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A COMBINED HEAT AND POWER SYSTEM OPERATION MODEL CONSIDERING THE DIFFERENT THERMAL CHARACTERISTICS OF BUILDINGS

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ABSTRACT

The thermal inertia of the district heating system (DHS), which are natural and great heat storages, have been considered in the combined heat and power (CHP) system operation to reduce wind curtailments. In this paper, according to the different thermal characteristics of public and residential buildings, a CHP system optimal operation model considering the thermal inertia of DHS and adopting a centralized control with flow varied by steps mode in DHS operation is proposed. Case study shows that the proposed model has much better performance in economic benefits and wind power integration.

Keywords: wind power integration, thermal inertia, DHS, operational mode

NONMENCLATURE

Indices and parameters	
Γ	Set of indices of scheduling periods
Γ_1 / Γ_2	Heating and non-heating periods for PB
$S_o^{pipe+} / S_o^{pipe-}$	Set of pipes entering/leaving node *o*
ρ_w	Density of heat water (kg/m^3)
c_w	Specific heat of water (J/ (kg ℃))
L/R	The length / radius of pipelines (m)
T_{soil}	The temperature of soil (℃)
$A_{b,j}$	Heat transfer coefficient of building *j* (MW/℃)
$T_{bs,j}$	Equivalent heat storage time coefficient
ψ	The price of the standard coal ($/t)
δ	The penalty coefficient ($/MWH)
Δt	Dispatch period (15min)
$c_{v2,i} / c_{m,i}$	Coefficient of the CHP unit *i*
$P_{chp,i}^{max} / P_{chp,i}^{min}$	Maximum/minimum power output of CHP unit *i* （MW）
Variables	
C_{total}	Daily operating cost of CHP system ($)
C_{chp} / C_{cg}	Cost of CHP/conventional unit ($)
C_{wp}	Penalty cost of wind power curtailment($)
$M_{n,t}$	Mass flow rate of pipe *j* at time *t* (kg/s)
λ_n	Heat transfer coefficient of pipe(W/m ℃)
$P_{chp,i,t}$	Electricity output of CHP unit *i* at time *t*
$H_{chp,i,t}$	Heat output of CHP unit *i* at time *t*(MW)
$P_{wp,i,t}$	Electricity output of wind *i* at time *t*(MW)
$T_{n,t}^{s} / T_{n,t}^{r}$	Temperature of the *n*th supply/return pipe at time *t*(℃)
$T_{n,t}^{in} / T_{n,t}^{out}$	Temperature at the inlet/outlet of the *n*th pipe at time *t*(℃)
τ_n	The time delay of the *n*th pipe
$T_{j,t}^{in} / T_{j,t}^{out}$	Indoor/outdoor temperature of building *j* at time *t*(℃)

1. INTRODUCTION

With the aggravation of global energy and environmental problems, wind energy as a kind of clean energy has a broad development prospect. By the end of 2018, the cumulative installed capacity of wind power connected to the grid in China has reached 180 million KW, accounting for 9.7% of the total generator capacity [1]. With the increasing proportion of wind power in energy supply, the problem of wind power consumption is becoming more and more prominent, especially in the winter heating period in the northern China, the phenomenon of abandoning wind and limiting electricity is very serious. It has become the main contradiction restricting the sustainable development of wind power in China. The main reason for the reduction of wind power in northern China is that CHP units are mainly used as heat source during heating period. CHP operates according to the heat-led mode. Wind power utilization is limited by the operational flexibility of CHP units under the traditional operation mode.

Therefore, improving the operation flexibility of CHP units can effectively promote the wind power integration. Many scholars have done a lot of research on this and proposed a variety of decoupling methods, including the installation of electric boiler, electric heat pump, heat storage tanks and other devices in the CHP system to improve the operation flexibility of CHP units to reduce the phenomenon of wind power curtailment [2-4] .However, these methods require a large amount of equipment investments, and need to take into account the economy and practicality.

Meanwhile, an increasing number of researchers begin to pay attention to how to make use of the thermal dynamic characteristics of the district heating networks (DHN) and buildings to promote wind power integration. Yang et al. considered the thermal inertia of the building and the thermal comfort of thermal users, used the flexibility of heating to combine more wind power generation with electricity demand [5] .Li et al. proposed an CHP dispatch model that considered pipe network as an energy storage device to promote wind power integration, and the dynamic characteristics of temperature and heat transfer of pipe network are explored [6]. Dai et al. explored the heat transfer process of pipe network in detail and proposed a detailed model for these three components, namely DHN, building envelopes, and Thermal Energy Storage devices [7] .

The above research on improving the flexibility of CHP units focuses on the constraints related to the power system and the thermal inertia constraints of DHS. Few studies have compared the operation regulation modes of a DHS on a CHP system for wind power integration. The traditional operational of the DHS adopts the quality regulation. There are several operational modes in the DHS by changing mass flow or temperature of hot water in the DHN.

Based on the thermal inertia of the DHS, this paper further analyzes the influence of DHS operational mode and the difference of building heat demand on the CHP system. In this paper, the operation regulation of a DHS is the centralized control with flow varied by steps. The advantage of the proposed model is that flexibility of power system could be significantly improved, and along with the promotion of wind power integration, meanwhile, the operational cost could be significantly reduced.

2. MAIN IDEA OF THE PROPOSED MODEL

2.1 Basic principles

The climate in the Northern China is cold in winter, and the outdoor temperature is even lower during the period of high incidence of wind power curtailment at night. Even after considering the thermal inertia of the DHS in the CHP system, during the night of winter, with high heat load, the heat output of CHP increased a lot, as well as the electric output.

The key to solve this problem is how to reduce the heat output of CHP units at night in cold heating areas. In the CHP system, heating for buildings is the main heat load in winter. On the one hand, considering that the heat demand of different buildings varies greatly in different periods of time, and Public Buildings (PB) do not need to use heat at night, we can reduce the night heat supply of PB. On the other hand, the quality regulation for continuous heating of buildings can not give full play to the characteristics of PB. The centralized control with flow varied by steps provides a method for reducing the heat load at night. This method is stable, safe, and more energy saving. It is very suitable for reducing night heat load of heating system and plays a role in reducing the peak heat load at night.

2.2 Operational mode of the DHS

The operational mode of the DHS adopts centralized control with flow varied by steps. The heating process of the day is usually divided into two stages. During the daytime working hours, the mass flow rate of the DHS is equal to the design flow rate(100%M);during the off-duty period at night, the mass flow rate of the DHS maintains a small flow rate(usually 60%M).At each stage, the mass flow rate remains constant. In terms of centralized control with flow varied by steps, the heat demand of PB in one heat load node of DHS could be adjusted by the variable mass flow rates during one period without changing mass flow rates in other heat load nodes of Residential Buildings (RB).

3. MODELING THE DHS

3.1 Model structure

A typical DHS consists of the heat source, heating network, substation and heat loads(usually RB and PB), as shown in Fig 1.the thermal energy generated by the heat source CHP unit is transferred from the primary network, the heat exchange station and the secondary network to heat loads by means of water.

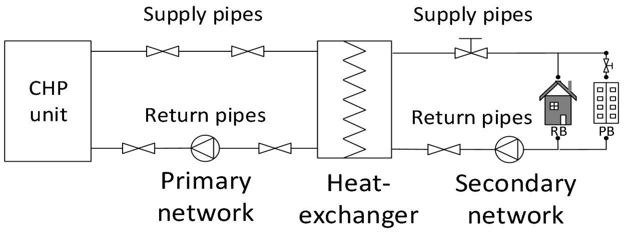

Fig. 1 Schematic diagram of the DHS

3.2 Heat source

The operational feasible region of extraction-condensing units can be illustrated in polyhedrons. The electric and heat power output range of CHP units can be expressed as follows:

$$\begin{cases} P_{chp,i,t} \geq \max\{P_{chp,i}^{\min} - c_{v2,i} H_{chp,i,t}, \varphi_i + c_{m,i} H_{chp,i,t}\} \\ P_{chp,i,t} \leq P_{chp,i}^{\max} - c_{v1,i} H_{chp,i,t} \end{cases} \tag{1}$$

$$0 \leq H_{chp,i,t} \leq H_{chp,t}^{\max} \tag{2}$$

The heat power output of the CHP unit is used to heat the water of the TPHS.

$$H_{chp,i,t} = c_w M_{n,t} (T_{n,t}^s - T_{n,t}^r) \tag{3}$$

In order to ensure the heating quality, the water supply temperature of the heat source needs to be satisfied a certain range.

$$T^{s,\min} \leq T_{n,t}^s \leq T^{s,\max} \tag{4}$$

3.3 Heating network

A heating network contains several nodes and pipe sections, the node part describes the flow balance and energy conservation of the pipe network, and the pipe section describes the thermal dynamic characteristics of the pipe network.

3.3.1 The heat balance for node

The heat energy flowing into one node is equal to the heat energy flowing out. the heat balance for node can be formulated as Eqs. (5) and (6).

$$\sum_{n \in S_o^{pipe-}} T_{n,t}^{out} M_{n,t} = T_{mix,t}^o \sum_{m \in S_o^{pipe+}} M_{m,t} \tag{5}$$

$$T_{m,t}^{in} = T_{mix,t}^o \tag{6}$$

3.3.2 Pipe

Because the primary pipe network is much longer than the secondary pipe network, the heat transfer characteristics of primary pipe network are studied in this paper. According to Sukhov's temperature drop formula, the thermal characteristics of heating pipes are mainly manifested in temperature loss and transmission delay, as written in Eq. (7).

$$\begin{cases} T_{n,t+\tau_n}^{out} = (T_{n,t}^{in} - T_{soil}) e^{-\frac{\lambda_n L_n}{c_w M_{n,t}}} + T_{soil} \\ \varphi_n = \begin{cases} \dfrac{\pi R_n^2 \rho_w L_n}{M_{n,t}^1} & t \in \Gamma 1 \\ \dfrac{\pi R_n^2 \rho_w L_n}{M_{n,t}^2} & t \in \Gamma 2 \end{cases} \\ \tau_n = round(\dfrac{\varphi_n}{\Delta t}) \end{cases} \tag{7}$$

3.4 Heat exchanger

The *heat* exchanger is connected with the primary pipe network and the secondary pipe network. The heat balance of the heat exchanger can be expressed as

$$H_{n_1,t}^{s,out} - H_{n_2,t}^{r,in} = (H_{n_3,t}^{s,in} - H_{n_4,t}^{r,out}) / \eta_{ex,f} \tag{8}$$

3.5 Buildings

Heating for residential and public buildings is the main thermal load in winter, usually accounting for 80%-90% of the total heat load. Heating load are expressed by (9).

$$H_{b,j,t} = c_w M_{b,t} (T_{n_1,t}^s - T_{n_2,t}^r) \tag{9}$$

The thermal dynamics of a building is considered in this work. Due to the adoption of the TPHS, it is necessary to discuss the changes of indoor temperature in residential buildings and public buildings.

(1) Residential buildings

The indoor temperature at time step *t* can be expressed as:

$$T_{j,t+1}^{in} = (T_{j,t+1}^{out} + \frac{H_{b,j,t}}{A_{b,j}}) \cdot (1 - \exp(-\frac{\Delta t}{T_{bs,j}})) + T_{j,t}^{in} \cdot \exp(-\frac{\Delta t}{T_{bs,j}}) \tag{10}$$

In order to ensure the comfort and quality of heating, the indoor temperature of continuous heating is within a certain range.

$$T_{in}^{\min} \le T_{j,t}^{in} \le T_{in}^{\max} \tag{11}$$

(2) Public buildings

The variation law of indoor temperature in public buildings is as follows:

$$T_{j,t+1}^{in} = \begin{cases} (T_{j,t+1}^{out} + \frac{H_{b,j,t}}{A_{b,j}}) \cdot (1 - \exp(-\frac{\Delta t}{T_{bs,j}})) + T_{j,t}^{in} \cdot \exp(-\frac{\Delta t}{T_{bs,j}}) & t \in \Gamma_1 \\ T_{j,t+1}^{out} \cdot (1 - \exp(-\frac{\Delta t}{T_{bs,j}})) + T_{j,t}^{in} \cdot \exp(-\frac{\Delta t}{T_{bs,j}}) & t \in \Gamma_2 \end{cases} \tag{12}$$

The variation range of indoor temperature of the buildings is represented as:

$$\begin{cases} T_{in}^{\min} \le T_{j,t}^{in} \le T_{in}^{\max} & t \in \Gamma_1 \\ T_{in}^{end,\min} \le T_{j,t}^{in} \le T_{in}^{\max} & t \in \Gamma_2 \end{cases} \tag{13}$$

Based on the improved the operation regulation mode of a DHS, the mode of the TPHS was first completely proposed.

4. OPTIMIZATION MODEL OF THE COMBINED HEAT AND POWER SYSTEM

4.1 Decision Variables

In the ICHPS model, the electricity decision variables include the electricity generation of CHP units($P_{chp,i,t}$) and wind farms ($P_{wp,i,t}$). The heat decision variables include the heat generation of CHP units($H_{chp,i,t}$),mass flow rate of pipelines ($M_{n,t}$), heat power supplied by pipelines to buildings ($H_{b,i,t}$) and indoor temperature of buildings ($T_{\mathrm{i},t}^{in}$).

4.2 Objective function

The objective is to minimize the daily operating cost of the CHP system, which includes the operation cost of thermal power units and the penalty cost of wind power curtailment.

$$\min C_{total} = \sum_{t=1}^{\Gamma} (C_{chp} + C_{cg} + C_{wp}) \tag{14}$$

$$\begin{cases} C_{chp,t} = \sum \begin{bmatrix} (a_{chp,i}(P_{chp,i,t} + c_{v1,i}H_{chp,i,t})^2 + \\ b_{chp,i}(P_{chp,i,t} + c_{v1,i}H_{chp,i,t}) + c_{chpi}) \cdot \psi \end{bmatrix} \\ C_{cg,t} = \sum \left[(a_{cg,i}P_{cg,i,t}{}^2 + b_{cg,i}P_{chp,i,t} + c_{cg,i}) \cdot \psi \right] \\ C_{wp,t} = \sum \left[(P_{wp,i,t}^{\max} - P_{wp,i,t}) \cdot \delta_i \right] \end{cases} \tag{15}$$

4.3 constraints

4.3.1 *Electric power system constraints*

(1) Power balance constraints

The total generation and demand of electricity are balanced at each period:

$$\sum P_{chp,i,t} + \sum P_{cg,i,t} + \sum P_{wp,i,t} = \sum P_{load,j,t} \tag{16}$$

(2) Constraints of CHP units

The Constraints of CHP units are defined in Eqs.(1) – (4).

(3) Constraints of conventional units

Generation output of conventional units and its ramping capability.

$$\begin{cases} P_{cg,i}^{\min} \le P_{cg,i,t} \le P_{cg,i}^{\max} \\ \left| P_{cg,i,t+1} - P_{cg,i,t} \right| \le \Delta P_{cg.i} \Delta t \end{cases} \quad \forall t \in \Gamma \tag{17}$$

4.3.2 *DHS constraints*

The Constraints of the DHS are defined in Eqs. (1) –(13).

5. CASE STUDY

5.1 System description

A case study was carried out in CPLEX 12.6.1 to demonstrate the proposed method. Fig 4 shows the configuration of the studied improved combined heat and power system. The EPS was composed of six buses with two CHP units, two conventional units and one wind farm. The TPHS consists of 6 buildings (including two PB and four RB), and was operated with the modes of centralized control with flow varied by steps. The test data came from [8], including parameters of CHP units and conventional units, parameters of heating networks and buildings. The forecasts of electric load, available wind power and outdoor temperature were shown in Fig.5 and 6.

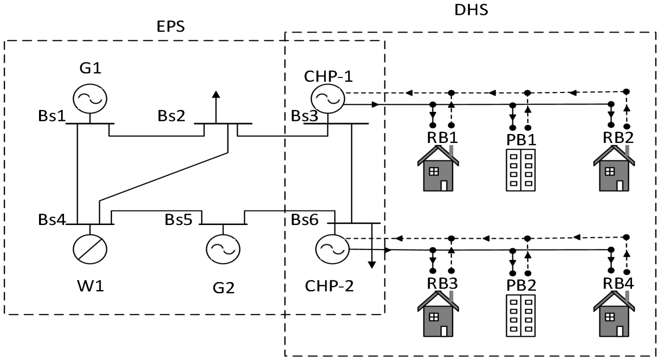

Fig .2 Combined heat and power system

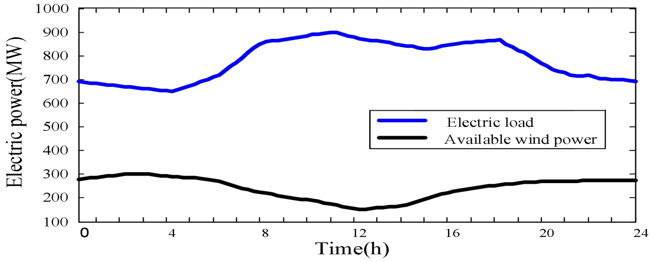

Fig .3 Forecasts of electric load ,available wind power

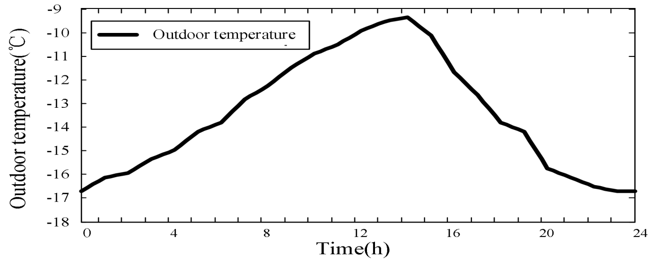

Fig .4 Outdoor temperature

5.2 Scenario settings

To demonstrate the influence of thermal inertia and operation regulation mode of DHS, on the joint operation of heat and power, three cases are stimulated. *Scenario* 1 is an ordinary *scenario* without considering the dynamic characteristics of the DHS. *Scenario* 2 considers thermal inertia of DHS, but the operation regulation mode of DHS is variable temperature control. *Scenario 3* is the proposed model.

5.3 Result analysis

5.3.1 Comparison of Scenario 1 and Scenario 2

*C*ompared with scenario 1 and *scenario* 2, the influence of thermal dynamic characteristics of the DHS on the operation results of the CHP system is analyzed. The integration wind power, power output of the CHP1 unit were shown in Figs.5-6.Because the power output trend of CHP1 unit and CHP2 unit is basically the same, the CHP1 unit is analyzed here.

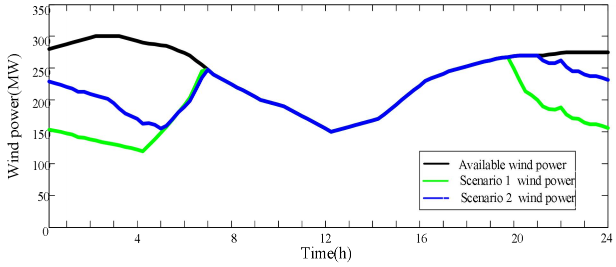

Fig. 5 Wind power curve

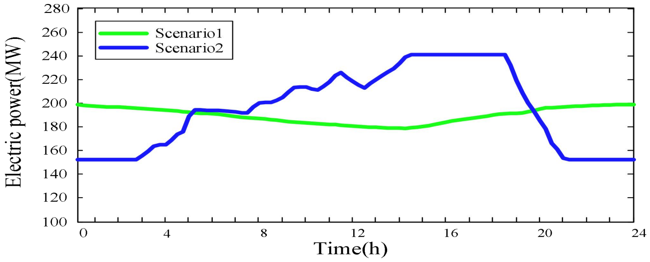

Fig. 6 Power outputs of CHP1 unit

As shown in Fig.5, in scenario 1, the period of wind power curtailment is concentrated during 19:00-24:00 and 00:00-07:00, which is due to the decrease of outdoor temperature at night and in order to ensure the heating quality, CHP units have to increase the heat output at night, then The electric power output of CHP units increases with the increase of the heat power output during this period because of the coupling characteristics of itself. The increase of electric output of CHP units affects the grid space of wind power, and finally leads to the generation of a large number of wind power curtailment.

Compared with scenario 1, the abandoned wind power in scenario 2 decreased from 1277.2MWh to 651.7MWh, which decreased by 48.98%, and the wind power integration in scenario 2 increased by 625.5MWh. During the period of low wind power generation, the heat output of CHP units increases, which meets the demand of heat load and stores the surplus heat in the heating network and buildings. During the period of high wind power generation, the heat network and buildings release the stored heat to meet the demand of heat load, reduce the thermal output and electric output of CHP units, and thus absorb more wind power.

5.3.2 Comparison of Scenario 2 and Scenario 3

Compared with scenario 2 and scenario 3, the influence of operation regulation mode of the DHS on the operation results of the CHP system is analyzed. The integration wind power, power output of the CHP1 unit were shown in Figs.7-8.

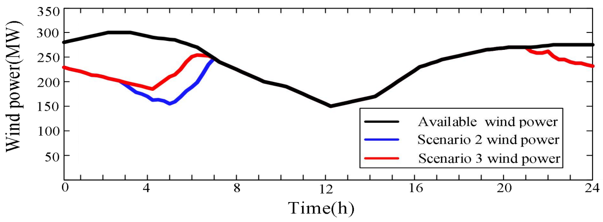

Fig. 7 Wind power curve

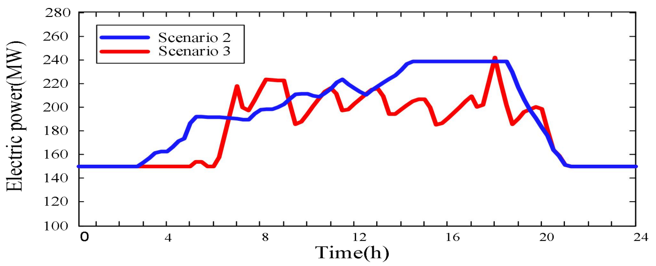

Fig. 8 Power outputs of CHP1 unit

As shown in Fig.7, compared with scenario 2, after the time-sharing and partitions heating of buildings by means of centralized control with flow varied by steps, the abandoned wind power in scenario 3 is further reduced from 651.7MWh to 500.8MWh, which decreased by 23.1%, and the wind power integration in scenario 3 increased by 150.9MWh. During the period of large wind power generation at night (21:00-24:00 and 00:00-06:00), the heat demand of the heat load decreases, so that CHP units can maintain the minimum technical output at night, which improves the regulation range of CHP units, and greatly increases the space of wind power grid. During the daytime (07:00-21:00), due to the heat demand of the TPHS at night is less than that that of the DHS, the heat output of the CHP units is slightly lower than that of scenario 2, so that the thermal inertia of heating system can be more flexible.

5.3.3 Economic and abandonment wind rate

Table 1 compare the daily operation cost and abandonment wind rate under 3 scenarios. Table 1 shows that scenario 3 is more economic than scenario 1 and scenario 2 in the CHP system, which is 19.2% less than scenario 1 and 11.3% less than scenario 2 in operation costs. The absorption of abandoned wind in scenario 3 is more obvious than that in scenario 1 and 2, which is 13.9% less than scenario 1 and 3% less than scenario 2 in terms of abandonment wind rate. Scenario 3 was recommended to be applied in the improved CHP system for wind power integration in terms of its feasibility, operation cost and energy saving.

Table 1

Operation cost abandonment wind rate

Scenario	Abandonment wind rate (%)	Operation cost($/d)
1	22.1	620564
2	11.2	564608
3	8.2	500812

6. CONCLUSION

In this paper, a CHP system optimal operation model considering the thermal inertia of DHS and adopting a centralized control with flow varied by steps mode in DHS operation is proposed. The different thermal characteristics of public and residential buildings are considered in this model, make the model more practical and operational. Case study based on 6-bus and 20-pipeline system indicated that the proposed model can reduce the total cost of generation and improve wind power integration. These conclusions can provide theoretical reference and support for energy suppliers to make the day-ahead dispatching plan.

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