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Research Article

Optimization Strategy of Multiarea Interconnected Integrated Energy System Based on Consistency Theory

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A collaborative optimization strategy of an integrated energy system aiming at improving energy efficiency is studied in this paper for the cluster optimization of an integrated energy system (IES). In this paper, an improved discrete consistency method based on the coordination optimization method for IES is proposed. An IES model considering the mixed energy supply of electricity, heat, and gas is constructed in a single region. And then an objective function with the maximum return is established, on the premise of assuming that the prices of electricity, heat, and gas can be used as an economical means to adjust the energy utilization. Finally, the consistency theory is applied to the IES, and the improved discrete consistency algorithm is utilized to optimize the objective function. In the case study, a certain region IES is taken as an example in Northeast China. The case study demonstrates the effectiveness and accuracy of the coordination optimization method for IES.

1. Introduction

With the progress of renewable energy technology and the development of energy Internet, the research on technology related to comprehensive energy system containing a high proportion of renewable energy is gradually becoming a hot topic [1–3]. Integrated energy system, with grid as the core, is connected to various types of energy sources such as electricity, heat, and gas, which makes the high proportion of the renewable energy grid more capable of dealing with uncertainty and randomness, and can be effectively compatible with various forms of energy to ensure the sustainable and reliable operation of diversified energy supply systems. In order to promote the synergistic development of multiregional integrated energy systems, it is important to study the optimal operation of multiregional integrated energy systems [4].

Currently, research methods include economic operation and robust operation for the optimization of an integrated energy system operation. Economic operation refers to the use of an integrated energy system to minimize the operating cost of each equipment and put forward optimization problems and solutions [5–7]. About the economic operation problem, electric energy, heat energy, and gas energy are analyzed by the unified combined power method, and the research focuses on the synergies of multienergy sources and the application of energy inertia at different time scales. In addition, in the study of some economic operation problems, the optimization target is not only the operation cost of equipment but also the environmental cost, investment cost, and network loss cost. In the robust optimization problem, an optimization problem with the aim of reducing the source and load uncertainty or enhancing the system's ability to withstand the fault risk is proposed and its solution is studied. The research focuses on the synergistic gain of multiple energy sources and the quantitative characterization of uncertainty in the system [8, 9]. However, as the scale of integrated energy systems continues to increase, the interconnectivity of multiregional integrated energy systems is gradually strengthened, and the system is gradually characterized by a distributed system. Therefore, it is necessary to do further research on the problem description and solution method which is more suitable to the practical system.

Research on the operation strategy of the integrated energy system based on price has become one of the research hotspots. The economically optimized operation model of cogeneration unit was solved using improved genetic algorithm in [10], based on the implementation of the electricity price. In [11], a deadline and cost-aware scheduling algorithm was proposed for structured tasks of the IoT. In [12], the optimal dispatch model of the smart grid was established, which allows the combined heat and power units and wind turbines to be used efficiently. The objective function with the maximum revenue was established, and the particle swarm algorithm of the mutation operator was used to optimize the microgrid of the cogeneration unit in [13]. In [14], a multiobjective function was established, which considered the randomness of distributed generation and load. In [15], taking into account load fluctuations and equipment characteristics, the optimization of power distribution for the combined heat and power systems was studied and an analytical method using nonlinear programming was proposed. In [16], a sparsity alleviation recommendation approach is presented for the incomplete model after data preprocessing. In [17], a minimum model of the total cost of fuel in the energy system was studied. In [18], based on the load-unknown and uncontrollable randomness, the optimized model was solved, using the corresponding constraint equation. In [19], a system optimization objective function was added with constraints such as appropriate equipment, cost savings, and economic benefits. In [20], based on the IES model, the optimized objective function with the lowest cost was analyzed. In [21], a dynamic reconfiguration was proposed for verifying the interactive behaviour of Web service. In [22], an objective function with the lowest cost and PV model was solved. In [23], different electrical loads were redivided in IES to strengthen the system optimization accuracy. The current comprehensive energy system optimization strategy can make certain accurate decisions when dealing with sudden changes. In order to improve the information processing capability of the system, the collaborative distributed optimization operation strategy of the integrated energy system based on the consensus algorithm is proposed in [24]. However, for the multiarea interconnected integrated energy system, the working conditions change very quickly because of the high complexity of the system. The calculation of the system is very high. Therefore, the discrete consistency algorithm is usually used for the real integrated energy system with multiregion interconnection. In this paper, a uniform algorithm is used to solve the operation optimization problem of the multiarea interconnected integrated energy system. The optimal solution is achieved and the solving speed is improved.

The remainder of the paper is organized as follows. In Section 1, an IES model considering the mixed energy supply of electricity, heat, and gas is constructed in a single region. In Section 2, an objective function with the maximum return is established on the premise of assuming that the prices of electricity, heat, and gas can be used as an economical means to adjust the energy utilization. Then, the consistency theory is applied to the IES, and the improved discrete consistency algorithm is used to optimize the objective function. In Section 3, an actual example, including increment of electric income, the increment of heat income, and the increment of gas income as consistent variables, is studied. According to the improved discrete consensus algorithm flow, the model is continuously iteratively calculated, and the prices of electricity, heat, and gas in each region are constantly updated. The validity and correctness of the proposed method in this paper have been verified.

2. Integrated Energy System

As an energy area, IES has a role in integrating and converting energy. IES is the important component in the energy Internet, which realizes integrated energy management by interconnection among multiple energy conversion equipment. The house is equipped with electric loads, gas loads, heat loads, and solar cells, which can be self-sufficient through photovoltaic power generation and can also interact with other energy areas. The IES consists of solid state transformer (SST), battery, electric boiler (EB), microturbine (MT), heat exchanger, and heat storage (HS), which can realize the generation of electric energy and heat energy, the conversion of electric energy to heat energy, and the storage of electric energy and heat energy.

The wind power generation model is

$$P_{\mathrm{WP},i,t} \le P_{\mathrm{WP},i,\max}, \tag{1}$$

where $P_{\mathrm{WP},i,t}$ is the wind output in power system node i at t and $P_{\mathrm{WP},i,\max}$ is the upper limit of the wind power output.

The PV model is

$$P_{\mathrm{PV},i,t} \le P_{\mathrm{PV},i,\max}, \tag{2}$$

where $P_{\mathrm{PV},i,t}$ is the PV output in power system node i at t and $P_{\mathrm{PV},i,\max}$ is the upper limit of the PV output.

The electricity storage model is

$$S_{\mathrm{EEs},i,t} = \left(1-\delta_{\mathrm{EEs}}\right)S_{\mathrm{EEs},i,t-1} + \left(\eta_{\mathrm{EEs}}^{\mathrm{ch}}P_{\mathrm{EEs},i,t}^{\mathrm{ch}} - \frac{P_{\mathrm{EEs},i,t}^{\mathrm{dis}}}{\eta_{\mathrm{EEs}}^{\mathrm{dis}}}\right)\Delta t, \tag{3}$$

where $P_{\mathrm{EEs},i,t}^{\mathrm{ch}}$ and $P_{\mathrm{EEs},i,t}^{\mathrm{dis}}$ are charging and discharging power for the electricity storage, respectively, and δ_{EEs}, $\eta_{\mathrm{EEs}}^{\mathrm{ch}}$, and $\eta_{\mathrm{EEs}}^{\mathrm{dis}}$ are loss rate, efficiency of energy conversion, and efficiency of charging and discharging.

The electric load model is

$$P_{\mathrm{ELoad},i,\min} \le P_{\mathrm{ELoad},i,t} \le P_{\mathrm{ELoad},i,\max}, \tag{4}$$

where $P_{\mathrm{ELoad},i,t}$ is electric load, of which the upper and lower limits are $P_{\mathrm{ELoad},i,\max}$ and $P_{\mathrm{ELoad},i,\min}$, respectively.

The energy flow model for a power system is

$$\begin{cases} \Delta\mathbf{P} = \mathbf{P}_{i,t} - \mathrm{Re}\left\{\dot{U}_{i,t}\left(\mathbf{Y}\dot{U}_{i,t}\right)^{*}\right\} = 0, \\ \Delta\mathbf{Q} = \mathbf{Q}_{i,t} - \mathrm{Im}\left\{\dot{U}_{i,t}\left(\mathbf{Y}\dot{U}_{i,t}\right)^{*}\right\} = 0, \end{cases} \tag{5}$$

where $\mathbf{P}_{i,t}$ and $\mathbf{Q}_{i,t}$ represent injected active and reactive power at nodes in power systems considering an energy coupled unit, respectively, $\mathbf{Y}$ is power system node admittance matrix, and $\dot{U}$ is power system node voltage phasor.

The model of the electric boiler is

$$P_{\mathrm{HEs},j,t}^{\mathrm{ch}} = P_{\mathrm{EB},j,t}\eta_{\mathrm{EB}}, \tag{6}$$

where $P_{\mathrm{EB},j,t}$ is electric power of electric boiler and η_{EB} is efficiency of electric boiler.

The heat storage model is

$$S_{\mathrm{HEs},j,t} = (1-\delta_{\mathrm{HEs}})S_{\mathrm{HEs},j,t-1} + \left(\eta_{\mathrm{HEs}}^{\mathrm{ch}}P_{\mathrm{HEs},j,t}^{\mathrm{ch}} - \frac{P_{\mathrm{HEs},j,t}^{\mathrm{dis}}}{\eta_{\mathrm{HEs}}^{\mathrm{dis}}}\right)\Delta t, \quad (7)$$

where $P_{\mathrm{HEs},j,t}^{\mathrm{ch}}$ is the heating power of the electric boiler at the time t of the heat network node j, that is, the heat injected power of the heat storage device; $P_{\mathrm{HEs},j,t}^{\mathrm{dis}}$ is the heat power released to the heat network by the heat storage device when it acts as heat source for the heat network; and δ_{HEs}, $\eta_{\mathrm{HEs}}^{\mathrm{ch}}$, and $\eta_{\mathrm{HEs}}^{\mathrm{dis}}$ are loss rate, efficiency of energy conversion, and efficiency of charging and discharging.

The heat load model is

$$P_{\mathrm{HLoad},j,\min} \le P_{\mathrm{HLoad},j,t} \le P_{\mathrm{HLoad},j,\max}, \quad (8)$$

where is $P_{\mathrm{HLoad},j,t}$ heat load, of which the upper and lower limits are $P_{\mathrm{HLoad},j,\max}$ and $P_{\mathrm{HLoad},j,\min}$, respectively.

The energy flow model of the heat supply network is

$$\begin{cases} \Delta\mathbf{H} = C_p\mathbf{m}_t\left(\mathbf{T}_{s,t} - \mathbf{T}_{o,t}\right) - \mathbf{\Phi}_{Sta} = 0, \\ \Delta\mathbf{Pr} = \mathbf{BKm|m|} = 0, \end{cases} \quad (9)$$

where C_p is the specific heat capacity of water; $\mathbf{m}_t$ is outflow matrix for heat network nodes; $\mathbf{T}_{s,t}$ and $\mathbf{T}_{o,t}$ are the hot water input and output temperature matrix in the heat network node; Φ_{Sta} is the initial thermal power matrix in the thermal network; $\mathbf{B}$ is the relational matrix of the heat supply network loop-branch; $\mathbf{m}$ is the hot network pipeline flow matrix; and $\mathbf{K}$ is the damping coefficient matrix of heat network piping.

The model of the miniature gas turbine is

$$\begin{cases} P_{\mathrm{MT}}^{e} = \sigma_{g2e}.\rho.P_{\mathrm{MT}}, \\ P_{\mathrm{MT}}^{h} = \eta_{g2h}.H_u.\rho.P_{\mathrm{MT}}, \end{cases} \quad (10)$$

where P_{MT}^{e} is output electrical power of MT; σ_{g2e} is efficiency of electricity; P_{MT}^{h} is output heat power of MT; η_{g2h} is efficiency of heat; and H_u is low calorific value of natural gas.

3. Optimization Algorithm of Multiarea Interconnected IES

3.1. Objective Function and Constraints. Based on the mixed energy supply of electricity, heat, and gas, the objective function of the highest energy sales revenue of users is as follows:

$$\begin{aligned} &\max R\left(\Delta P_e^{\mathrm{out}} + \Delta P_h^{\mathrm{out}} + \Delta P_g^{\mathrm{out}}\right), \\ &\Delta P_e^{\mathrm{out}} = P_{t,i}^{\mathrm{ein}} + P_{\mathrm{MT},t,i}^{e} + P_{t,i}^{\mathrm{es}} - P_t^{\mathrm{EL}} - P_{t,i}^{\mathrm{EB}}, \\ &\Delta P_h^{\mathrm{out}} = Q_t^{\mathrm{hin}} + P_{t,i}^{\mathrm{MT}\longrightarrow h} + Q_{t,i}^{\mathrm{hs}} - Q_t^{\mathrm{HL}} + P_{\mathrm{EB},t,i}^{h}, \\ &\Delta P_g^{\mathrm{out}} = E_t^{\mathrm{gin}} - P_{t,i}^{\mathrm{MT}} + E_{t,i}^{\mathrm{gs}} - E_t^{\mathrm{GL}}, \\ &R\left(\Delta P_e^{\mathrm{out}} + \Delta P_h^{\mathrm{out}} + \Delta P_g^{\mathrm{out}}\right) = \begin{bmatrix} \mathrm{pr}_e & \mathrm{pr}_h & \mathrm{pr}_g \end{bmatrix}\begin{bmatrix} \Delta P_e^{\mathrm{out}} \\ \Delta P_h^{\mathrm{out}} \\ \Delta P_g^{\mathrm{out}} \end{bmatrix}, \end{aligned} \quad (11)$$

where $\Delta P_e^{\mathrm{out}}$ is user output power in IES; $\Delta P_h^{\mathrm{out}}$ is user output heat power in IES; and $\Delta P_g^{\mathrm{out}}$ is user output gas power in IES.

There is a limit to the objective function:

$$\begin{cases} \begin{cases} 0 \le P_{\mathrm{ES,ch}}(t) \le \gamma_{\mathrm{ES,ch}}S_{\mathrm{ES}}, \\ -\gamma_{\mathrm{ES,dis}}S_{\mathrm{ES}} \le P_{\mathrm{ES,dis}}(t) \le 0, \end{cases} \\ S_{\mathrm{SOC}}^{\min} \le S_{\mathrm{SOC}} \le S_{\mathrm{SOC}}^{\max}, \\ P_{\mathrm{EB},i}^{\min} \le P_{\mathrm{EB},i}(t) \le P_{\mathrm{EB},i}^{\max}, \\ P_{\mathrm{MT},i}^{e\min} \le P_{\mathrm{MT},i}^{e}(t) \le P_{\mathrm{MT},i}^{e\max}, \\ P_{\mathrm{MT},i}^{h\min} \le P_{\mathrm{MT},i}^{h}\{t \le P_{\mathrm{MT},i}^{h\max}, \\ \begin{cases} P_{E,i}^{\min} \le P_E^t \le P_{E,i}^{\max}, \\ P_{H,i}^{\min} \le P_H^t \le P_{H,i}^{\max}, \\ P_{G,i}^{\min} \le P_G^t \le P_{G,i}^{\max}. \end{cases} \end{cases} \quad (12)$$

3.2. Improved Discrete Consistency Algorithm. Graph theory is an important mathematical tool for the analysis of consistency problems. The multiarea interconnected IES can be decomposed into the power grid topology, heat network topology, and natural gas network topology by applying the consistency theory. All regions use communication network for information exchange, and all independent nodes in the system are represented by sets. The directed graph in the system is marked as $G = (A, B)$, which contains n independent nodes. Set A represents the set of all independent nodes in the system, i.e., $A = (a1, a2, ..., an)$; set B represents the set of all adjacent edges of the independent nodes in the system, i.e., $B = (b1, b2, ..., bn)$. If node i can obtain all the information of node j, and similarly, node j can also obtain all the information of node i, and the network topology graph is called a strong connection graph. The power gird, heating grid, and natural gas grid, which are selected in this paper, are all strongly connected network topologies.

The Laplacian matrix is derived from the difference between the degree of the adjacency matrix and the matrix, so the element size is only related to the topology of the network. However, each region IES has different income increments and the particularity of each system. If the adjacency matrix still adopts the 0-1 matrix form, it will reduce the convergence rate of the system in the actual multiarea interconnected IES. Under the premise of maintaining the same accuracy, the coefficients in the Laplacian matrix are changed without affecting. The size of the elements in the Laplace matrix is changed, which can increase the speed of convergence. Changing the size of the elements is usually carried out by giving weights. The weight size is calculated as follows:

$$\sum_{j=1}^{j=n} z_{ij}(k)l_{ij} = 0, \quad i = 1, 2, \ldots, n. \quad (13)$$

The iteration rules are as follows:

$$\xi_i(k+1) = \sum_{j=1}^{n} d_{ij}(k)\xi_j(k), \tag{14}$$

where $d_{ij} = (z_{ij}(k)|l_{ij}(k)|)/(\sum_{j=1}^{n} z_{ij}(k)|l_{ij}(k)|)$. It is calculated by

$$\xi_j(k+1) = \sum_{j=1}^{n} \frac{z_{ij}(k)\left|l_{ij}(k)\right|}{\sum_{j=1}^{n} z_{ij}(k)\left|l_{ij}(k)\right|}\xi_j(k). \tag{15}$$

Matrix can be expressed by

$$\xi(k+1) = D(k)\xi(k). \tag{16}$$

3.3. Income Increment Consistency Algorithm. In a multiarea interconnected IES, due to the mutual coupling of power subsystems, heating subsystems, and natural gas subsystems in each region and the conversion between electricity, heat, and gas energy, there is no consistency between income increment of subsystems in various regions. As a result, there is no consistency between subsystems in various regions. Therefore, an optimization plan is established, which is conducive to improving the operating efficiency and profitability of IES. In the traditional power system, according to the criterion of equal increase rate of consumption, the optimal distribution of each active power supply in the system can be achieved.

In this paper, the principle of equal consumed energy increase ratio law is used to optimize and solve the multiregion interconnected integrated energy system. The system with the largest income increment performs energy interaction with the outside world until its income increment decreases to the same as the other two system's income increment, and then the electricity, heat, and gas income increment of each regions reach the consistency. When the clearing price of any energy is changed to increase its income, it will cause the total income of other subsystems to decrease more than its income increment, which indicates that the total income of the system is reduced. And in order to improve the convergence speed, an improved discrete consistency algorithm is established to iterate. After many iterations, the consistency variable is calculated to meet the convergence accuracy, and the income increment is consistent. The optimization of system benefits is achieved.

The optimal income of multiarea interconnected IES is as follows:

$$\alpha_i(k) = \frac{\partial R_i\left(\Delta P_e^{\text{out}}\right)}{\partial \Delta P_e^{\text{out}}} = \frac{\partial R_i\left(\Delta P_h^{\text{out}}\right)}{\partial \Delta P_h^{\text{out}}} = \frac{\partial R_i\left(\Delta P_g^{\text{out}}\right)}{\partial \Delta P_g^{\text{out}}}. \tag{17}$$

According to consistency theory, $\alpha_i(k)$ denotes consistency information and k denotes number of iterations. The consistency variable of each subsystem in each area is adjusted according to its adjacent subsystems. As the number of iterations increases, the income increment $\alpha_i(k)$ in the i region and the income increment $\alpha_i(k)$ in the j region tend to be consistent, which means $|\alpha_i(k) - \alpha_j(k)| \longrightarrow 0$. When the income increment of each subsystem in each region is consistent within the range of convergence conditions, the income balance is achieved in a multiarea interconnected IES.

Income increment consistency algorithm of multiarea interconnected IES is established, which is to obtain the energy clearing price instruction issued by the dominant region through the automatic control area and to redistribute the energy clearing prices according to the steps in Figure 1. The specific process is as follows.

3.4. Convergence Verification of Income Increment Consistency Algorithm. After multiple iterations of the income increment consistency algorithm, the energy clearing prices of the multiregion interconnected IES can be expressed as

$$\frac{\partial R_i\left(\Delta P_{e,k}^{\text{out}}\right)}{\partial \Delta P_{e,k}^{\text{out}}} = \frac{\partial R_i\left(\Delta P_{h,k}^{\text{out}}\right)}{\partial \Delta P_{h,k}^{\text{out}}} = \frac{\partial R_i\left(\Delta P_{g,k}^{\text{out}}\right)}{\partial \Delta P_{g,k}^{\text{out}}}, \tag{18}$$

where k is number of iterations; ΔP_e^{out} is output electricity of IES user; ΔP_h^{out} is output heat of IES user; ΔP_g^{out} is output gas of IES user; $R_i(\Delta P_e^{\text{out}})$ is electric supply income in region i; $R_i(\Delta P_h^{\text{out}})$ is heat supply income in region i; and $R_i(\Delta P_g^{\text{out}})$ is gas supply income in region i. When $R_i'(\Delta P_{e,k}^{\text{out}}) = (\partial R_i(\Delta P_{e,k}^{\text{out}}))/\partial\Delta P_{e,k}^{\text{out}}$, $R_i'(\Delta P_{h,k}^{\text{out}}) = (\partial R_i(\Delta P_{h,k}^{\text{out}}))/\partial\Delta P_{h,k}^{\text{out}}$, and $R_i'(\Delta P_{g,k}^{\text{out}}) = (\partial R_i(\Delta P_{g,k}^{\text{out}}))/\partial\Delta P_{g,k}^{\text{out}}$, equation (18) can be expressed by

$$R_i'\left(\Delta P_{e,k}^{\text{out}}\right) = R_i'\left(\Delta P_{h,k}^{\text{out}}\right) = R_i'\left(\Delta P_{g,k}^{\text{out}}\right). \tag{19}$$

Thus, the income increment consistency algorithm can realize the formulation of the clearing price of multiregion interconnected IES.

In this paper, the method of constructing Lyapunov function is used to prove the convergence of the income increment consistency algorithm.

Assuming that each energy clearing price output by the IES is a one-dimensional continuously differentiable convex function, the definition domain is $Y = [\Delta\text{pr}_{\min}, \Delta\text{pr}_{\max}]$. Income R within domain Y can be expressed as

$$R_{i,k+1}\left(\Delta P^{\text{out}}\right) \geq R_{i,k}\left(\Delta P^{\text{out}}\right) + R_{i.k}'\left(\Delta P^{\text{out}}\right)\left(\Delta\text{pr}_{\max} - \Delta\text{pr}_{\min}\right). \tag{20}$$

Equation (20) can be simplified to

$$R_i(y) \geq R_i(x) + R_i'(x)(y-x). \tag{21}$$

A Lyapunov multivariate function V for each energy clearing price of a multiregion interconnected integrated energy system is defined, and its definition domain is the upper and lower limit values of each energy clearing price. The function V can be described as

$$V_i\left(\Delta P_k^{\text{out}}\right) = \sum_{i=1}^{n} R_i\left(\Delta P_k^{\text{out}}\right). \tag{22}$$

It is assumed that the income $R \geq 0$ and $V_i(\Delta P_k^{\text{out}}) \geq 0$. In summary, after k iterations, the multiregion interconnected IES has the following relationship:

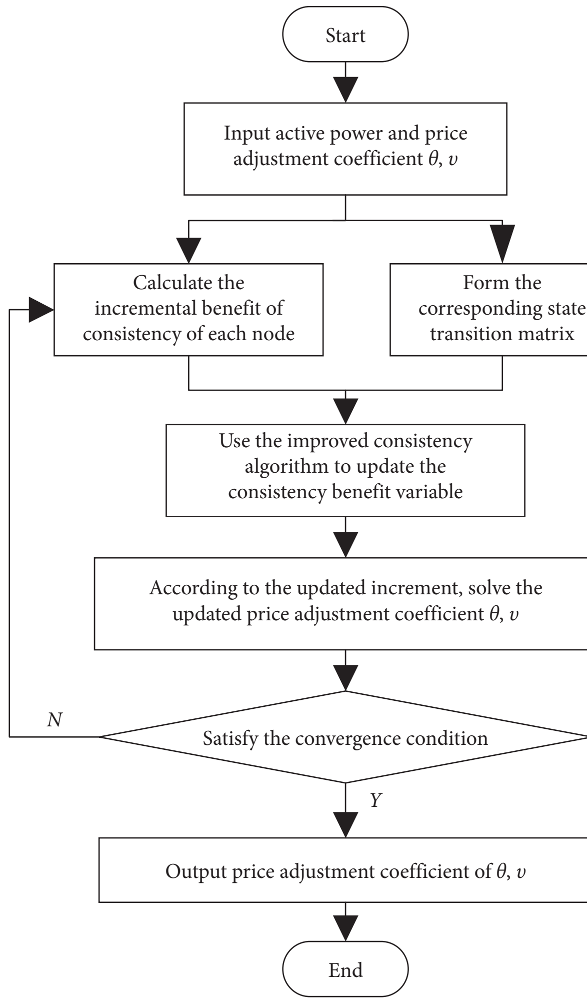

Figure 1: Consistency algorithm flowchart.

$$\begin{aligned} V_{i,k+1}\left(\Delta P^{\text{out}}\right) - V_{i,k}\left(\Delta P^{\text{out}}\right) &= \sum_{i=1}^{n} R_{i,k+1}\left(\Delta P^{\text{out}}\right) - \sum_{i=1}^{n} R_{i,k}\left(\Delta P^{\text{out}}\right) \\ &\leq R_{i,k}\left(\Delta P^{\text{out}}\right) - R_{i,k}\left(\Delta P^{\text{out}}\right) + \left(\Delta \text{pr}_{\max} - \Delta \text{pr}_{\min}\right) = 0. \end{aligned} \quad (23)$$

The results can be modeled and formulated as

$$V_{i,k+1}\left(\Delta P^{\text{out}}\right) - V_{i,k}\left(\Delta P^{\text{out}}\right) = 0. \quad (24)$$

Thus, the convergence verification of income increment consistency algorithm is proved.

4. Results and Discussion

In this paper, a certain multiregion IES in three regions (region 1, region 2, and region 3) is taken as an example in Northeast China. Based on MATLAB, the simulation model of the coupled system with multienergy sources is established, and CPLEX is used to solve the problem. Detailed parameters of power, heat, and gas supply networks in integrated multiregional energy systems are given in [10–14]. The dispatching period shall be 24 h with unit dispatching step length of 1 h.

In three regions, the data of multiple energy loads are described by distribution characteristics, where electric load capacity is 150 MW, heat load capacity is 150 MW, and gas load capacity is 100 MW in each region. In the simulation system, electrical storage capacity is 10 MW, heat storage capacity is 10 MW, gas storage capacity is 8 MW, and microgas turbine capacity is 100 MW in each region. The initial transaction price is 0.1 yuan for electricity, 0.12 yuan for heat, and 0.09 yuan for gas. The wind and PV output are both the typical daily output [10].

The predicted values for the various energy loads are shown in Figures 2–4, respectively.

Figure 5 is iteration result of selling price of power, heat, and gas. After the 38th iteration, the prices of electricity, heat, and natural gas stabilized at 0.1 yuan, 0.14 yuan, and 0.08 yuan, respectively. At this point, the price of each energy clearing between regions tends to stabilize. This result shows that the consistency algorithm is effective for multiregional integrated energy system coordination.

Figure 6 is the revenue increment of power, heat, and gas in each area. Revenue increment shows consistency in intraregional coordination. As can be seen from the graph, revenue increment also tends to stabilize within each region

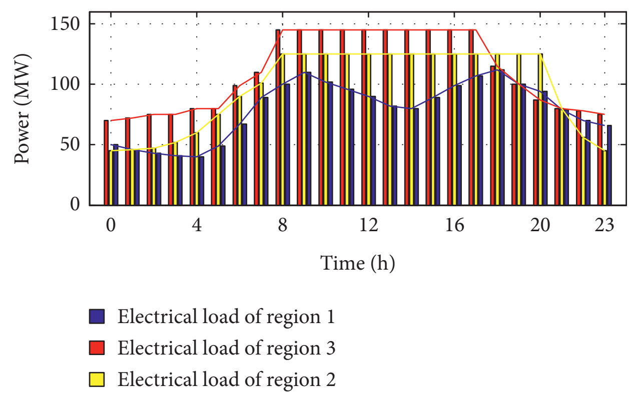

Figure 2: Forecast curve of electrical load.

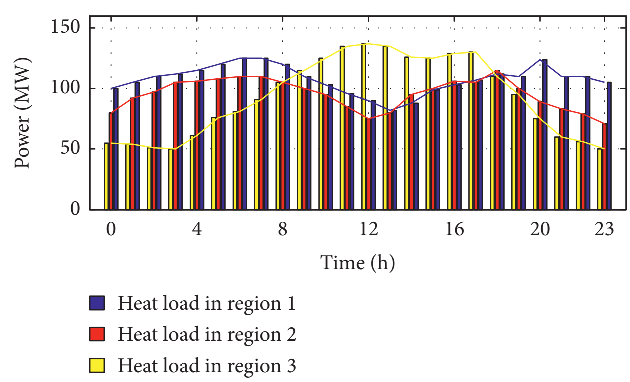

Figure 3: Forecast curve of heat load.

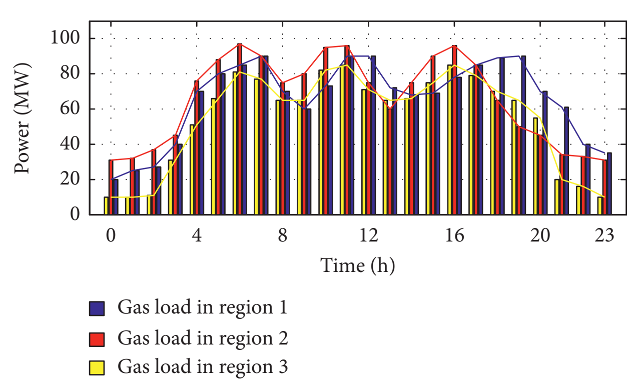

Figure 4: Forecast curve of gas load.

under the condition that prices are stable between every region after iteration 38.

Figure 7 is selling prices of various energy sources at various times. In each period, the clearing price of each energy source can vary according to the load value and the operating state of the system. According to the above analysis, each clearing price is calculated under the condition that the system is stable. Between 900 and 20 : 00, the price of electricity and gas price goes up, and the price of heat price goes down, which shows the effectiveness of multienergy coordinated operation in reducing the overall operating cost of the system and its user-friendliness to energy users.

Figure 8–10 are the power curve of electric storage, heat storage, and gas storage, respectively. Storage of energy can achieve energy regulation through its own energy storage characteristics. Storage energy utilizes the energy from the low price and the peak price. This property can effectively improve the system's ability to support dynamic risk. The energy storage in each region can not only harmonize the energy imbalance among regions but also reduce the

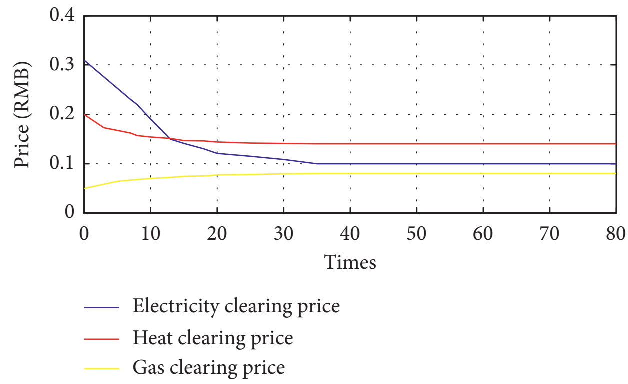

Figure 5: Selling price of power, heat, and gas.

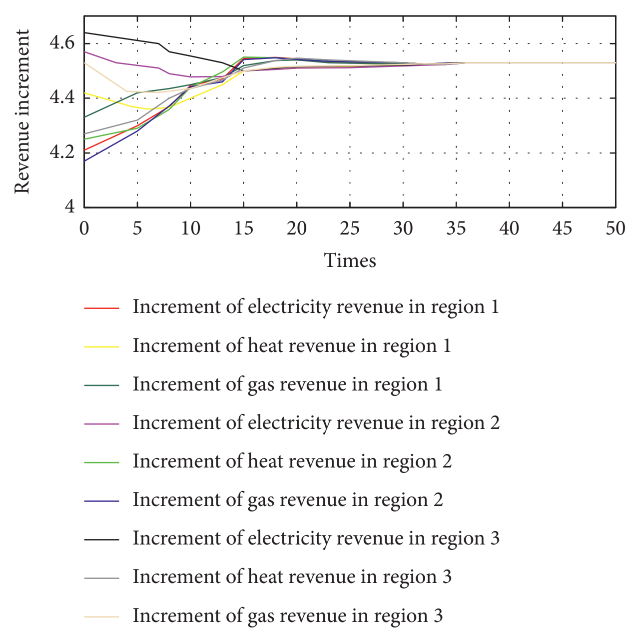

Figure 6: Revenue increment of power, heat, and gas in each area.

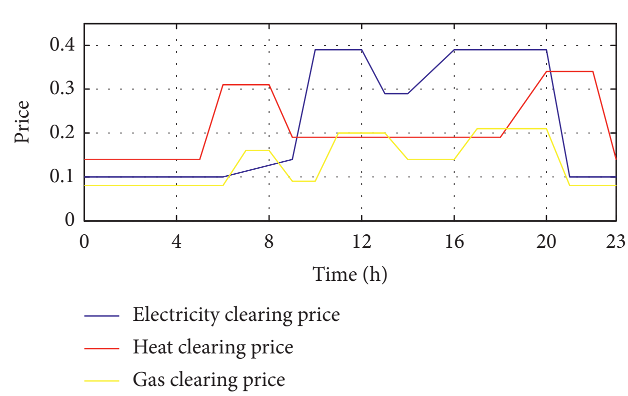

Figure 7: Selling prices of various energy sources at various times.

difference between peaks and valleys and enhance the stability of the system.

Figure 11 is the power curve of microgas turbine. As an energy coupling unit in the integrated energy system, the microgas engine has the characteristic of flexible regulation. It can achieve the complementary coordination of electric energy, heat energy, and gas energy. In the rising phase of electricity price, the microcombustion engine can increase

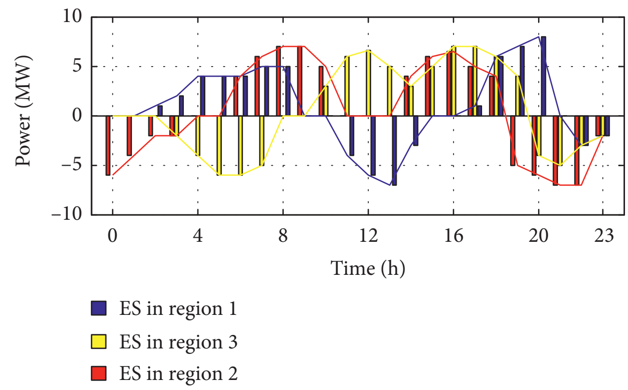

Figure 8: Power curve of electric storage.

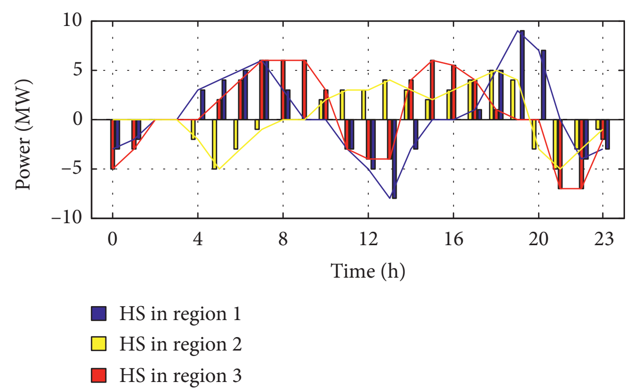

Figure 9: Power curve of heat storage.

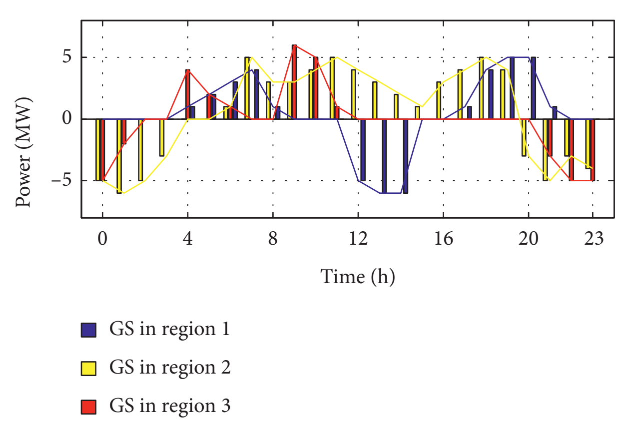

Figure 10: Power curve of gas storage.

its own output to deal with the peak load period and realize the thermoelectric decoupling by using energy storage technology. The synergistic operation of microgas turbine can not only meet the demands of multienergy load but also realize the synergistic energy of the system.

Figure 12 is the power curve of electric boiler. Electric boilers, as both electrical devices and heating sources, play an important role in the energy balance in the integrated energy system. According to the algorithm presented in this paper, the operation mode of electric boiler is calculated. It is shown in Figure 12 that electric boilers can use the low price for heating, which can reduce the operating cost of electric boilers and improve the coordination of electric and thermal energy.

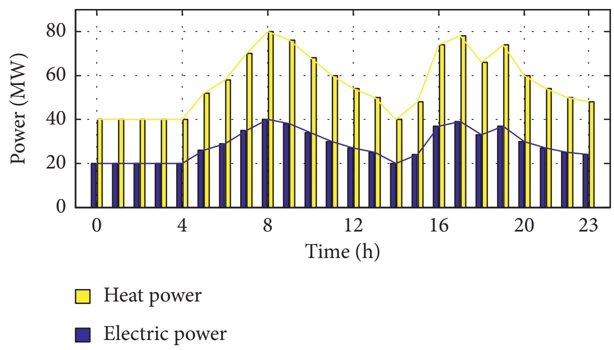

Figure 11: Power curve of microgas turbine.

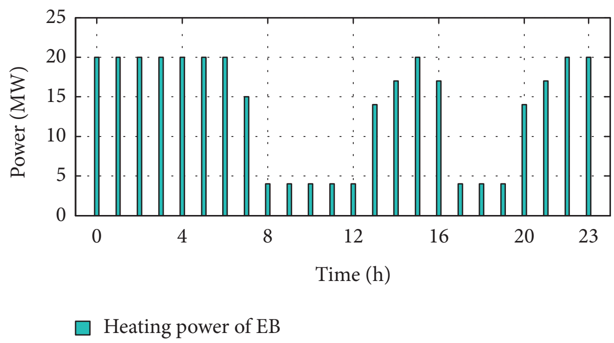

Figure 12: Power curve of the electric boiler.

5. Conclusions

In this paper, consistency theory is applied to the integrated energy system. Through the selection of energy clearing price and the reasonable coordination between the units, this paper calculates the consistency vary according to the equal consumption increment rate. In the process of establishing the model and solving the model, the increment of electric energy, heat energy, and gas energy in each region is consistent with each other by iterative calculation, so as to realize the cooperative optimization of the integrated energy system with multiregions interconnection.

In the part of simulation, an example of an integrated energy system with three interconnected regions is given, and the results show that the improved discrete-time consistency algorithm can improve the computation speed and reduce the computation time and achieve the goal of cooperative optimization of the integrated energy system with interconnected regions by selecting the energy clearing price.

Data Availability

The data required to reproduce these findings cannot be shared at this time as the data also form part of an ongoing study.

Disclosure

This is an extended version of a paper entitled "Research on Coordinating Optimization Strategy of Integrated Energy System Based on Multiagent Consistency Theory" published in the 2020 IEEE International Conference on Computer, Information, and Telecommunication Systems (CITS 2020).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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