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Completely Distributed Optimal Scheduling of Multi-region Integrated Energy System Based on ADMM Algorithm

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Abstract. With the development of energy Internet, the energy coupling relationship between multiple regions is increasingly strengthened. How to guarantee the safety of the information between regions to realize the distributed optimal scheduling of multi-region system has become a crucial problem. In this paper, a completely distributed optimal scheduling method of multi-region integrated energy system (IES) based on alternating direction method of multipliers (ADMM) is proposed to solve the problems of information exchange obstacles and data leakage in centralized scheduling method. Firstly, a typical distributed scheduling model consisting of three park-level IESs is established to analyze inter-regional coordination optimization mechanism. Then, using a distributed solution method based on ADMM that can cancel the upper scheduling center to protect the safety of the data information of each region. Furthermore, this method assigns the calculation work of multipliers to interconnected regions to replace the data processing center. Before each region starts the next iteration, the interconnected regions are responsible for updating the multipliers, thus realizing the completely distributed scheduling strategy. Finally, the proposed method is adopted to solve the optimization problem of the three interconnected IESs and compared with the traditional centralized scheduling method to verify its effectiveness and correctness.

Keywords: Alternating direction method of multiplier, multi-region, integrated energy system, completely distributed optimal scheduling.

1. Introduction

Due to the continuous progress of energy technology, more and more scholars begin to study the optimal scheduling of integrated energy system (IES) in recent years [1-3]. With the emergence of energy coupling equipment such as gas turbine and power-to-gas (P2G), large regional interconnected IES has become an inevitable pattern. In order to realize the optimal allocation of resources among regions, the energy transmission and exchange among different regional systems are becoming increasingly frequent, which makes the optimal scheduling problem of multi-region system become a hot topic research.

At present, the optimal scheduling of multi-region systems mostly adopts traditional centralized scheduling methods, such as interior point method [4] and Lagrange method [5], which needs to establish a scheduling center with higher scheduling power to collect detailed information of each region, conduct data analysis and calculation, and uniformly deploy the operation mode of each region. The biggest advantage of the centralized scheduling method is that it can directly realize the optimization of the overall situation, but it also has some limitations. Firstly, the collection of information from multi-region systems by the upper scheduling center will result in data communication obstacles and improper data processing. Secondly, the existence of the upper scheduling center requires all regions to send data information such as the topology structure of network, the number of devices and parameters to the scheduling center, which may lead to data privacy leakage.

In order to solve above problems, the distributed scheduling method should be adopted to realize the global optimal scheduling under the premise of exchanging as little information as possible between regions. In recent years, many scholars have been devoted to the research of distributed scheduling methods. In [6-7], the distributed scheduling method is applied to the study of optimal power flow strategy of interconnected systems. Literature [6] proposed a parallelized distributed optimal power flow model for large-scale regional interconnection systems, and verified by simulation of medium-sized systems. Based on Ref. [6], two mathematical decomposition method, predictor-corrector proximal multiplier (PCPM) and alternating direction method (ADM) are introduced to realize the proposed distributed scheme in [7].

In addition, the alternating direction multiplier method (ADMM) [8-14] is also widely used in distributed optimization problems. In [8], ADMM algorithm is applied to the economic scheduling of micro grid. Based on distributed scheduling model of single micro grid, a completely distributed algorithm is proposed in [9] which can deal with the economic scheduling problem of interconnected micro grid flexibly. In this scheme, each microgrid only solves its local problems and exchanges a little information with neighboring microgrids. Literature [10] and [11] proposed the distributed robust collaborative scheduling model and used ADMM algorithm to decouple the connection of each region. In order to improve energy efficiency, a distributed optimization strategy of IES that analysed the uncertainties of source side and load side is proposed in [12]. Then, the above model is re-expressed through ADMM to realize the distributed solution with multi-energy complement. Literature [13] presents a decentralized optimal operation model of multi-energy system based on ADMM algorithm, which realizes the cascade utilization of energy.

In the existing distributed scheduling model of multi-region IES, the connection of each region is not completely decoupled, and a small data processing center is still needed to collect the information of each tie line to complete the calculation and update work of multipliers. Even though each region is hardly inevitable to share its own key information, the data processing center still has a certain authority and cannot realize the completely distributed scheduling strategy. In order to address above problems, a completely distributed scheduling model is established. Firstly, the ADMM algorithm is adopted to decouple the connection of multi-region IES, which can ensure the information safety of each region. Then, the calculation and update work of multipliers are directly handed over to the interconnected regions and the system obtains the optimal solution by solving iteratively. Finally, in order to verify the effectiveness and correctness of the proposed method, three power-gas interconnected IESs are built for testing.

Compared with existing research, the main contributions of this paper are summarized as follows:

1) A completely distributed optimal scheduling method is proposed in this paper, which introduces ADMM to decouple connection of multi-region IES and transform the centralized scheduling problem into optimization problems within each region to ensure the information security of regions to the greatest extent.

2) Assign the calculation work of the multipliers to the interconnected regions to replace the data processing center. Before a region starts the next iteration, the interconnected regions are responsible for updating the multipliers and transmitting the latest results of tie lines for the newest iteration, thus realizing the completely distributed optimal scheduling strategy of multi-region IES.

The rest of the paper is organized as follows. Section II introduces the framework of basic scheduling model of multi-region and the decoupling idea and processing based on ADMM. The completely distributed scheduling model is described in Section III. Section IV gives the case studies, and Section V draws the conclusions.

2. Framework and Algorithm

The scheduling model of the multi-region electricity-gas IES is shown in Fig. 1. Each region is composed of the electric network with a variety of renewable energy, natural gas network, gas turbine and other coupling equipment, and the transmission and exchange of energy between each region is realized through tie lines. At present, the economic scheduling of multi-region system mostly adopts traditional centralized scheduling method, which needs the upper scheduling center to uniformly collect the data information of each region and implement an optimal scheduling decision. But when the data information can’t be shared completely or there is a lot of regions, the distributed scheduling method should be adopted to decouple the connection between regions. The augmented Lagrange relaxation (ALR) is mostly used in distributed scheduling, which adds a secondary penalty term about relaxation constraints to the objective function, so that the step size of multiplier update is fixed, thus solving the problem of low convergence of Lagrange relaxation. However, the addition of the secondary penalty term destroys the decomposition of the problem, which is the main drawback of the ALR. This problem is usually solved by the auxiliary problem principle (APP) method [14]-[16] and ADMM algorithm. The two methods both have their own advantages and disadvantages: the APP method can realize distributed parallel solution, but the convergence speed is moderate; ADMM method can only solve the serial problems, but the convergence speed is fast. Considering that the number of interconnected regions in the existing IES structure are not too large, the ADMM algorithm is adopted to realize the completely distributed scheduling of multi-region IES.

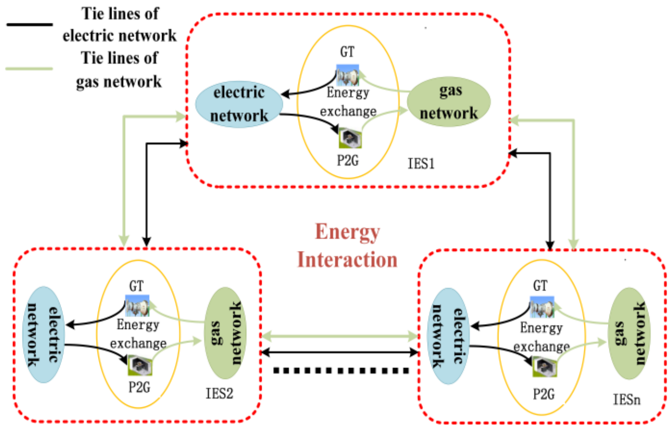

Fig. 1: Conceptual diagram of multi-region IES scheduling model.

2.1. Introduction of Algorithm

ADMM algorithm is a computational mode for solving optimization problems, which has been widely used in solving distributed convex optimization problems in recent years. ADMM algorithm decomposes large global problems into several small local subproblems which are easy to be solved, and finally obtains the global optimal solution through coordinating the solution of subproblems. The existing optimization problem is as follows:

$$\begin{aligned} &\min \ f(x)+g(z) \\ &s.t.\ Ax+Bz=c \end{aligned} \tag{1}$$

The equation constraint is relaxed into an unconstrained optimization problem by using the augmented Lagrange.

$$\begin{aligned} L_p(x,z,\lambda) = f(x)+g(z)+y^T(Ax+Bz-c)+ \\ \frac{\rho}{2}\| Ax+Bz-c \|_2^2 \end{aligned} \tag{2}$$

where λ is the Lagrange multiplier; ρ is the positive coefficient of secondary penalty term. The most important idea of ADMM algorithm is that when solving a variable, the remaining variables are treated as constants, and uses the latest result of iteration. The iteration process is as follows:

$$\begin{aligned} x^{k+1} &= \arg\min{}_x\ L_\rho(x,z^k,\lambda^k) \\ z^{k+1} &= \arg\min{}_z\ L_\rho(x^{k+1},z,\lambda^k) \\ \lambda^{k+1} &= \lambda^k + \rho(Ax^{k+1}+Bz^{k+1}-c) \end{aligned} \tag{3}$$

ADMM algorithm continues to iterate according to this process until the original and dual residuals meet the accuracy requirements.

2.2. Decoupling Idea and Processing

Taking two regions a and b as an example, regions are coupled by $T_{ab,t}$ and $G_{ab,t}$ in the centralized scheduling model and the transmitted energy is related to each two connected regions. If the constraints of tie lines in the centralized scheduling model are relaxed directly, the connection between regions cannot be decoupled. Therefore, the constraints of tie lines need to be rewritten as (4).

$$\begin{aligned} &T_{ab,t}^a = T_{ab,t}^b\ ,\ G_{ab,t}^a = G_{ab,t}^b\ , \\ &-T_{ab,\max} \le T_{ab,t}^a\ ,\ T_{ab,t}^b \le T_{ab,\max}\ , \\ &-G_{ab,\max} \le G_{ab,t}^a\ ,\ G_{ab,t}^b \le G_{ab,\max}\,. \end{aligned} \tag{4}$$

where $T_{ab,t}$ and $G_{ab,t}$ respectively represent the transmitted electricity and natural gas of tie line between region a and b at time t; $T_{ab,t}$ and $G_{ab,t}$ respectively represent transmitted electricity and natural gas of tie line between region a and region b at time t when solving the subproblem of region a. $T_{ab,t}$, $G_{ab,t}$ respectively represent transmitted electricity and natural gas when solving the subproblem of region b. The conversion process of above constraints is clearly shown in Fig. 2. The same tie line is converted into two lines, which belongs to their respective region and meet the same capacity constraints, trading quantity constraints and planned exchange electricity constraints.

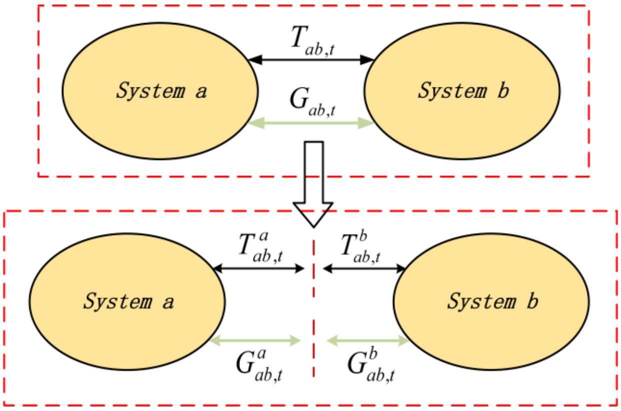

Fig. 2. Schematic diagram of tie line constraints transformation.

By analyzing the decoupling process, it can be found that only constraints of tie lines are relaxed after applying ADMM algorithm, and energy information transmitted on tie lines is only related to the two interconnected regions, and the Lagrange multiplier is only used by the two interconnected regions. Therefore, the tie line constraint is not a global constraint. The Lagrange multiplier calculation and updating process can be completed between the two interconnected regions, and multipliers allocation can also be carried out by each subregion without the existence of the data processing center, so as to realize the completely distributed scheduling strategy. The process of completing the update and allocation work of multipliers between region a and b independently is introduced as follows:

1) In the k^{th} iteration, the optimization problem of region a is solved and obtain the transmitted energy results of the corresponding tie lines. Then, region a will transmit the result to the interconnected region b to participate in solving optimization problem of b as the latest iteration value;

2) After solving the optimization problem of region b, region b already has the newest values of transmitted energy to calculate and update the multipliers of tie lines of interconnected regions directly;

3) Before the $(k+1)^{th}$ iteration, region b transmits the latest multipliers to region a to start the next iteration.

Though the number of regions is large, the multipliers are still updated independently between two interconnected regions in accordance with above process, and there is no need for the existence of an data processing center.

3. Completely Distributed Scheduling Model

3.1. Objective Function

The objective function of the multi-region IES is to minimize the total operating cost. And this paper mainly considers the cost of generating unit output and gas source output. In the traditional centralized model, the objective function can be expressed as (5):

$$\min \sum_{r\in R}\left\{\sum_{t\in T}\left[\sum_{u\in U_r}\left(a_u P_{u,t}^2 + b_u P_{u,t} + c_u\right) + \sum_{m\in M_r} C_m P_{m,t} + \sum_{g\in G_r} C_g P_{g,t} + \sum_{w\in W_r} C_w Q_{w,t}\right]\right\} \tag{5}$$

where R is the set of region numbers; T is the dispatch period; U_r, G_r, W_r, M_r are respectively the set of thermal power units, gas turbines, gas sources and P2G equipment in region r; a_u, b_u, c_u are the generating output characteristic coefficients of thermal power unit u; C_g is the operating cost coefficient of gas turbine g; C_w is the gas production cost coefficient of gas well w; C_m is the P2G cost coefficient of P2G m; $P_{u,t}$ is the output of thermal power unit u at time t; $P_{g,t}$ is the output of gas turbine g at time t; $P_{m,t}$ is the power consumed by P2G device m at time t; $Q_{w,t}$ is the natural gas production of gas well w at time t.

Then, this paper also takes two regions a and b as an example and use the ADMM to decouple the connection of regions that is proposed in section II and applying the augmented Lagrange to the constraints of $T_{ab,t}^a = T_{ab,t}^b$ and $G_{ab,t}^a = G_{ab,t}^b$ to obtain the new objective function as (6).

$$\begin{aligned} F_L = \sum_{t\in T}\Bigg[& \sum_{u\in U_a}\left(a_u P_{u,t}^2 + b_u P_{u,t} + c_u\right) + \\ & \sum_{m\in M_a} C_m P_{m,t} + \sum_{g\in G_a} C_g P_{g,t} + \sum_{w\in W_a} C_w Q_{w,t}\Bigg] + \\ & \sum_{b\in a, b\neq a} \lambda_{ab,t}^T\left(T_{ab,t}^a - T_{ab,t}^b\right) + \sum_{b\in a, b\neq a} \frac{\rho}{2}\| T_{ab,t}^a - T_{ab,t}^b \|_2^2 + \\ & \sum_{b\in a, b\neq a} \mu_{ab,t}^T\left(G_{ab,t}^a - G_{ab,t}^b\right) + \sum_{b\in a, b\neq a} \frac{\beta}{2}\| G_{ab,t}^a - G_{ab,t}^b \|_2^2 \end{aligned} \tag{6}$$

where $\lambda_{ab,t}^T$, $\mu_{ab,t}^T$ is the Lagrange vector multiplier; ρ, β are respectively the penalty coefficients of the secondary penalty term of the electricity and gas tie line. When a region is being solved, the variables in other regions are regarded as constants. Therefore, the objective function of optimization problem of region a in the k^{th} iteration is as follows.

$$\begin{aligned} \min\ F_L^{a,k} = \sum_{t\in T}\Bigg[& \sum_{u\in U_a}\left(a_u P_{u,t}^2 + b_u P_{u,t} + c_u\right) + \\ & \sum_{m\in M_a} C_m P_{m,t} + \sum_{g\in G_a} C_g P_{g,t} + \sum_{w\in W_a} C_w Q_{w,t}\Bigg] + \\ & \sum_{b\in a, b\neq a} \lambda_{ab,t}^{T,k-1} T_{ab,t}^a + \sum_{b\in a, b\neq a} \rho \| T_{ab,t}^a - T_{ab,t}^{b,new} \|_2^2 + \\ & \sum_{b\in a, b\neq a} \mu_{ab,t}^{T,k-1} G_{ab,t}^a + \sum_{b\in a, b\neq a} \beta \| G_{ab,t}^a - G_{ab,t}^{b,new} \|_2^2 \end{aligned} \tag{7}$$

where $T_{ab,t}^{b,new}$, $G_{ab,t}^{b,new}$ are the latest iteration values of $T_{ab,t}^b$, $G_{ab,t}^b$ and the latest values are taken as (8).

$$\begin{aligned} T_{ab,t}^{b,new} &= \begin{cases} T_{ab,t}^{b,k}, & b < a, \\ T_{ab,t}^{b,k-1}, & b > a, \end{cases} \\ G_{ab,t}^{b,new} &= \begin{cases} G_{ab,t}^{b,k}, & b < a, \\ G_{ab,t}^{b,k-1}, & b > a. \end{cases} \end{aligned} \tag{8}$$

After each iteration, the update of the Lagrange multiplier is formulated as (9).

$$\begin{aligned} \lambda_{ab,t}^k &= \lambda_{ab,t}^{k-1} + \rho\left(T_{ab,t}^{a,k} - T_{ab,t}^{b,k}\right), \\ \mu_{ab,t}^k &= \mu_{ab,t}^{k-1} + \beta\left(G_{ab,t}^{a,k} - G_{ab,t}^{b,k}\right). \end{aligned} \tag{9}$$

Other constraints of electricity network, gas network, coupling equipment and tie lines in the completely distributed scheduling model are the same as those in traditional centralized scheduling model, which can be described as follows.

3.2. Electric Network Constraints

1) Constraint of node power balance. The electricity flowing into the node is equal to the electricity flowing out of the node at any time. It can be described as (10).

$$\sum_{u\in i} P_{u,t} + \sum_{g\in i} P_{g,t} = P_{i,t}^{load} + \sum_{m\in i} P_{m,t} + \sum_{j\in i} P_{ij,t}\ ,\ i, j \in I \tag{10}$$

where I is the set of power nodes; $P_{i,t}^{load}$ is the power load at node i at time t. $P_{m,t}$ is the load consumed by P2G equipment m connected to node i at time t; $P_{ij,t}$ is the power of branch ij at time t.

2) The output constraint of unit is described as (11).

$$P_{e,\min} \le P_{e,t} \le P_{e,\max} \qquad e \in U \cup G \tag{11}$$

where $P_{e,t}$ represents the output of generator unit; $P_{e,min}$, $P_{e,max}$ represent the lower limit and upper limit of the output at the time t; generator unit e is the combination of thermal power units and gas turbines.

3) Ramp rate constraint of generator unit is formulated as (12).

$$r_e^{down}\Delta t \le P_{e,t} - P_{e,t-1} \le r_e^{up}\Delta t \qquad e \in U \cup G \tag{12}$$

where r_e^{up}, r_e^{down} are respectively the limits of the upward and downward climbing rates of the generator unit e.

4) Constraint of branch power flow. The power flow model is nonlinear. In order to simplify the calculation, the direct current power flow model is adopted in this paper. The formula is described as (13).

$$-P_{ij\max} \le P_{ij,t} = \frac{1}{x_{ij}}\left(\theta_i - \theta_j\right) \le P_{ij\max} \tag{13}$$

where x_{ij} is the reactance of branch ij; θ_i and θ_j are the voltage phase angles of node i and j.

3.3. Gas Network Constraints

1) Constraint of node flow balance. At any time, the sum of the gas flow into the node is equal to the sum of the gas flow out of the node. It can be described as (14).

$$\sum_{w\in k} Q_{w,t} + \sum_{m\in k} Q_{m,t} = Q_{k,t}^{load} + \sum_{h\in k} Q_{kh,t} + \sum_{g\in k} Q_{g,t}, k,h \in K \tag{14}$$

where K is the set of gas network nodes; $Q_{m,t}$ is the gas production of P2G equipment m at node k at time t; $Q_{k,t}^{load}$ is the gas load at node k at time t; $Q_{kh,t}$ is the natural gas flow of branch kh at time t; $Q_{g,t}$ is the gas consumption of the gas turbine connected to node k at time t.

2) Output constraint of gas source is formulated as (15).

$$Q_{w,\min} \le Q_{w,t} \le Q_{w,\max} \tag{15}$$

where $Q_{w,min}$, $Q_{w,max}$ respectively represent the lower and upper limit of the output of gas well w.

3) Constraint of node pressure is expressed as (16).

$$p_{k,\min} \le p_{k,t} \le p_{k,\max} \tag{16}$$

where $p_{k,min}$, $p_{k,max}$ are the lower and upper limits of pressure of node k; $p_{k,t}$ is the pressure of node k at time t.

4) Compressor constraint. In order to transmit natural gas safely and reliably, it is indispensable to install pressurized stations in specific locations to reduce transmission losses. This paper adopts a simplified compressor model, it can be described as (17).

$$p_{h,t} \le \beta p_{k,t} \tag{17}$$

where β is the compression coefficient of the compressor.

5) Constraint of pipeline flow can be formulated as (18)-(19).

$$\tilde{Q}_{kh,t} \,|\, \tilde{Q}_{kh,t} \,| = C_{kh}^2\left(p_{k,t}^2 - p_{h,t}^2\right) \tag{18}$$

$$Q_{kh,\min} \le Q_{kh,t} \le Q_{kh,\max} \tag{19}$$

where $\tilde{Q}_{kh,t} = \left(Q_{kh,t}^{in} + Q_{kh,t}^{out}\right)/2$ represents the average flow of pipeline kh; C_{kh} is a constant coefficient related to pipe diameter, temperature, length, friction coefficient, etc [17]-[18]; $Q_{kh,min}$、$Q_{kh,max}$ is the lower limit and upper limit of the flow of pipeline kh. Since the dynamic characteristics of natural gas network will make the problem become nonconvex and nonlinear problem, this paper only considers the steady-state model.

3.4. Coupling Constraints

1) Gas turbine

$$P_{g,t} = \eta_g H_{GV} Q_{g,t} \tag{20}$$

where η_g is the gas-to-electricity conversion efficiency of gas turbine g; H_{GV} is the high calorific value of natural gas, which is $39MJ/m^3$.

2) P2G

$$P_{g,t} = \eta_g H_{GV} Q_{g,t} \tag{21}$$

where η_m is the power-to-gas conversion efficiency.

3.5. Tie Line Constraints

In the scheduling of multi-region power-gas IES, each two regions are connected by two tie lines, one of which realizes electricity transmission and the other realizes natural gas transmission.

1) Constraints on transmission capacity of the tie line are described as (22)-(23).

$$-T_{ab,\max} \le T_{ab,t} \le T_{ab,\max}\ ,\quad a,b \in R \tag{22}$$

$$-G_{ab,\max} \le G_{ab,t} \le G_{ab,\max}\ ,\ a,b \in R \tag{23}$$

where $T_{ab,max}$, $G_{ab,max}$ are constants, which respectively represent the limit of electricity and natural gas flow transmitted through tie lines. Equations (22) and (23) indicate that two-way transmission can be conducted between regions.

2) Constraints of transaction contract of tie line mean that within the specified period of time, the electricity and natural gas transmitted between regions meet the prior agreement of the transaction contract. They are expressed as (24)-(25).

$$\sum_{t\in T} T_{ab,t} = E_{ab}\ ,\ a,b \in R \tag{24}$$

$$\sum_{t\in T} G_{ab,t} = F_{ab}\ ,\ a,b \in R \tag{25}$$

where E_{ab}, F_{ab} represent the total amount of electricity and natural gas traded between region ab within the specified period of time.

3) Constraints of exchange plan are formulated as follows.

$$T_{ab,\min}^{plan} \le T_{ab,t} \le T_{ab,\max}^{plan} \tag{26}$$

$$G_{ab,\min}^{plan} \le G_{ab,t} \le G_{ab,\max}^{plan} \tag{27}$$

where $T_{ab,\max}^{plan}$, $T_{ab,\min}^{plan}$ are the maximum and minimum values of planned exchange electricity between region a and b at time t; $G_{ab,\max}^{plan}$, $G_{ab,\min}^{plan}$ are the maximum and minimum values of planned exchange gas between region a and b at time t.

3.6. Model Linearization

The nonlinear parts of model are the cost characteristic coefficients of thermal power units in the objective function equation (5) and the pipeline flow constraint in equation (18). In order to reduce the difficulty of model solving and improve the speed of model solving, the piecewise linearization method [19]-[21] was adopted in this paper to linearize the nonlinear parts of the model. This method approximates the function as equation (28)-(31).

$$f(x) \approx f(X_1) + \sum_{i \in D} \left(f(X_{i+1}) - f(X_i) \right) \delta_i \,, \tag{28}$$

$$x = X_1 + \sum_{i \in \mathrm{P}} (X_{i+1} - X_i) \delta_i \,, \tag{29}$$

$$x = X_1 + \sum_{i \in \mathrm{P}} (X_{i+1} - X_i) \delta_i \,, \tag{30}$$

$$0 \le \delta_i \le 1 \;\; \forall i \in D. \tag{31}$$

where D is the number set of segmented intervals; δ_i represents the continuity variable for each segment; ψ_p is a binary number used to guarantee the continuity of a piecewise function: if $\delta_i > 0$ and $2 \le i \le k$-1, for $1 \le j \le i$, δ_j is equal to 1. That is to say, if a segmented interval is to be used, then all the intervals to the left of it must be completely used.

3.7. Solving Steps

Through above processing, the proposed method can realize the completely distributed scheduling strategy. The detailed solving steps of the completely distributed scheduling method for multi-region are as follows.

Step 0: Assigning the initial values to all variables and parameters in the optimization problem. (The number of iteration k=0, region number: a=1, b=2, c=3, etc.)

Step 1: Solving the optimization problem of subregion a according to ADMM serial algorithm.

Step 2: Comparing the serial number of region a with its interconnected region: If the serial number of region a is greater than that of all interconnected regions, region a is responsible for updating and transmitting the multipliers.

Step 3: Increasing the serial number: a=a+1. If the serial number of region a is greater than the maximum serial number, go to **Step 4**; Otherwise, go to **Step 1**.

Step 4: Solving the initial residuals and dual residuals and comparing the solved residuals with given allowable value to see whether the error is within the allowable range or not. If the error is within the allowable range, the algorithm ends; Otherwise, k=k+1, a=1, then go to **Step 1**.

4. Case Studies

Based on the IEEE standard test systems and some gas systems data, this paper builds three park-level electricity-gas interconnected IESs and adopts the completely distributed scheduling method to solve it.

The node numbers are tagged according to the region own serial number and the number of interconnected selected node. The daily load data is constructed according to typical daily load variation characteristics of two peaks and one valley. The maximum transmission capacity of the electricity tie line between regions is set as 150MW, and the maximum transmission capacity of the gas tie line is set as 25Km^3. Meanwhile, the electricity and natural gas volume transmitted from region b to a in a day are set as 1000MW and 150Km^3; The electricity and natural gas volume transmitted from a to c in a day are set as 2300 MW and 280Km^3. The electricity and natural gas volume transmitted from b to c in a day are set as 1400 MW and 190Km^3.

4.1. Compared with Centralized Scheduling Model

Values of ρ and β are both set as 0.5, and the maximum errors of the constraints of electricity tie line and gas tie line are both set as 0.1MW and 0.1Km^3. Then, applying the traditional centralized scheduling method and completely distributed scheduling method based on ADMM algorithm respectively to solve the optimization problem, the results are shown in Tab. I. Results shows that the total cost of the two scheduling methods is basically the same, and the number of iterations in the distributed scheduling is also within a reasonable range.

Taking regions a and b as an example to study the difference of electricity or natural gas exchanged between regions, results are shown in Fig. 3. Meanwhile, the output of the same unit and gas source in each dispatch period is also shown in Fig. 4 and Fig. 5 It can be found that the electricity and natural gas transmitted and the output of an arbitrary unit and gas source in each scheduling period are basically the same. Therefore, adopting the completely distributed scheduling method can replace the centralized scheduling method well to obtain the global optimal solution under the premise of exchanging as little information as possible between regions and solve the problems of data leakage and the obstruction of multi-region information exchange in the centralized scheduling method.

Table 1: Comparing of solving results

Scheduling method	Total cost / ¥	Number of iterations
Centralized scheduling method	43101.72	—
Completely distributed scheduling method	43114.53	20

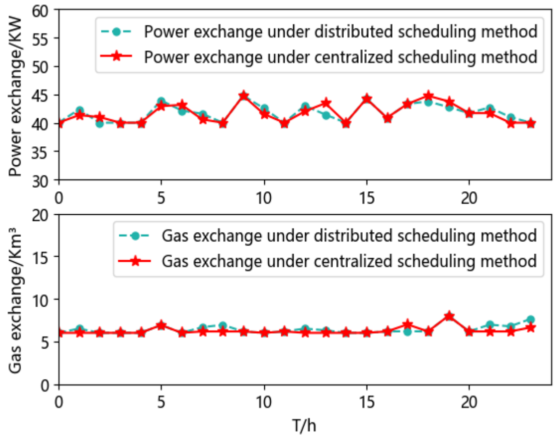

Fig. 3: Comparison diagram of energy exchange between region ab under two scheduling methods.

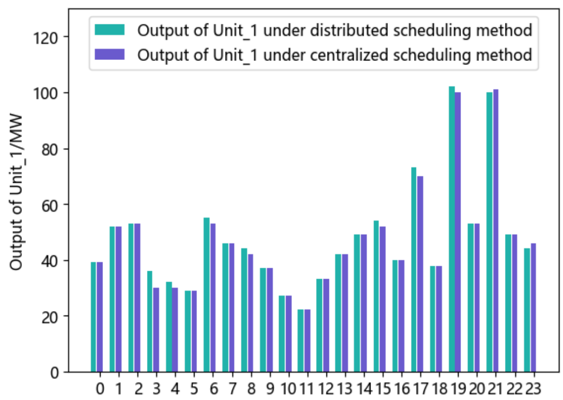

Fig. 4: Comparison diagram of the output of the same unit under two scheduling methods.

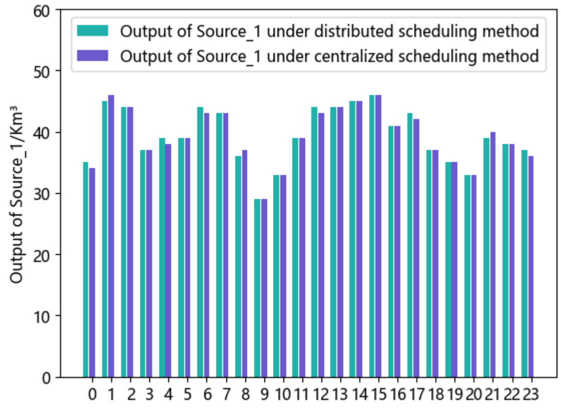

Fig. 5: Comparison diagram of the output of the same gas source under two scheduling methods.

4.2. Impact of Different Iteration Order

In the ordinary distributed scheduling method, a small data processing center is still needed to achieve calculation work of the multipliers, so the completely distributed scheduling strategy cannot be realized. But in this paper, the calculation work of the multiplier is directly assigned to the interconnected regions to replace the data processing center. Before a region starts the next iteration, the interconnected regions are responsible for updating the multipliers and transmitting the latest results for the newest iteration, and the global solution is obtained by solving iteratively.

In order to further explore the influence of the iteration order on the updating processing of multipliers when the calculation work of multipliers is directly assigned to the interconnected regions and verify the correctness of the proposed completely distributed scheduling method, the iteration order is changed in this experiment under the parameters remain unchanged, results are shown in Tab. II. It can be found that the number of iterations is basically the same, which indicates the iteration order of region has little effect on the updating work of multipliers, the completely distributed scheduling strategy can be realized effectively, which can ensure the information security of each region to the greatest extent.

4.3. Selection of Parameter ρ and β

This part further analyzes the influence of the value of parameters ρ and β. Tab. III shows the number of iterations under different values of ρ and β when the maximum allowable errors of the electricity tie line and gas tie line are respectively 0.1MW and 0.1Km^3. And the value of ρ is always same as β in this study. It can be found that when ρ and β are too large or small, the convergence speed will slow down and the number of iterations will increase.

To study the effect of the maximum allowable errors of tie lines on the completely distributed scheduling method, the values of ρ and β are respectively set as 0.05, 0.5 and 2. Fig. 7 show the influence of different maximum errors on the number of iterations, and the value of maximum allowable errors of the electricity tie lines are always set the same as that of the gas tie lines. The Fig.6 indicates that when the penalty coefficients are different, the effect of the maximum errors of the tie line constraint on the numbers of iteration is different. When values of ρ and β are both 0.005, the curve drops slowly because small values of ρ and β affect the updating speed of multipliers, leading to the increase of number of iterations; when ρ and β are both 2, the curve is steeper, and the descending speed is fast, but it is unstable.

Table 2: Impact of different order of region iteration

Iteration order	Number of iterations
$a \to b \to c$	20
$a \to c \to b$	20
$b \to a \to c$	21
$b \to c \to a$	17
$c \to a \to b$	20
$c \to b \to a$	19

Table 3 Impact of different values of ρ and β

Values of ρ and β	Number of iterations
0.005	72
0.01	24
0.1	20
0.4	21
0.5	20
1	24
2	30

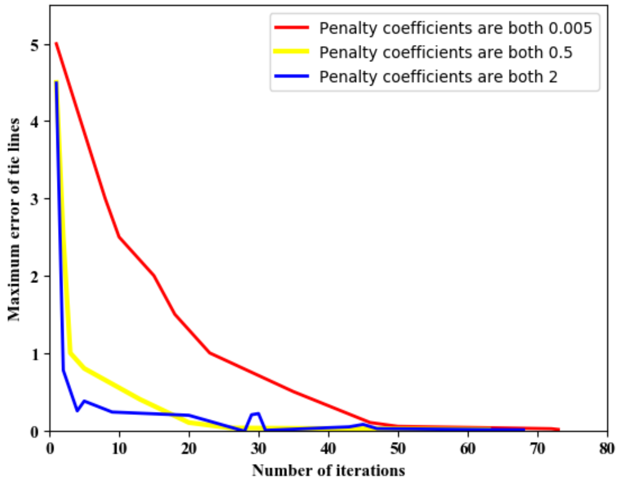

Fig. 6: Effect of the maximum error of tie lines on the number of iterations when ρ and β are different.

It illustrates that the large value will make the processing of iteration fluctuate; when ρ and β are both 0.5, the curve has a moderate descending speed, and there is no fluctuation phenomenon, and the number of iterations is within a reasonable range. Therefore, the value of ρ and β not only affects the updating process of multiplier, but also affects the iterative process. When solving the practical problems, the appropriate value of ρ and β can be selected through pre-experiment, so as to improve the solving speed of the system and reduce the number of iterations.

5. Conclusion

To solve the problems of data leakage and information exchange obstruction in the centralized scheduling method, a completely distributed optimal scheduling method based on ADMM is proposed in this paper, which decouples the connection of multiple regions and transform the scheduling problem of multi-region IES into the optimization problem within each region. Moreover, the method assigns the calculation and updating work of multipliers directly to the interconnected regions to replace the data processing center. Before a region starts the next iteration, the interconnected regions are responsible for updating the multipliers and transmitting the latest results for the newest iteration, thus realizing the completely distributed scheduling strategy and ensuring the information security of each region to the greatest extent.

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