Optimal operation method of integrated energy system considering thermal inertia

Yongli Wang 1, Zhen Liu1*, Chengcong Cai1, Hekun Shen1, Xin Chen 1 and Yang Yang2

1 School of Economics and Management, North China Electric Power University, Changping District, Beijing 102206, China
2 Economic and Technological Research Institute of State Grid Hebei Electric Power Co. Ltd, Hebei 050000, China
*Corresponding author’s e-mail: lz_15737038162@163.com

Abstract. This paper proposes a comprehensive energy system operation optimization method considering the thermal inertia of the heating system. Firstly, based on the energy network of the integrated energy system, establish the thermal inertia and heat storage model of the heating pipeline; secondly, the goal is to minimize the total operating cost of the electricity-heat-gas integrated energy system. Considering constraints such as power balance and safe operation of equipment, an integrated energy system operation optimization model based on thermal inertia is established; the results show that the model can better balance scheduling cost and reliability.

1. Introduction
With the development of economy and society, the connection of multiple energy sources has become increasingly close. In this context, an integrated energy system came into being. Integrated energy system refers to a new type of energy system formed by coupling multiple energy systems such as electricity, heat, cooling, and gas in the links of energy production, transmission, and consumption, which can realize the scientific dispatch and energy cascade among multiple energy sources use. However, the transportation characteristics and time scales of different energy sources in the integrated energy system are quite different, which brings great challenges to the synchronization and coordination of source and load in the integrated energy system.

Scholars at home and abroad have conducted a lot of research on the thermal inertia and dynamic physical processes of thermal systems. The literature [1-2] studied the time lag of the heating network and the loss of the transportation process, and established the operation optimization model of the heat storage of the heating network and the thermal inertia of the building. Literature [3] considers the multiple thermal inertia of the thermal system, and proposes a dual-time-scale electric-heat coordination optimization method. Literature [4-5], in order to deal with the challenge of high proportion of renewable energy access, proposed an urban integrated energy system planning model that considers the reliability of energy supply and the uncertainty of wind and solar; Literature [6-8] considers the load side Regulate resources, propose a multi-energy system optimal dispatching plan that integrates demand response and game; Literature [8] introduces electric heat storage boiler device, establishes an energy flow model based on heat storage and heat transfer charge heat leakage dynamic
process, and analyzes thermal characteristics impact on the operation of the combined electric and heating system; Based on the thermal system, this paper studies the operation optimization method of the integrated energy system considering thermal inertia. Establish a typical architecture based on IES simple topology to model the characteristics of the thermal system. Construct an optimal scheduling model for IES operation. Taking an IES in a certain place in Northeast China as a simulation example, the results verify the feasibility of the model.

2. Integrated energy system considering thermal inertia

2.1. Typical architecture of integrated energy system

Fig.1 Schematic diagram of integrated energy system. The conventional multi-energy system is shown in Figure 1. The energy matrix can describe the energy production, conversion, storage and consumption of the integrated energy system:

\[ L = CP + S \]  

In the formula, \( C \) is the energy conversion matrix of the integrated energy system; \( P \), \( L \), and \( S \) are the input vector, load vector and energy storage vector of the integrated energy system;

\[
\begin{bmatrix}
L_G \\
L_E \\
L_H
\end{bmatrix} =
\begin{bmatrix}
\alpha_1 & \beta_1 & 0 \\
\alpha_2 \eta_{E2G} & 0 & 0 \\
\alpha_2 \eta_{H2G} & \beta_2 & 1
\end{bmatrix}
\begin{bmatrix}
P_{G\text{ex}} \\
P_{E\text{ex}+P_{\text{wind}}} \\
P_{H\text{ex}}
\end{bmatrix}
+ \begin{bmatrix}
S_G \\
0 \\
S_H
\end{bmatrix}
\]  

In the formula, \( L_E \), \( L_H \), and \( L_G \) are the electricity, heat, and gas loads in the integrated energy system, respectively; \( \alpha_i \) and \( \alpha_i \) are the distribution coefficients of natural gas to gas loads and gas turbines, respectively; \( \beta_1 \) and \( \beta_2 \) are electrical energy input to electricity to gas and electric boilers The distribution coefficient of; \( \eta_{E2G} \) and \( \eta_{H2G} \) are the energy interaction between the multi-energy system and the power grid, heating network, and gas grid respectively; \( P_{\text{wind}} \) is output for wind power; \( S_G \) and \( S_H \) are the output of gas storage and heat storage devices respectively; \( \eta_{E2G} \) and \( \eta_{H2G} \) are power conversion The conversion efficiency of gas and electric boilers; \( \eta_{E2G} \) and \( \eta_{H2G} \) are the gas-to-electricity and gas-to-heat efficiencies of the gas turbine, respectively.

2.2. Thermal system inertia model and energy storage characteristics

The district heating network has large time lag and non-linear characteristics. Due to the influence of parameters such as the flow rate of the heat medium and the length of the heating pipe, the temperature change from the heat source to the user will have a certain time delay. This time lag is regarded as the thermal inertia of the heating network. At the same time, the heating network contains huge heat energy, which can be regarded as a kind of heat storage device. The two characteristics are analyzed below.
(1) Thermal inertia of heating pipes
Affected by the heating medium, the temperature change at the inlet of the heating pipe needs to be transmitted to the outlet of the pipe after a period of time. Its thermal inertia time can be expressed as:

\[ \tau_{\text{pipe}} = \frac{\pi \rho_w l d_o^2}{4m} \]  

In the formula, \( \tau_{\text{pipe}} \) is the thermal inertia time of the pipe; \( l \) is the length of the pipe; \( \rho_w \) and \( m \) are the density and flow rate of the heating medium respectively; \( d_o \) is the inner diameter of the pipe.

(2) Energy storage characteristics of heating network
Since the dynamic process of thermal energy transmission has a large time lag, and the hot water heat energy at the inlet and outlet of the pipeline at the same time is inconsistent, the heating network can be regarded as a special energy storage device that can provide energy buffering and delayed response. Therefore, the heat storage of DHN should be the difference between the heating output and the load of the system:

\[ Q_{\text{DHN}}(t) = L_{\text{H}t} - (Q_{\text{CHP}}(t)) + Q_{\text{EB}} + Q_{\text{HS}}(t) \]

In the formula, \( L_{\text{H}t} \) is the heat load of \( t \) period; \( Q_{\text{DHN}} \) is the energy storage power of the heating network. \( Q_{\text{CHP}}, Q_{\text{EB}}, \) and \( Q_{\text{HS}} \) are the heat output power of gas turbine, electric boiler and heat storage in \( t \) period, respectively.

In this paper, the heating pipe network is regarded as a special kind of energy storage, so the temperature range of the supply and return pipes is the adjustable ability of the heating network and can be matched with the thermal inertia of the heating network.

\[ \begin{cases} T_{\text{pipe, sup}}(t) \leq T_{\text{pipe, sup, max}} \\ T_{\text{pipe, back}}(t) \geq T_{\text{pipe, back, min}} \end{cases} \]

In the formula, \( T_{\text{pipe, sup}}(t) \) and \( T_{\text{pipe, back}}(t) \) are the pipe temperature of the water supply and return water respectively; \( T_{\text{pipe, sup, max}} \) is the upper limit of the temperature of the water supply pipe; \( T_{\text{pipe, back, min}} \) is the lower limit of the temperature of the return water pipe.

3. Operational optimization model of integrated energy system considering thermal inertia

3.1. Objective function
This article aims to minimize the cost of integrated energy system scheduling, and establishes a two-stage optimal robust scheduling model of integrated energy system considering thermal inertia. The day-ahead scheduling stage optimizes the start and stop costs of all controllable equipment; the real-time scheduling stage adjusts the output of each equipment in the system based on the actual output of the wind and solar based on the known output of the day-a-day scheduling. The optimization goals are as follows:

\[ C = \min \left\{ f_1 + \max_w \min_y f_2 \right\} \]

In the formula, \( C \) represents the total operation cost of the integrated energy system dispatch; \( f_1 \) is the total start-up and shutdown cost of each equipment; \( f_2 \) is the sum of the integrated energy system energy purchase cost and the wind curtailment cost, and \( x \) corresponds to the controllable equipment (CHP, P2G, electricity Boiler, heat storage and gas storage) start and stop status, \( l \) represents the 0-1 variable of the equipment operating status; \( y \) is the output corresponding to each equipment, represents the equipment (CHP, P2G, electric boiler, heat storage, gas storage, and Heating network
(heat storage) is a continuous variable of output; \( w \) is the actual thermal inertia time of the heating pipeline in the project.

3.2. Restrictions

(1) Power supply balance constraint

\[
L_E(t) = P_{CHP}(t) + P_{wind}(t) - P_{P2G}(t) - P_{EB}(t) + P_{ext}(t) 
\] (7)

In the formula, \( L_E(t) \) is the electric load of \( t \) period; \( P_{CHP}(t) \) is the output electric power of the gas turbine in \( t \) period; \( P_{P2G}(t) \) and \( P_{EB}(t) \) are the electric power of the electric to gas and electric boiler in \( t \) period.

(2) Heat exchange constraints

\[
Q_{CHP}(t) + Q_{EB}(t) = c_{water}m(t)[T_{pipe,up}(t) - T_{pipe,back}(t)] 
\] (8)

In the formula, \( Q_{CHP} \) and \( Q_{EB} \) are the heat supply of the cogeneration unit and the electric boiler; \( T_{pipe,up}(t) \) and \( T_{pipe,back}(t) \) are the temperature of the supply and return water at the heat source, respectively.

(3) Equipment output and climbing constraints

\[
\begin{align*}
P_{i,min} \leq P_i(t) & \leq P_{i,max} \\
-R_i^{down} \Delta t \leq P_i(t) - P_i(t-1) & \leq R_i^{up} \Delta t
\end{align*}
\] (9)

In the formula, \( P_{i,min} \) and \( P_{i,max} \) are the minimum and maximum output of the first device \( i \), \( P(t) \) is the output of the device \( i \) during \( t \) period, \( R_i^{down} \) and \( R_i^{up} \) are the climbing power and landslide power of the device \( i \).

3.3. Model solving

Genetic algorithm is a computational model that simulates the biological evolution process of natural selection and genetic mechanism of Darwin’s biological evolution theory. It is a method of searching for the optimal solution by simulating the process of natural law.

In this paper, a genetic algorithm is used to solve the model, and the process is shown in Figure 2.

![Fig.2 Genetic algorithm flow chart.](image-url)
4. Numerical example simulation

4.1. Basic data

Taking an integrated energy system in a certain area of Northeast China as a simulation example, the specific parameters are shown in Table 1, Table 2, Figure 3 and Figure 4.

Table 1 Heating network pipeline parameters.

| Pipeline | Head end note | End note | Length/km |
|----------|---------------|----------|-----------|
| 1        | N1            | N2       | 2.2       |
| 2        | N2            | N3       | 3.6       |
| 3        | N3            | N4       | 2.5       |

Table 2 Equipment parameters.

| Type   | Power/MW | Adjustment rate/(MW/min) |
|--------|----------|--------------------------|
|        | Lower limit | Upper limit | Lower limit | Upper limit |
| CHP    | 3         | 10          | 0.2         | 0.5         |
| EB     | 0         | 10          | 0.6         | 1           |
| P2G    | 0         | 10          | 0.5         | 1           |
| HS     | 0         | 5           | 0.4         | 1           |
| GS     | 0         | 5           | 0.5         | 1           |

The following two scenarios are used to analyze the dispatch operation of the integrated energy system.

Scenario 1 is the dispatch of the integrated energy system without considering the inertia of the thermal system.

Scenario 2 considers the thermal inertia and heat storage capacity of the heating network to test the operating economy at this time.

4.2. Simulation results

Fig.3 Wind power and multi-energy load forecast.

Fig.4 Price of electric, gas and heat.

Fig.5 The output curve of each device under electrical balance (Scenario 1).

Fig.6 The output curve of each device under heat balance (Scenario 1).
In Scenario 1, the electric boiler and P2G consume this power. Due to the high wind power output and high thermal load, the wind abandonment is serious, as shown in Fig. 5 and Fig. 6. Scenario 2 after considering the thermal inertia, the output of the CHP unit is significantly reduced at night, reducing the wind abandonment phenomenon, as shown in Fig. 7 and Fig. 8.

5. Conclusion

The heat load demand of the heating network is mainly supplied by CHP and electric boilers. At night, the limited capacity of the heat storage device in scene one makes it difficult to reduce the output of the CHP unit. In Scenario 2, thermal inertia is considered. The waste heat generated by CHP is stored in the heating network first, and is released during peak heat load hours to increase the space for wind power grids. The simulation results show that: the coordination and optimization of the thermal inertia and energy storage characteristics of the thermal system is beneficial to reduce the CHP strong electrothermal coupling, and can effectively improve the wind power absorption capacity of the system and improve the flexibility of the integrated energy system.

References

[1] YI Zhongkai, LI Zhimin, Combined Heat and Power Dispatching Strategy Considering Heat Storage Characteristics of Heating Network and Thermal Inertia in Heating Area[J]. Power System Technology. 2018, 42(5):1378-1384.
[2] WANG Mingjun, MU Yunfei, MENG Xianjun, et al. Optimal Scheduling Method for Integrated Electro-thermal Energy System Considering Heat Transmission Dynamic Characteristics[J]. Power. System Technology. 2020, 44(1): 132-142.
[3] LIN Li, GU Jia, WANG Ling. Optimal Dispatching of Combined Heat-power System Considering Characteristics of Thermal Network and Thermal Comfort Elasticity for Wind Power Accommodation[J]. Power System Technology, 2019, 43(10): 3648-3661.
[4] ZHOU Xianzheng, CHEN Wei, GUO Chuangxin. An urban multi-energy system planning method incorporating energy supply reliability and wind-photovoltaic generators uncertainty[J]. Transactions of China Electrotechnical Society, 2019, 34(17): 3672-3686.
[5] JIN Hongyang, TENG Yun, LENG Ouyang, et al. Non-waste urban multi-energy coordinated energy storage model based on source-charge uncertainty state perception [J]. Journal of Electrical Engineering and Technology: 2020, 35(13): 2830-2842.
[6] XU Yeyan, LIAO Qingfen, LIU Dichen. Multi-player Intraday Optimal Dispatch of Integrated Energy System Based on Integrated Demand Response and Games[J]. Power System Technology, 2019, 43(7): 2506-2518.
[7] Nguyen D T, Le L B. Optimal bidding strategy for microgrids considering renewable energy and building thermal dynamics[J]. IEEE Transactions on Smart Grid, 2014, 5(4): 1608-1620.
[8] Liu X, Wu J, Jenkins N, et al. Combined analysis of electricity and heat networks[J]. Applied Energy, 2016, 162: 1238-1250.