{gas}^{\min} \le G_{gas}^t \le G_{gas}^{\max} \tag{18}$$

$$\left\{ G_{gas}^t = \sum_{i=1}^{N_{IES}} G_{in,i}^t ,\ P_{grid}^t = \sum_{i=1}^{N_{IES}} P_{in,i}^t ,\ \sum_{i=1}^{N_{IES}} Q_{in,i}^t = 0 \right\} \tag{19}$$

where $P_{grid}^{\min}$, $P_{grid}^{\max}$, $G_{gas}^{\min}$ and $G_{gas}^{\max}$ are the upper and lower limits of energy purchased by ECC from the distribution network and gas company; N_{IES} is the number of IESs.

IV. SOLUTION OF ATC ALGORITHM

A. Decoupling of Upper and Lower Model

According to [10], the objective functions of the original bi-level model can be simplified as follows:

$$\begin{aligned} &\min \quad f_i\left(y_i, \zeta_i\right) \\ &\min \quad F\left(x, \zeta_1, \zeta_2, \cdots, \zeta_{N_{IES}}\right) \end{aligned} \tag{20}$$

where y_i is the local specific variable of IES$_i$; x is the local specific variable of ECC; ζ_i is the shared variable between ECC and IES$_i$.

Decoupling shared variables by introducing decoupled variables, η_i of ECC and μ_i of IES$_i$, ECC and IES$_i$ are divided into two independent models.

$$\eta_i = \zeta_i, \mu_i = \zeta_i \tag{21}$$

Therefore, the quadratic penalty function is added to the original objective function, and the consistency constraint (21) is added. The objective function of the upper and lower layers after decoupling are:

$$\begin{aligned} &\min \quad f_i\left(y_i, \zeta_i\right) + \lambda \left\| \left(\eta_i^* - \mu_i\right) \right\|_2^2 \\ &\min \quad F\left(x, \zeta_1, \zeta_2, \cdots, \zeta_{N_{IES}}\right) + \lambda \sum_{i=1}^{N_{IES}} \left\| \left(\eta_i - \mu_i^*\right) \right\|_2^2 \end{aligned} \tag{22}$$

where μ_i^* is the reference value of the penalty term of ECC, equal to the result value of the lower IES$_i$ optimization; η_i^* is the reference value of the penalty term of IES$_i$, equal to the result value of the ECC; λ is the penalty coefficient.

B. Solution Steps of ATC Algorithm

1) Set initial value: Equipment parameters, electricity load and heat load of each IES, number of iteration $w = 0$ and penalty function coefficient λ ; $\eta_{i,w}^* = 0,\ \mu_{i,w}^* = 0$.

2) Solving Model of ECC: $w = w+1$. Receive the results of all IESs, solve the model of ECC, and pass the results, $\eta_{1,w}, \eta_{1,w}, \cdots, \eta_{N_{IES},w}$, to the lower IESs.

3) Solving Model of IES$_i$: Receive the results of ECC, solve the model of IES$_i$, and pass the result, $\mu_{i,w}$, to the upper ECC.

4) Convergence judgement: If the convergence criterion (23) is satisfied, stop. Otherwise jumps to *2)*.

$$\begin{cases} \left|\eta_{i,w}^{t} - \eta_{i,w-1}^{t}\right| \le \varepsilon \\ \left|\mu_{i,w}^{t} - \mu_{i,w-1}^{t}\right| \le \varepsilon \\ \left|\eta_{i,w}^{t} - \mu_{i,w}^{t}\right| \le \varepsilon \\ i \in \left[1, N_{IES}\right] \end{cases} \tag{23}$$

where ε is the convergence threshold, set as 0.1.

V. CASE STUDY

Fig.3 shows the network topology of multi-region IESs, which is divided into three areas. Each area has the IES, and the heating network structure of each area refers to [1]. For simplicity, only the heat network structure in each IES is shown in Fig. 3. The parameters of pipelines refer to [2]. The time delay of pipelines, P_3, P_5, P_9, P_{10}, P_{12}, P_{15}, is 1h, and other pipelines have no time delay. The scheduling period is 24h and the scheduling interval is 1h. Fig.4 shows the electricity load, heat load, the power of photovoltaic and wind turbine, and transaction price in each region.

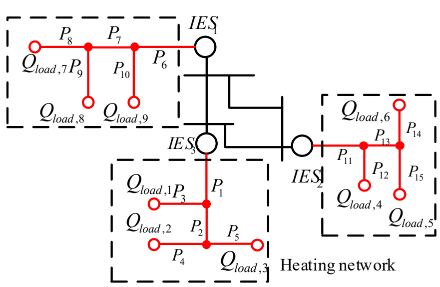

Figure 3. The network topology of multi-region IESs.

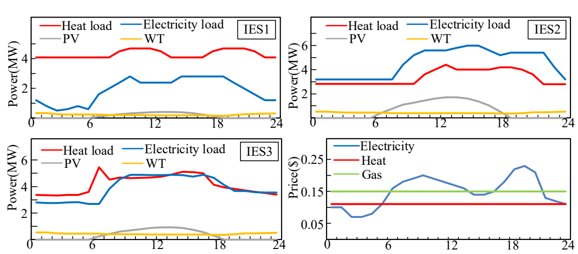

Figure 4. Transaction price and data of IESs.

A. Comparative Analysis of Models

In order to highlight the advantages of the proposed distributed electricity-heat joint optimization scheduling method, the target values of each IES and ECC are calculated by using conventional centralized method and the proposed distributed method respectively. The results are shown in Table I.

It can be seen that under the centralized and distributed models, the optimization results of each IES are different but the total cost are the same without considering calculation error. In the centralized model, the value of the objective function of IES$_1$ is smaller than that in the distributed model, while the values of the objective function of IES$_2$ and IES$_3$ are larger than those in the distributed model. This is because that by using the proposed distributed optimization method, each IES tries to optimize its own objectives and the final convergence is reached by the coordination of the upper layer. However, by using the centralized method, the objective functions of IESs has not been considered separately. When the convergence threshold ε is 0.1, the difference of the objective function of ECC between two method is about 0.16%. The difference will go smaller, when the convergence threshold ε is smaller.

TABLE I. COMPARISON BETWEEN CENTRALIZED MODEL AND DISTRIBUTED MODEL

Categories	f_1 ($)	f_2 ($)	f_3 ($)	F ($)
Centralized	35767.31	52031.81	48913.36	100261.83
Distributed	39090.50	49449.41	47997.61	100423.01

Therefore, in the distributed model, the independence of optimization considering its own requirement of each IES and ECC is guaranteed. The overall energy purchase cost, the objective function of ECC, can be guaranteed as the same as the centralized model within error permissibility.

B. Analysis of Scheduling Results

The optimization results of IESs are shown in Fig.5. It can be seen that during the period of 0:00-6:00 in IES$_1$, because the electricity load is low and the heat-electricity ratio of load is high, the GT outputs surplus electricity. The surplus electricity is dispatched to other areas by the ECC. IES$_2$ and IES$_3$ mainly rely on purchasing electricity when the electricity price is low. When the electricity price is high, the electric energy generated by GT increases for reducing the cost.

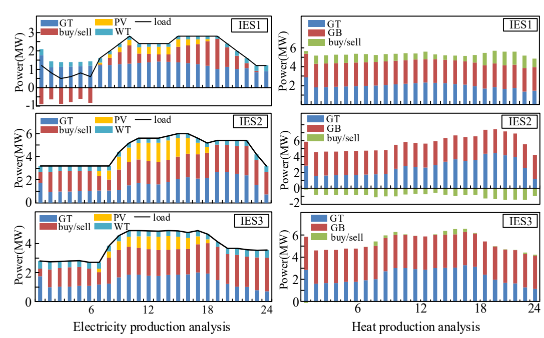

Figure 5. Optimization results of three IESs.

IES$_2$ has excess heat in the entire scheduling cycle. IES$_3$ only has excess heat in the period from 0:00 to 1:00, and there are different degrees of heat purchase from other regions during the period from 8:00 to 17:00. IES$_1$ purchases heat from other IESs throughout the scheduling period. Since the gas price is lower than the electricity price for most of the period, the heat output of GB of each IES is higher, close to the upper limit of the operating power. During this period, the insufficient heat is generated by the GT or purchased from other IESs. There was no abandonment of heat and electricity in the entire area. The entire region achieves economic optimization through joint scheduling, and each IES achieves its own optimality while ensuring the user's electricity and heat demand.

C. *Influence of Heating Network on Scheduling*

The heat outputs and the heat loads of the IES_2 and IES_3 are shown in Fig.6. Due to the existence of heating network, the delay characteristic causes the heat output of the IES and the heat load of consumers to be different at each time. However, the heat energy transmitted by the heating network to consumers is equal to the heat load of consumers. IES can raise the temperature of return water by raising the temperature of supply water, so that the supply water temperature can meet the requirements by providing less heat energy to heat the return water in the next scheduling cycle. Therefore, the heating network is a heat storage device for IES. By increasing the temperature of supply water, the degree of heat storage in the heating network can be improved.

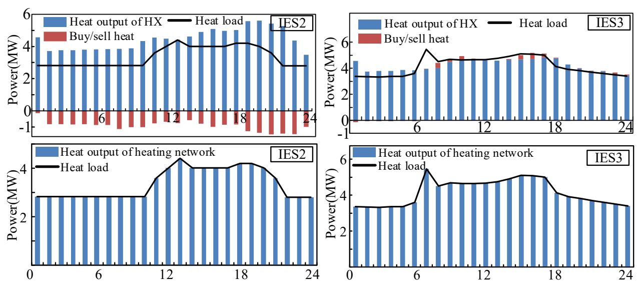

Figure 6. Heat outputs and heat loads of IES_2 and IES_3.

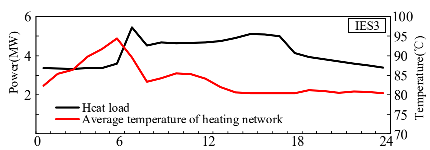

Figure 7. Heat load and average temperature of heating network of IES_3.

In this paper, the degree of heat storage in heating network is estimated by the average value of the temperature of all pipes in the supply water network. The higher the temperature is, the more heat is stored. Fig.7 shows the heat load and the average temperature of heating network of IES_3.

The peak heat load of IES_3 appears at 7:00. During the period from 0:00 to 6:00, the temperature of heating network continues to increase, that is, the heat stored in the heating network increases. After 7:00, the heat output of IES_3 is less than heat load. However, the temperature of heating network is greatly reduced because that IES_3 avoids the damage caused by the large fluctuation of heat load to the energy supply equipment, and uses the energy stored in the heating network to supply a part of the heat load, the average temperature of the heating network decreases therefore. Furthermore, during the period 0:00-1:00, the excess heat energy of IES_2 is more than the heat energy output. IES_2 inputs all surplus heat into the heating network to ensure the full utilization of heat energy.

In summary, by considering the transmission delay of heating network in the multi-region IESs joint optimization model, it can make full use of the storage capability of heating network to absorb the excess heat energy. Hence, stabilize the fluctuation of heat load and reduce energy cost.

VI. Conclusion

In this paper, a multi-region IESs joint optimization scheduling model considering regional heating network is proposed, which abstracts the joint scheduling between multiple regions into a bi-level model that ECC as the upper layer and IES as the lower layer. The upper and lower layers serve as different bodies to realize energy optimization management of the entire system. The influence of heating network structure on multi-region IESs joint scheduling is studied. The results show that under the distributed modeling, the interest game between multiple subjects can be refined, and through the decoupling and independent parallel solution between the ECC and IES, different subjects can achieve respectively their optimality. By analyzing the influence of heating network on scheduling, the heating network can provide a way IES to absorb excess heat energy which cannot be transmitted to other IESs, and reduce the impact of load fluctuation on IES.

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