Optimized Operation of Integrated Electricity-Heat-Gas Energy System Considering the Optimal Consumption of Wind and Photovoltaic Power Generation

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Abstract. The continuous expansion of installed capacity and grid-connected scale of new energy sources such as wind power and photovoltaic power generation will affect the stability and economic operation of the integrated energy system. Aiming at this problem, an optimized operation method of the electric-heat-gas interconnected Integrated Energy System considering the optimal wind and light absorption is proposed. The constraints of electric heating and gas systems, coupling constraints, wind-photovoltaic energy abandonment penalties, operating costs and environmental costs have been considered to construct an optimal energy abandonment cost model; with the goal of minimizing the total system cost in the dispatch period, the optimal operation of each unit is decided, including the optimal wind, light absorption, and the model is solved with the help of the commercial optimization software CPLEX.Finally, the example uses the improved IEEE-39-node electric power system, the Belgian 20-node natural gas system, and the 6-node thermal system for simulation analysis.The results show that the proposed model can effectively improve the stability and economy of system scheduling in the IES with electric heating and gas interconnection, and realize the optimal consumption of wind and photovoltaic power.

Keywords: Optimal Energy Consumption · Integrated Power · Heat and Natural Gas · Integrated Energy System · Mixed Integer Linear Programming

1 Introduction

Under the background of the "carbon peaking and carbon neutrality", Integrated Energy System (IES) has the high efficiency of energy supply and the strong flexibility of coordinated operation, which is one of the important ways to improve the consumption of renewable energy. However, there is a strong uncertainty of clean energy generation, resulting in its grid-connected operation facing many challenges.

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Domestic and foreign scholars have carried out some research on the optimal operation of IES with clean energy. Reference [1] regulated high energy load and conventional power supply to participate in power grid dispatching to improve wind power utilization. References [2, 3] proposed the IES optimal scheduling model considering the rational utilization of curtailed wind power, which reduced the operation cost of the system. In references [4–6], a coordinated optimal scheduling model of integrated electric heating system considering source-load uncertainty was proposed, and the improvement effect of the model on wind power consumption was verified. In reference [7], an electric heating and gas interconnection IES considering demand response was proposed to realize the environmental and economic optimal scheduling of the system. Reference [8] took the minimum sum of deterministic cost and random cost as the objective function to improve the reliability of power supply. In references [9, 10], the output of each device was optimized and the fluctuation of clean energy output was reduced by considering the prediction error of wind and light. However, the above literature did not cover the case of optimal renewable energy consumption rate in each period of time, and was less applied in Electro-Thermal-Gas coupled IES.

In summary, this paper constructs an optimization model of the integrated energy system considering the optimal wind and solar consumption. Considering the constraints and coupling constraints of the electric heating and gas system, the operation model of the electric heating and gas interconnection IES is constructed, and the minimum operating cost of the system is taken as the objective function. The IEEE-39 node power system, Belgium 20 node natural gas system and 6 node thermal system are used for example analysis to prove the effectiveness of the model.

2 IES Considering Optimal Accommodation of Wind Power and Photovoltaic Power

Wind power and photovoltaic power have anti-peak shaving characteristics, and their output fluctuation characteristics are opposite to the fluctuation of grid load. When the load decreases, wind farms and photovoltaic power stations compete for power generation; When the load increases, the wind power output may decrease. Based on this feature, on the basis of satisfying the operating constraints of the electric-heat-gas integrated energy system and the constraints of wind abandonment and photovoltaic abandonment rate, the conditions of wind and photovoltaic abandonment in different periods are optimized, so as to alleviate the phenomenon of wind and photovoltaic reverse peak shaving and improve the system. Overall operation stability and optimal economy are realized.

2.1 The Model of Wind Power and Photovoltaic Power

In order to avoid unreasonable wind abandonment and abandonment of light due to the search for minimum economy during the solution process, the optimization results are inconsistent with the goal of using renewable energy, the minimum allowable wind and light consumption must meet the following constraints respectively:

$$\mathrm{con}_{\mathrm{PW}}\sum_{t=1}^{T}P_{\mathrm{PW},t}\leq\sum_{t=1}^{T}con_{\mathrm{PW},t}P_{\mathrm{PW},t}\leq\sum_{t=1}^{T}P_{\mathrm{PW},t} \tag{1}$$

$$\mathrm{con}_{\mathrm{PV}}\sum_{t=1}^{T}P_{\mathrm{PV},t}\leq\sum_{t=1}^{T}\mathrm{con}_{\mathrm{PV},t}P_{\mathrm{PV},t}\leq\sum_{t=1}^{T}P_{\mathrm{PV},t} \tag{2}$$

where $con_{\mathrm{PW},t}$ and $con_{\mathrm{PV},t}$ denote the absorption rate of wind power and photovoltaic power during t period, $P_{\mathrm{PW},t}$ and $P_{\mathrm{PV},t}$ denote the output power of wind farm and photovoltaic power plant during t period, $P_{\mathrm{PWcon},t}$ and $P_{\mathrm{PVcon},t}$ denote the consumption of wind power and photovoltaic power plants in t period, $\mathrm{con}_{\mathrm{PW}}$ and $\mathrm{con}_{\mathrm{PV}}$ denote the minimum consumption rates of wind power and photovoltaic total output in the dispatch period.

In order to further refine the optimization model of wind power and photovoltaics, in addition to introducing penalty factors to restrict energy consumption behavior, and comprehensively considering the operating cost and environmental cost of the unit, the objective function can be expressed as:

$$C_{\mathrm{PW}}=\sum_{t=1}^{T}[(\lambda_{\mathrm{p}}+\lambda_{\mathrm{r}}-\lambda_{\mathrm{b}})\times\sum_{i=1}^{N_{\mathrm{PW}}}P_{\mathrm{PW},t}^{i}] \tag{3}$$

$$C_{\mathrm{PV}}=\sum_{t=1}^{T}[(\omega_{\mathrm{p}}+\omega_{\mathrm{r}}-\omega_{\mathrm{b}})\times\sum_{i=1}^{N_{\mathrm{PV}}}P_{\mathrm{PV},t}^{i}] \tag{4}$$

where C_{PW} and C_{PV} are respectively the total cost of optimized dispatch of wind and photovoltaic models, λ_{p} and ω_{p} are the penalty factors for wind abandonment and photovoltaic abandonment respectively, λ_{r} and ω_{r} are the operating costs of wind power and photovoltaics respectively, λ_{b} and ω_{b} are the environmental costs of wind power and photovoltaics respectively, N_{PW} and N_{PV} are the number of wind turbines and photovoltaic power plants respectively.

2.2 Optimization of IES Based on Electricity-Heat-Gas Considering the Optimal Accommodation of Wind Power and Photovoltaic Power

The schematic diagram of the IES considering optimal wind power and photovoltaic power is shown in Fig. 1. The system includes three types of networks with different energy attributes: electric power system, natural gas system, and thermal system. Among them, Gas Turbine (GT) and Power to Gas (P2G) realize the coupling of electric and gas systems. The Heat Recovery Steam Generator (HRSG) is connected to the gas turbine to realize the coupling of gas and heat systems. The Electric Boiler (EB) completes the energy conversion between heat and electricity systems [11].

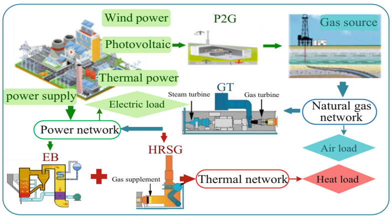

Fig. 1. Schematic Diagram of the IES

3 Optimal Scheduling Model of IES for Electric Heating Gas Interconnection

The optimization of the IES of electric heating and gas interconnection aims at minimizing the economic dispatch cost in the cycle. Dispatching costs mainly include the power generation cost of traditional thermal power units, the cost of gas source output in the natural gas system, the operating cost of wind power and photovoltaics, which can be calculated as:

$$\min F = \min(C_{\mathrm{e}} + C_{\mathrm{g}} + C_{\mathrm{PW}} + C_{\mathrm{PV}}) \tag{5}$$

where C_{e} and C_{g} respectively denote the operating costs of the power system and natural gas system.

3.1 Coupling Device Model

In the P2G realization of the electric-gas system coupling process, the relationship between the consumed electric energy and the natural gas produced can be described as:

$$V_{\mathrm{P2G},t} = \frac{\eta_{\mathrm{P2G}} \times P_{\mathrm{P2G},t}}{\mathrm{HHV}_{gas}} \tag{6}$$

where $V_{\mathrm{P2G},t}$ and $P_{\mathrm{P2G},t}$ are the volume value of natural gas and the electric energy consumed during the process of converting electricity to gas in t period, respectively; η_{P2G} is the energy conversion efficiency; $\mathrm{HHV}_{\mathrm{gas}}$ is the high calorific value of natural gas.

As the coupling node of the gas-electric system, the gas turbine has the relationship between its power generation and natural gas consumption can be cacluated as:

$$V_{\mathrm{GT},t} = \frac{P_{\mathrm{GT},t}}{\eta_{\mathrm{GT}} \times \mathrm{LHV}_{gas}} \tag{7}$$

where $V_{\mathrm{GT},t}$ denotes the gas consumption during the operation of the gas turbine during t period, $P_{\mathrm{GT},t}$ denotes the output electric power, η_{GT} denotes the power generation efficiency of the gas turbine, $\mathrm{LHV}_{\mathrm{gas}}$ denotes the low heating value of natural gas.

The energy conversion of waste heat boiler can be cacluated as

$$Q_{\mathrm{HR},t} = \eta_{\mathrm{HR}} \times \frac{P_{\mathrm{GT},t}(1 - \eta_{\mathrm{GT}} - \eta_{\mathrm{L}})}{\eta_{\mathrm{GT}}} \tag{8}$$

where $Q_{\mathrm{HR},t}$ denotes the output heat power during the operation of HRSG in t period, η_{HR} denotes the waste heat recovery efficiency of HRSG, η_{L} denotes the loss rate.

The output model of EB can be cacluated as:

$$Q_{\mathrm{EB},t} = \eta_{\mathrm{EB}} \times P_{\mathrm{EB},t} \tag{9}$$

where $Q_{\mathrm{EB},t}$ and $P_{\mathrm{EB},t}$ respectively denote the thermal power and input electric power during the operation of EB during t period, $\eta_{\mathrm{EB,h}}$ denotes the thermal efficiency of EB.

3.2 Power System Optimization Model

The operating cost of a thermal power unit can be expressed as:

$$C_{\mathrm{e}} = \sum_{t=1}^{T} F_{i,t} \tag{10}$$

$$F_{i,t} = \mathrm{a}_i (P_{\mathrm{PU},t}^i)^2 + \mathrm{b}_i P_{\mathrm{PU},t}^i + \mathrm{c}_i \tag{11}$$

where a_i, b_i, c_i respectively denote the cost coefficients of unit i, $P_{\mathrm{PU},t}^i$ denotes the output of thermal power unit i in period t.

The operation constraints of the power system include power balance constraints, generator output constraints, phase angle constraints and line power flow constraints when using DC power flow method.

The power consumption of the gas turbine is included in the node as the load of the power network.

$$P_{\mathrm{PU},t} + P_{\mathrm{GT},t} + P_{\mathrm{PW},t} + P_{\mathrm{PV},t} = P_{\mathrm{LD},t} + P_{\mathrm{L},t} \tag{12}$$

where $P_{\mathrm{LD},t}$, ${}_{\mathrm{L},t}$ respectively denote the electric load and line power flow during t period.

3.3 Natural Gas System Optimization Model

The optimization of natural gas network mainly considers natural gas sources, natural gas pipelines, pressurizing stations to supplement pressure loss, and natural gas loads. Among them, the coupling device P2G converts the excess electric energy of the system into natural gas and injects it into the natural gas system, acting as the gas source of the natural gas system; The natural gas consumed by the gas turbine is included in the gas load of the node.

Natural gas source cost can be calculated as:

$$C_{\mathrm{g}} = \sum_{t=1}^{T} c_g V_{\mathrm{s},t} \tag{13}$$

where C_{g} denotes the cost of gas source output, c_{g} is the unit price of natural gas, $V_{\mathrm{s},t}$ denotes the gas source output during t period.

The node energy balance constraint of the natural gas system can be calculated as:

$$V_{s,t} + V_{P2G,t} = V_{LD,t} + V_{L,t} \tag{14}$$

where $V_{LD,t}$ denotes the gas load at time period t, $V_{L,t}$ denotes the natural gas pipeline tidal current.

Natural gas pipelines will produce losses and pressure drops due to pipe wall friction and external factors during the transmission process. At this time, compressors are installed along the pipeline to alleviate this problem. The compressor model can be calculated as:

$$p_{out} = \Gamma_c p_{in} \tag{15}$$

where p_{out} and p_{in} respectively denote the pressure at the outlet and inlet of the compressor respectively, Γ_c is the compression ratio of the compressor, ignoring its own loss, the compression ratio is constant.

3.4 Thermodynamic System Optimization Model

Thermal network equilibrium constraints.

$$Q_{EB,t} + Q_{HB,t} = Q_{LD,t} + Q_{loss,t} \tag{16}$$

where $Q_{EB,t}$, $Q_{HB,t}$, $Q_{LD,t}$ respectively denote the heat production and heat load of electric heating boiler and waste heat boiler in t period.

The thermal power of each heat source node and load node is related to the water supply temperature, return water temperature and heat medium flow in the pipeline, which can be expressed as

$$H_i = C_p m_i (T_s^i - T_r^i) \tag{17}$$

where H_i is the thermal power flowing into node i, and it is specified that the inflow is positive and the outflow is negative, C_p is the specific heat capacity of water, m_i is the water flow out of node i, T_s^i, T_r^i respectively denote the node i heating temperature and regenerative temperature respectively.

$$H_{ij} = C_p m_j (T_r^i - T_r^j) \tag{18}$$

where H_{ij} denotes the heat loss of the heat pipe ij, m_j is the water flow out of node j, T_r^i, T_r^j respectively denote the heating temperature of nodes i and j.

4 Case Studies

Based on the optimal wind and light absorption model, the mathematical model of IES optimal scheduling including electric thermal gas is established. Under the MATLAB environment, the Yalmip toolbox is used to call the CPLEX solver for simulation analysis.

4.1 Introduction to the Example

For the optimal accommodation of wind power and photovoltaic power model proposed above, the improved IEEE-39 node power system, Belgium 20 node natural gas system, and 6-node thermal system are used for simulation in the calculation example. The specific structure of the IES for the electric-heat-gas interconnection is shown in the Fig. 2. Among them, the generators of the power system network nodes 30, 33, and 37 are set as gas turbines, which are connected to the natural gas network nodes 3, 6, and 19 respectively; nodes 6, 12 are connected to wind farms, and nodes 1, 17 are respectively equipped with photovoltaic power plants. The output of the unit is shown in Fig. 3. It is assumed that the gas source of the natural gas system network node 13 is an electric-to-gas device, which is connected to the power system network node 15. Node 1 of the thermal system network is the heat source. The electric boiler installed at this node is connected to node 24 of the power system network, and the waste heat boiler is connected to the gas turbine at node 30 of the power system network.

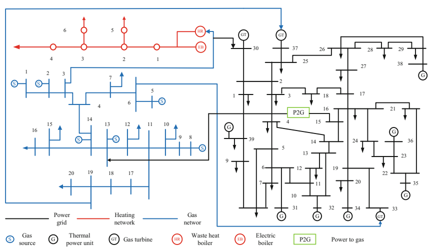

Fig. 2. Structure diagram of the integrated power, heat and natural gas energy system

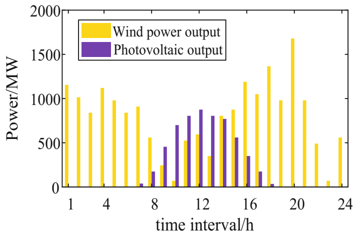

Fig. 3. The output of wind power and photovoltaic

The curves of the optimized electrical load, gas load and thermal load of the system on a typical day are shown in Fig. 4. The size of the system node load is distributed according to the node load ratio.

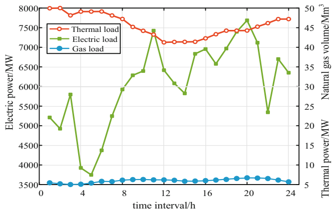

Fig. 4. The daily load curve of integrated power, heat and natural gas energy system

4.2 The Running Result Analys

In order to propose the optimal accommodation of wind power and photovoltaic power model for the research on the impact of the operation of the electric-heat-gas interconnected integrated energy system, two cases were set up for comparative analysis, respectively as follows:

Case 1: System optimization considering optimal wind and light absorption;
Case 2: Consider the system optimization of all wind and light absorption.

Table 1 shows the specific operating costs of each component of the system in the two cases (Tables 2 and 3).

Table 1. Comparison of results in two scenarios

case	Thermal power	Gas source	Wind power	photovoltaic	Total(/ten thousand dollars)
1	2377.522	4602.834	114.153	34.059	7133.567
2	2367.423	4612.346	115.500	34.461	7134.731

Table 2. Comparison of results in two scenarios about wind power

case	Function	Punishment	Environment	Total/ten thousand dollars
1	188.650	0.963	75.460	114.153
2	192.500	–	77.000	115.500

Table 3. Comparison of results in two scenarios about PV

case	Function	Punishment	Environment	Total(/ten thousand dollars)
1	56.286	0.287	22.515	34.059
2	57.435	–	22.974	34.461

The wind abandonment rate and the abandonment rate in each period under the optimal wind and light absorption are shown in Fig. 5.

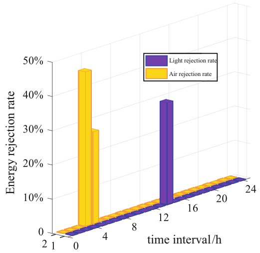

Fig. 5. The optimal abandonment rate in different time

Comparing the wind abandonment situation in Fig. 5 with the electric load curve in Fig. 5, it can be seen that the wind abandonment rate in the period 4–5 is significantly higher than that in other periods, and the electric load in the corresponding period is in a low state, which can explain the scenario The model applied in 1 has a positive effect on improving the anti-peaking characteristics of wind power.

It can be seen from Fig. 3 that the time period of photovoltaic output is concentrated in time period 7–18, which happens to be during the peak energy consumption period, which is only generated by the abandonment of light in time period 14, while the electrical load of time period 14 is at the lowest in time period 7–18. Therefore, it can be explained that the model applied in scenario 1 can improve the anti-peaking phenomenon of photovoltaic.

At the same time, wind power and photovoltaic anti-peaking characteristics will also affect the output of thermal power units. The output change curves of thermal power units under the two models are shown in Fig. 6.

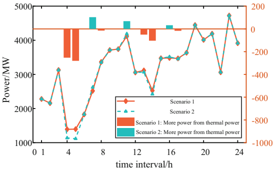

Fig. 6. Comparison of the output of thermal power units in two scenarios

Combined with the electric load curve in Fig. 4, when the reverse peak shaving phenomenon occurs, wind and light may compete for power generation during the trough periods of power consumption 4–5, 13–14, etc., and abandonment may occur during the peak period of power consumption 11, etc. The wind phenomenon increases the difficulty of peak shaving of the power grid.

The output of other units of the power system in scenario 1 is shown in Fig. 7.

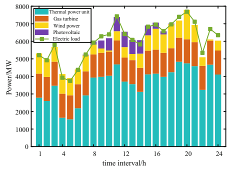

Fig. 7. Power system unit output under optimal wind and photovoltaic absorption

It can be seen from Fig. 6 that the total output of the units in each period of case 1 will be greater than that in case 2. Under the premise of constant electrical load, excessive electrical energy is converted into natural gas through P2G. In order to ensure the balance of the natural gas system, the gas production of the gas source will be reduced, and the cost of the gas source will be higher, leading to a significant reduction in the operating cost of the gas source. According to the data in Table 1, the gas source cost under case 1 is reduced by $951200 compared with case 2, and the proposed optimization model is effective.

5 Conclusion

With the objective of minimizing the economic operation cost of the two cases, this paper establishes a scheduling model for the IES of electric heating gas interconnection considering the optimal wind and light consumption, and calls CPLEX to solve the model. The main conclusions are as follows:The traditional wind power and photovoltaic full consumption method will put pressure on the operation of the grid and affect the economics of the dispatch of the integrated energy system of electric heating and gas interconnection; the optimal wind and light absorption model proposed in this paper comprehensively considers the power generation cost, gas source output cost, wind and photovoltaic operation and maintenance, and environmental cost of thermal power units, which improves the stability of system scheduling while ensuring the economics of IES.

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