Day-ahead optimal scheduling of integrated energy system with electric heat pump

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Abstract. The regional integrated energy system is an effective way to realize energy cascade utilization and improve the flexibility and economy of the load side operation. Combine cooling heating and power (CCHP) system is a typical form of integrated energy systems. However, due to heat-load-based operation mode, the peak modulation capacity of CCHP units and the accommodation of renewable energy are limited. This paper explores methods of increasing the flexibility and economy of the system. An optimal scheduling model is proposed for integrated energy systems containing an electric heat pump, considering heating network characteristics. Simulation results show that the electric heat pump can help the system realize heat-and-power decoupling, improve the flexibility of the system and reduce the operating cost of the system.

1. Introduction

In China, the CCHP technology is developing rapidly. As the heating demand and integration of wind power grows, the flexibility and economy of the CCHP system should be focused [1]. The development of the park-level CCHP system is strongly supported by the government. Many integrated energy systems (IES) entities have been built and put into use, such as the demonstration project of CCHP system sitting in the ZOL Software Park Software Plaza. However, CCHP units usually operate in heat-load-based mode so as to give priority to the heating load. The electric power output is forced to be at a high level to follow the heating power output. As a consequence, the range of electric power output is narrowed and the peak modulation capacity of CCHP units is restricted. Therefore, research on improving flexibility and economy of CCHP system is urgently needed to make up for the current shortcomings.

Many scholars have proposed to improve the flexibility and economy of CCHP system by installing electric boilers or heat storage tanks for IES. In [2-3], electric heating boilers and heat storage tanks are used to improve the flexibility of the cogeneration system and promote wind power accommodation. However, the investment cost of the heat storage tanks is too high and the heat storage effect is not quite satisfied. The price of electric boilers is lower, but the heat loss is much larger than that of heat pumps [4].

Some studies have proposed to establish an operational model of CCHP system considering the heat storage characteristics of buildings and heating pipelines. In [5-8], a heat storage model of buildings is established considering the performance of radiators and the consumption of buildings to transfer the...
heat load to other periods. Although it doesn’t require additional investment, its ability of adjusting is limited. Compared with electric boilers, electric heat pumps (EHP) are much more energy-efficient. Therefore, the application of EHP in CCHP system is promising. At present, the research on the optimal scheduling of the CCHP system containing an electric heat pump is rarely.

This paper is organized as follows. The second section introduces the structure of the CCHP system containing an EHP and establishes the day-ahead optimal scheduling model. In section three, test case of integrated system is presented and the simulation results are analyzed. Section four is the conclusion of the work.

2. Day-ahead optimal scheduling model

2.1. Modeling of coupling units

2.1.1. Gas turbine (GT). The GT mathematical model is shown equation (1).

\[
\begin{align*}
    \dot{P}_{GT} &= V_{HG} \cdot q_{HG} \cdot \eta_{GT} \\
    \dot{Q}_{GT}^w + \dot{Q}_{GT}^s &= V_{HG} \cdot q_{HG} \cdot (1 - \eta_{GT} \cdot (1 - \eta_{GT}^s)) \\
    \eta_{GT}^s &= \frac{\dot{Q}_{GT}^s}{\dot{Q}_{GT}} \\
    \eta_{GT}^w &= \frac{\dot{Q}_{GT}^w}{\dot{P}_{GT}}
\end{align*}
\]  

(1)

where \( \dot{P}_{GT} \), \( \dot{Q}_{GT}^s \), and \( \dot{Q}_{GT}^w \) represent the electric power output, steam heat power output and hot water heat power output, respectively. \( V_{HG} \) and \( q_{HG} \) represent the nature gas consumption and the unit calorific value of natural gas, respectively. \( \eta_{GT} \), \( \eta_{GT}^s \), and \( \eta_{GT}^w \) represent power generation efficiency, energy loss rate, steam thermoelectric ratio, and hot water thermoelectric ratio, respectively.

2.1.2. Gas boiler (GB). The GB mathematical model is shown in equation (2).

\[
\begin{align*}
    \dot{Q}_{GB}^s + \dot{Q}_{GB}^w &= V_{HG} \cdot q_{HG} \cdot \eta_{GB} \\
    \eta_{GB}^{sw} &= \frac{\dot{Q}_{GB}^s}{\dot{Q}_{GB}^w}
\end{align*}
\]  

(2)

where \( \dot{Q}_{GB}^s \) is the steam heat power output, \( \dot{Q}_{GB}^w \) is the hot water output, \( \eta_{GB} \) is the steam heat power generation efficiency, and \( \eta_{GB}^{sw} \) is the steam-water ratio.

2.1.3 Heat recovery boiler (HRB). The HRB mathematical model is shown in equation (3).

\[
\dot{Q}_{WH}^{out} = \dot{Q}_{WH}^{in} \cdot \eta_{WH}
\]  

(3)

where \( \dot{Q}_{WH}^{in} \) and \( \dot{Q}_{WH}^{out} \) represent the steam heat power input and output, respectively, \( \eta_{WH} \) is the energy conversion coefficient.

2.1.4. Electric refrigerator (ER). The ER mathematical model is shown in equation (4).

\[
\dot{C}_{EC} = \dot{P}_{EC} \cdot COP_{EC}
\]  

(4)

where \( \dot{P}_{EC} \) and \( C_{EC} \) represent the electric power input and the cooling power output, \( COP_{EC} \) is the cooling coefficient.

2.1.5. Steam operated absorption refrigerator (SOAR). A steam operated absorption refrigerator is used in the integrated system, and its mathematical model is shown in equation (5).

\[
\dot{C}_{CHIC}^{out} = \dot{Q}_{CHIC}^{in} \cdot COP_{CHIC}
\]  

(5)
where \( Q_{\text{CH}}^\text{in} \) and \( Q_{\text{CH}}^\text{out} \) represent the heating power input and the cooling power output, \( \text{COP}_{\text{CH/C}} \) is the cooling coefficient.

### 2.1.6. Electric heat pump (EHP).

\[
C_{\text{HP}}^\text{out} = P_{\text{HP}} \cdot \text{COP}_{\text{HP}}
\]

where \( C_{\text{HP}}^\text{out} \) and \( P_{\text{HP}} \) represent the electric power input and the heating power output, \( \text{COP}_{\text{HP}} \) is the heating coefficient.

### 2.2. Modeling of EH

The EH connects the energy input and output through the coupling matrix, which embodies the energy coupling relationship between the subsystems. The output matrix, the coupling matrix and the input matrix respectively correspond to the energy consuming unit, the coupling unit and the energy supply unit mentioned above. Based on the modeling of each unit equipment, this paper uses the concept of EH to model the IES [9]. The common mathematical expression of EH is shown in the figure 1.

![Figure 1. Mathematical model of energy hub.](image)

The mathematical expression of EH can also be formatted as:

\[
L = CP
\]

where \( L \) and \( P \) respectively represent the output and output matrix of the energy hub, \( C \) is the coupling matrix. The equation (7) reflects the energy conversion relationship between the units in IES, and \( C \) can be determined therefrom.

### 2.3. Modeling of heating network transmission delay and temperature loss

According to [8], there is a significant difference in the transmission delay and energy transmission loss between the heating system and the electric power system. The transmission loss will increase the total demand of the system thermal power, and the transmission delay will cause the supply and demand out of sync, so that the optimal scheduling results of the entire system will also be affected. The transmission medium of the heating network is usually hot water or steam. The heating network is regulated by quality regulation method considering hydraulic conditions. The time delay caused by media transfer will contribute to a time delay in the transmission of heat power.

In the park-level integrated system, the distance between the heat sources and the heat load is not far, so the transient process of heat medium changing is very short. For the day-ahead optimal scheduling model, the scheduling period is one hour. It can be interpreted that the temperature of the medium has reached a fixed value and keep stable after one adjustment and before the next scheduling [8]. Supposing the heat power of the medium only radiated to the outside through the pipeline, the temperature from the heat source \( x \) at time \( t \) is shown in equation (8).

\[
T_{i}(x,t) = \left\{ \begin{array}{ll}
\left( T_{i0} - T_{i0}\right) \exp \left(-\frac{x}{Rc_{i}f}\right) t + T_{i0} \exp \left(-\frac{x}{Rc_{i}f}\right) \left[ 1 - \exp \left(-\frac{x}{Rc_{i}f}\right) \right] & \text{if } t \in \left[ 0, \pi d_{i}^{2}x/ l(4f) \right] \\
T_{i0} \exp \left(-\frac{x}{Rc_{i}f}\right) + \left[ 1 - \exp \left(-\frac{x}{Rc_{i}f}\right) \right] & \text{if } t \in \left[ \pi d_{i}^{2}x/ l(4f), +\infty \right]
\end{array} \right.
\]

(8)
where \( T_{s0}^t \) and \( T_{s0}^{t-1} \) respectively represent the temperature of the heating source at time \( t \) and \( t_{t-1} \). \( R \) is the equivalent thermal resistance, \( c \) is the specific heat capacity, \( \rho \) is hot water density, \( \Delta t \) is the scheduling period, \( T_r \) and \( T_b \) respectively represent the backwater temperature and ambient temperature. Considering the characteristics analyzed above, the power requirements at the heat source can be derived and calculated according to [8].

2.4. Day-ahead optimal scheduling model

2.4.1. Objective function. This paper focuses on the operational cost of systems, regardless of the cost of equipment investment, maintenance or overhaul. The objective function is to minimize operating costs, which include the cost of purchasing electricity from the grid and the cost of purchasing natural gas.

\[
\min C = C_e + C_g
\]

\[
C_e = \sum_{i=1}^{n} c_i P_{eG}^i \Delta t
\]

\[
C_g = c_i \sum_{i=1}^{n} \left( P_{eU}^i + P_{eCHC}^i + P_{eGB}^i \right) \Delta t
\]

where \( n \) is the number of the total scheduling period, \( i \) represent the ith period, \( C_e \) is the cost of purchasing electric power from the grid, \( C_g \) is the cost of the natural gas consumed.

2.4.2. Constraints on the CCHP units.

\[
\begin{align*}
P_{GT}^{\min} & \leq P_{GT} \leq P_{GT}^{\max} \\
Q_{GB}^{\min} & \leq Q_{GB} \leq Q_{GB}^{\max} \\
Q_{WH}^{\min} & \leq Q_{WH} \leq Q_{WH}^{\max} \\
C_{EC}^{\min} & \leq C_{EC} \leq C_{EC}^{\max}
\end{align*}
\]

where subscript min and subscript max respectively represent the upper and lower limit of the output power, the constraints on the GT, GB, HRB, ER, SOAR, EHP, PV are represented in equation (11).

2.4.3. Constraints on ramping power.

\[
\begin{align*}
-P_{GT}^{\downarrow} & \leq P_{GT} - P_{GT}^{\uparrow} \leq P_{GT}^{\uparrow} \\
-Q_{GB}^{\downarrow} & \leq Q_{GB} - Q_{GB}^{\uparrow} \leq Q_{GB}^{\uparrow}
\end{align*}
\]

2.4.4. Constraints on battery operation.

\[
\begin{align*}
P_{ES,C}^{\min} & \leq P_{ES,C} \leq P_{ES,C}^{\max} \\
P_{ES,D}^{\min} & \leq P_{ES,D} \leq P_{ES,D}^{\max}
\end{align*}
\]

\[
E_{\min} \leq E_e \leq E_{\max}
\]

\[
E(t+1) = (1 - \sigma) E(t) + \left( P_e \eta_c - P_d \eta_d \right) \Delta t
\]

\[
X(1,t) \leq X(2,t) \leq 1
\]

The constraints on battery charging/discharging is shown in equation (13). The equation (14) represents the constraints on the battery state. The battery mechanism constrains is shown in the
equation (15), where \( \eta_C \) and \( \eta_D \) respectively represented the charging/discharging efficiency. \( X(1, t) \) and \( X(2, t) \) shown in the equation (16) are all 0-1 variables, equation (16) represent the constraint that the battery can’t be charged or discharged at the same time.

2.4.5. Power balance. The input and output power of cold, heat, and electricity should meet the balance.

3. Case study

3.1. Test system and scenarios

The test system proposed in this paper is presented in figure 2 and the simulation data used are presented in figure 3 according to [8, 10, 11]. In order to verify the effect of the EHP on improving the flexibility and economy of IES, this paper sets up two scenarios for comparative analysis. Scenarios 1: The system does not install an EHP; Scenarios 2: The system contains an EHP. The optimized scheduling results in the two cases were compared and analyzed, and the results are as follows.

![Figure 2. Modified test system (CCHP system containing an EHP).](image)

![Figure 3. Predicted curves of system load and time of use electricity price.](image)

3.2. Results

3.2.1. Operating cost. The optimized cost of the system operation in different scenarios is shown in table 1. The minimum operating cost of Scenario 1 is 40556.8 yuan, and the minimum operating cost of Scenario 2 is 34670.1 yuan. It can be seen that the operating cost of the system is greatly reduced due to the EHP.

| Scenario | Electric Heat Pump installed or not | Operation cost (RMB) |
|----------|-----------------------------------|----------------------|
| 1        | No                                | 40556.8              |
| 2        | Yes                               | 34670.1              |

3.2.2. Hourly power balance. The hourly power output of each unit for the two scenarios is shown in figure 4 to figure 11. Figure 3 shows that the heat load is at the peak during the period 9 to 19. In Scenario 1, the hot water power is provided by a gas boiler, a gas turbine, and a heat exchanger. In Scenario 2, the hot water power is provided by a gas boiler, a gas turbine, a heat exchanger, and an electric heat pump. It can be seen from figure 6 and figure 10 that the output of the gas boiler is greatly reduced during period 9 to 19. In the heat-load-based operation mode, when the heat load is large, the
electric power output by CCHP unit will be excessive. However, the EHP can help solve this problem by converting electric power into heating power, so that the system will achieve heat-and-power decoupling. What’s more, as shown in figure 7 and figure 11, during period 9 to 19, the heat power generated by GT is greatly reduced. This also illustrates that the EHP has helped the system achieve heat-and-power decoupling and has improved the flexibility of the CCHP system.

**Figure 4.** Optimal scheduling of Electric power without electric heat pump.

**Figure 5.** Optimal scheduling of cooling power without electric heat pump.

**Figure 6.** Optimal scheduling of hot water power without electric heat pump.

**Figure 7.** Optimal scheduling of steam power without electric heat pump.

**Figure 8.** Optimal scheduling of Electric power with electric heat pump.

**Figure 9.** Optimal scheduling of cooling power with electric heat pump.
Figure 10. Optimal scheduling of hot water power with electric heat pump.

Figure 11. Optimal scheduling of steam power with electric heat pump.

4. Conclusion
A day-ahead optimal scheduling model for a CCHP system containing an EHP is proposed in this paper, and the effect of EHP is analyzed. The simulation results show that the EHP can effectively help the system realize “heat-and-power decoupling” by converting excess electric power into heating power, and improve the flexibility of CCHP system. The installation of the EHP greatly reduces the daily operating cost as well. It is verified that the EHP can improve the flexibility and economy of CCHP systems. In future work, wind power prediction will be considered to reduce wind power curtailment. Besides, the prediction of cold, heat and electric load will be attached importance to improve the robustness of the system.

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