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OPTIMAL DISPATCH OF COMBINED HEAT AND POWER SYSTEM WITH DISTRIBUTED HEAT PUMPS

Chen Cheng[1], Ye Zhihao[2*], Xia Yihui[1], Yu Yanjuan[1]

1 School of Electrical Engineering, Naval University of Engineering, China

2 School of Electrical Engineering, Naval University of Engineering, China (Corresponding Author)

ABSTRACT

Utilizing heat pumps (HPs) is recognized as a promising approach to promote the flexibility of the combined heat and power (CHP) units for better wind power integration in the combined heat and power system (CHPS). This paper investigates the coordinated operation of the CHP units with the HPs which are distributed at heat exchange stations (HES). We propose the method for controlling the on-off status and running power of the HPs considering the thermal inertia of the district heating system (DHS). Finally, the optimal dispatch model of the CHPS is established. The effectiveness of the distributed HPs on reducing wind power curtailment is verified with numerical studies.

Keywords: combined heat and power, heat pump, wind power integration

NONMENCLATURE

Symbols	
S, R; Nt	Supply, return pipe; Total scheduling time interval
ρ^w, c^w	Density, specific heat capacity of water
l_n^S, A_n^S, G_n^S, λ^S	Length, sectional area, mass flow rate, average loss coefficient of the *n*th pipe
T_1^S	Supply water temperature at CHP side
h_m	Heat load at the *m*th heat station
$x_{i,k}$, $q_{i,k}$, $p_{i,k}$	Combination coefficient, heat power, electric power of the *k*th corner point in the operation region of the *i*th CHP
Q_t^{HP}, P_t^{HP}, P_{cap}^{HP}, β^{HP}	Heat power, electric power, capacity, average energy efficiency of the HP
P_t^E, P_t^H	Power load, heat load at time *t*
$P_{gen,t}^W$, $P_{int,t}^W$	Generated, integrated wind power
$P_{min,j}^{CON}$, P_{min}^{OTH}	Minimum power of CON, OTH units
ΔQ_t^{CHP}	Reduced thermal power of CHP units
C_{pen}^W, ε^W	Penalty term, penalty cost coefficient of curtailed wind power
T_{max}^S	Maximum supply water temperature

1. INTRODUCTION

The serious problem of wind power curtailment is in urgent need to be solved in Northern China where the wind farms take quite a large percentage of the national total installed wind capacity [1]. The combined heat and power (CHP) units, as the leading power supply source of Northern China, are not able to provide enough flexibility for wind power integration because they are scheduled to satisfy heat demand primarily instead of regulating electric power output [2]. Therefore, decoupling electric power production from heat demand is the key point to improve the flexibility of the CHP units for reducing curtailed wind power [3].

Introducing heat pumps (HPs) into the combined heat and power system (CHPS) is well known as a promising approach to address the conflict between the inflexible operation of the CHP units and integration of abundant wind power [4,5]. Wang et al. in [6] utilize the HPs to heat the return water in the district heating network for relieving the heating pressure of the CHP units. Mollenhauer et al. in [7] investigate the optimal operation of the CHP units equipped with the HPs and heat storages considering electricity market, and the HPs are useful for enhancing the flexibility of the CHP units with lower cost. Dengiz et al. in [8] propose a heuristic control strategies for modulating HPs to reduce heating costs and wasted renewable energy. Salpakari et al. in [9] research on the control strategies of the power-to-heat

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systems including the HPs, electric boilers, and heat storages in terms of demand-side management. Positive effects of the HP on increasing the flexibility of the CHPS are well verified in previous studies such as [10,11], and the HP is proved to be more cost-effective than electric boiler on consuming surplus wind energy [12]. However, few of the studies consider the impacts of the thermal inertia of the district heating system (DHS) when operation plans of the CHP units and HPs are made.

This paper focuses on the coordinated operation of the CHP units and distributed HPs in consideration of the thermal inertia of the district heating system. Basing on the proposed method for controlling the on-off status and running power of the HPs, an optimal optimization model of the CHPS is conducted with the objective of reducing the operation cost and wasted wind power.

2. METHODS

2.1 Modeling the district heating system

The topology of the DHS is assumed to be tree-shaped as shown in Fig. 1 and it is controlled with the quality regulation mode according to the most common application of the DHS in Northern China. For simplicity, only the primary pipelines which are much longer than the secondary pipelines are considered, and all the buildings and secondary pipelines connected with the same heat exchange station (HES) are equivalent to a heat load, denoted as H_m($m=1,2,\ldots M$). All the heat loads are served by the centralized heat source (CHP plant) and the distributed HPs located at each HES.

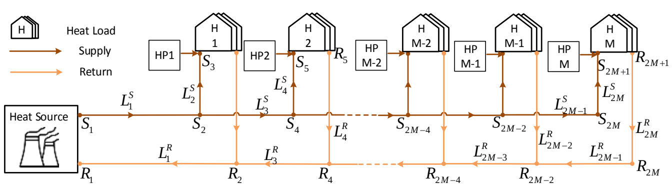

Fig. 1 Simplified diagram of the tree-shaped DHS.

2.1.1 Thermal inertia of the DHS

Thermal inertia of the DHS is mainly embodied in the transmission delay of the hot water flowing from the heat source side to the heat load side. During the transmission process, water temperature in the pipeline changes when the thermal energy is consumed by heat loads and wasted by transmission loss. The transmission time and transmission loss in the nth supply pipe are expressed as:

$$\begin{aligned} \Delta\tau_n^S &= \frac{\rho^w l_n^S A_n^S}{G_n^S} \quad n=1,\ldots,2M \\ \Delta Q_n^S &= \lambda^S l_n^S \end{aligned} \tag{1}$$

Temperature differences between the inlet and outlet sides of the supply pipe and the mth HES caused by transmission loss and heat consumption respectively are expressed as:

$$\begin{aligned} \Delta T_n^S &= \frac{\Delta Q_n^S}{G_n^S c^w} \\ \Delta T_m^H &= \frac{h_m}{G_{2m}^S c^w} \end{aligned} \tag{2}$$

As the return pipes and supply pipes are buried in pairs, calculation methods of the transmission delay and transmission loss in the return pipes are the same with that of supply pipes. Considering the transmission delay, transmission loss, and the dynamic water temperature, the supply and return water temperatures at the source side are expressed as a nonlinear function of heat loads:

$$\left(\sum_{m=1}^{M} G_{2m}^S T_{1,t-2\alpha_m}^S - G_1^S \cdot T_{1,t}^R\right) c^w = \sum_{m=1}^{M} h_{m,t-\alpha_m} + \sum_{n=1}^{2M} (\Delta Q_n^S + \Delta Q_n^R) \tag{3}$$

The total transmission time from the heat source to the mth HES is denoted as α_m, and it is expressed as the integral multiple of the scheduling time interval Δt:

$$\alpha_m = round\left(\frac{\Delta\tau_1^S + \Delta\tau_{2m}^S + \sum_{n=1}^{m-1} \Delta\tau_{2n+1}^S}{\Delta t}\right) \tag{4}$$

Then the thermal energy supplied by the CHP units can be regulated according to the thermal demand.

2.1.2 Heat sources

Coal-fired extraction-condensing CHP units are widely employed as the major heat source in the DHS of Northern China. In the operation region of the CHP unit, the relationship between the produced thermal power and electric power can be formulated as convex combination functions. Details are elaborated in [13]:

$$\begin{aligned} Q_{i,t}^{CHP} &= \sum_{k=1}^{M_i} q_{i,k} x_{i,k}^t \\ P_{i,t}^{CHP} &= \sum_{k=1}^{M_i} p_{i,k} x_{i,k}^t \\ \sum_{k=1}^{M_i} x_{i,k}^t &= 1,\ 0 \le x_{i,k}^t \le 1 \end{aligned} \tag{5}$$

The distributed HPs are used as auxiliary heat sources to produce thermal energy when the CHPS needs the CHP units to supply more flexibility for improving wind power integration. When the CHP units reduce the thermal power output, the jointly produced electric power is allowed to be decreased. The output power of the HP is expressed as:

$$\begin{aligned} Q_t^{HP} &= \beta^{HP} \cdot P_t^{HP} \\ 0 \le P_t^{HP} &\le P_{cap}^{HP} \end{aligned} \tag{6}$$

2.2 Control strategies of the HPs

The HPs are expected to be activated only when the wind power is abundant in view of the better energy economy. Thus, the time intervals of surplus wind power are estimated first to control the on-off status of the HP, and then the running power is determined.

2.2.1 On-off status of the HPs

Given that all the wind power is consumed when the condensing (CON) units and other (OTH) peak-load regulation units operate at the minimum output, the electric power output of the CHP units is constrained by:

$$\sum_{i=1}^{I}\sum_{k=1}^{M_i} p_{i,k}x_{i,k}^{t} + \sum_{j=1}^{J} P_{min,j}^{CON} + P_{min}^{OTH} = P_t^E - P_{gen,t}^W \tag{7}$$

Then the maximum generated thermal power of the CHP units is derived by:

$$Q_{max,t}^{CHP} = max \quad \sum_{i=1}^{I}\sum_{k=1}^{M_i} q_{i,k}x_{i,k}^{t} \tag{8}$$

The status of the HPs at time *t* is denoted as S_t^{HP}. If $P_t^H > Q_{max,t}^{CHP}$, $S_t^{HP}=1$. The HPs need to be activated. If $P_t^H \le Q_{max,t}^{CHP}$, $S_t^{HP}=0$. The HPs can be shut down.

2.2.2 Running power of the HPs

Temperatures of the water at the CHP plant side and the HES side will decrease along with the reduction of the thermal power produced by the CHP units. In consideration of the transmission delay, changes of the water temperatures at the CHP plant side and the inlet side of the *m*th HES are given by:

$$\Delta T_{1,t}^{SO} = \frac{\Delta Q_t^{CHP}}{G_1^S \cdot c^w} \qquad \Delta T_{1,t}^{SO} = \Delta T_{m,t+\alpha_m}^{HS} \tag{9}$$

In order to satisfy the total heat demand, the reduced thermal power of the CHP units is filled by the HPs. The thermal power produced by the HPs is given by:

$$\Delta Q_t^{CHP} = P_{sum,t}^{HP} \cdot \beta^{HP} = \sum_{m=1}^{M} P_{m,t+\alpha_m}^{HP} \cdot \beta^{HP} \tag{10}$$

In addition, the water temperature at each HES side should be kept at the required level. Thus the output thermal power of the HP at the HES is given by:

$$P_{m,t+\alpha_m}^{HP} \cdot \beta^{HP} = G_{2m}^S \cdot c^w \cdot \Delta T_{m,t+\alpha_m}^{HS} \tag{11}$$

Basing on the equations (9)~(11), the relationship between the generated thermal power of the CHP units and the HPs is formulated as:

$$P_{m,t+\alpha_m}^{HP} = \frac{G_{2m}^S}{G_1^S \cdot \beta^{HP}} \cdot \Delta Q_t^{CHP} \qquad P_{m,t+\alpha_m}^{HP} \le P_{cap,m}^{HP} \tag{12}$$

2.3 Optimal dispatch model of the CHPS

2.3.1 Objective function

The objective of the optimal dispatch is to reduce the wasted wind power and the consumed coal of the coal-fired CHP units and the CON units in the CHPS. The objective function is given by:

$$min \quad C_{coal} = C_{coal}^{CHP} + C_{coal}^{CON} + C_{pen}^{W} \tag{13}$$

$$C_{coal}^{CHP} = \sum_{t=1}^{Nt}\left(\sum_{i=1}^{I}\sum_{k=1}^{M_i} c_{i,k}x_{i,k}^{t}\right)\cdot \Delta t$$

$$C_{coal}^{CON} = \sum_{t=1}^{Nt}\left(\sum_{j=1}^{J} k_{1,j}^{CON}(P_{j,t}^{CON})^2 + k_{2,j}^{CON}P_{j,t}^{CON} + k_{3,j}^{CON}\right)\cdot \Delta t \tag{14}$$

$$C_{pen}^{W} = \sum_{t=1}^{Nt} \varepsilon^W (P_{gen,t}^W - P_{int,t}^W)\cdot \Delta t$$

2.3.2 Constraints

Constraint of the electric power balance:

$$\sum_{i=1}^{I} P_{i,t}^{CHP} + \sum_{j=1}^{J} P_{j,t}^{CON} + P_t^{OTH} + P_{int,t}^{W} = P_t^E + S_t^{HP}\cdot P_{sum,t}^{HP} \tag{15}$$

Constraints of the thermal power balance:

$$\sum_{i=1}^{I} Q_{i,t}^{CHP} = G_1^S \cdot c^w (T_{1,t}^S - T_{1,t}^R) = P_t^H \qquad P_t^H = \sum_{m=1}^{M}(h_{m,t+\alpha_m} - P_{m,t+\alpha_m}^{HP}\cdot\beta^{HP}) + \sum_{n=1}^{2M}(\Delta Q_n^S + \Delta Q_n^R) \tag{16}$$

Constraint of the regulated thermal power of the CHP units:

$$\sum_{i=1}^{I}(Q_{i,t}^{CHP} - Q_{i,t-1}^{CHP}) \le \min_{m\in M}(P_{cap,m}^{HP}\cdot\beta^{HP}\cdot\frac{G_1^S}{G_{2m}^S}) \tag{17}$$

Constraints of the supply and return water temperatures:

$$T_{1,t}^R = \frac{\sum_{m=1}^{M} G_{2m}^S \cdot T_{1,t-2\alpha_m}^S}{G_1^S} - \frac{\sum_{m=1}^{M}(h_{m,t-\alpha_m} - P_{m,t-\alpha_m}^{HP})}{G_1^S\cdot c^w} \qquad T_{1,t}^S \le T_{max}^S \quad T_{1,t}^S > T_{1,t}^R \tag{18}$$

Other constraints of the electric power system such as generation output constraints, ramp rate constraints, spinning reserve constraints should also be satisfied.

3. CASE STUDIES

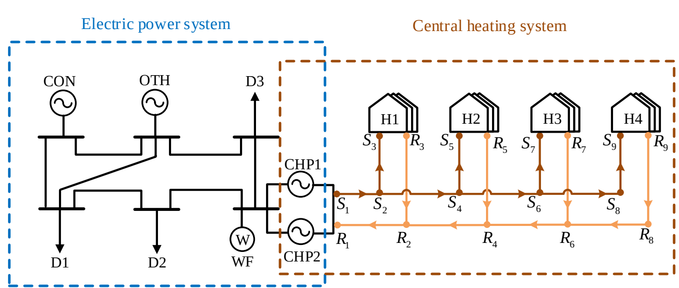

Fig. 2 Simplified configuration of the CHPS.

A simplified configuration of the CHPS is shown in Fig. 2. The installed capacities of the generators are set according to the actual system of Jilin province in China and details are listed in Table 1. The installed capacity of the wind farm is 190 MW. The indoor temperatures of all the buildings are assumed to be maintained at 20˚C. The scheduling is one day and each time interval is 15 minutes. Curves of the power load and heat loads are displayed in Fig. 3.

Table 1 Parameters of the generators

Generator	Capacity/MW	P_{max}/MW	P_{min}/MW
CHP1	300	323	150
CHP2	200	210	100
CON	300	300	150
OTH	260	260	130

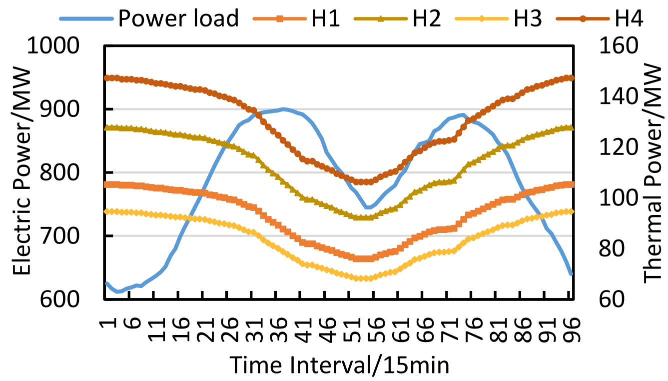

Fig. 3 Curves of power load and heat loads.

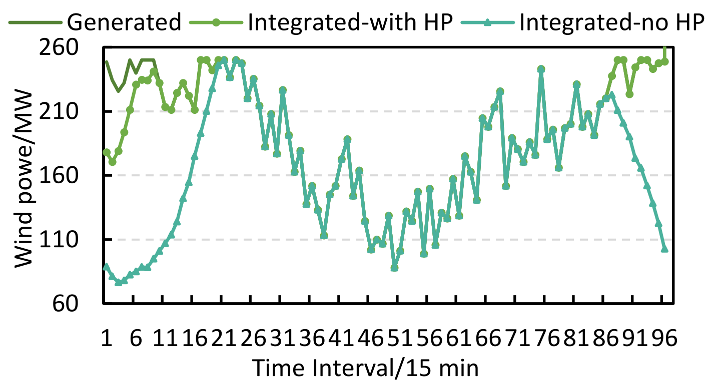

Fig. 4 Curves of generated and integrated wind power.

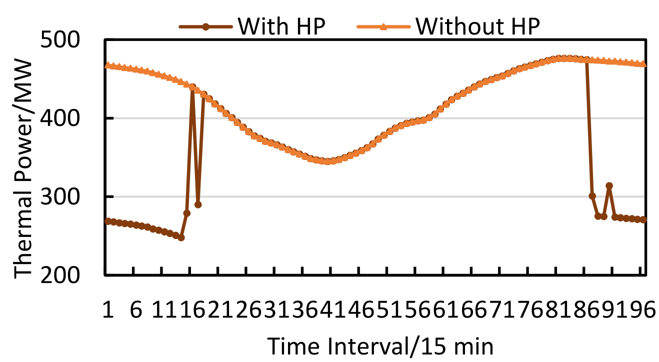

Fig. 5 Total thermal power of the CHP units.

Total capacity of the HPs is 66MW. It is assumed that the capacity of each HP is allocated according to the heating area of the heat station. Curves of the generated and integrated wind power are shown in Fig. 4, and the running power of the HPs is drawn in Fig. 5.

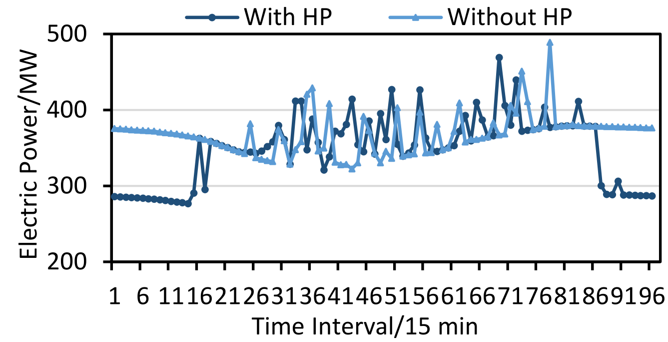

Fig. 6 Total electric power of the CHP units.

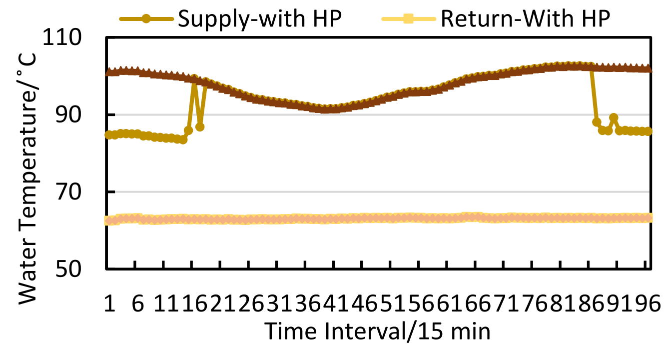

Fig. 7 Supply and return water temperatures at the CHP side.

It can be seen from Fig. 4 that wind power is definitely redundant during time intervals of 1~20 and 87~96 without HPs. On the contrary, the integrated wind power is enhanced considerably during the same intervals while the HPs play a role in the CHPS. For example, during time intervals of 1~20, the total thermal power from the CHP units is decreased as shown in Fig. 5. Then the CHP units get the chance to reduce the electric power as drawn in Fig. 6, contributing to better wind power integration. In Fig. 7, the variation of supply water temperature is similar to that of the thermal power. But the return water temperature is not affected by the variation of generated thermal power as the thermal energy supplied to heat users can always keep following the heat demand with the help of the HP at each HES.

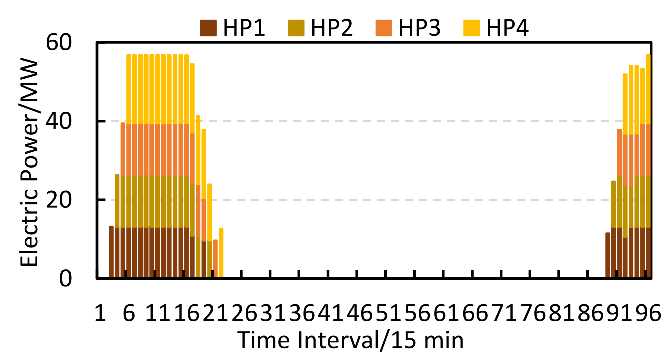

Fig. 8 Running Power of the HPs.

It is worth noting that the actual startup time of the HPs lags behind the order time of activation instruction because the water temperature at the HES is affected by the reduction of thermal power at the CHP plant side after the transmission delay. As shown in Fig. 8, the more distance between the HES and the CHP plant, the later the HP starts up.

Furthermore, by the above equation (17), the allowable thermal power reduction of the CHP units is limited by the capacity of the HP and the mass flow rate. Under the quality regulation mode, the total capacity of the HPs is constant at 66MW, and capacities of the distributed HPs are allocated by three ways: s1) allocated by heating area of the HES; s2) allocated uniformly; s3) allocated by inlet flow rate of the HES. Total integrated wind energy during a scheduling period is listed in Table 2 under different scenarios, and the integrated wind energy in s3 is the best. Therefore, it is necessary to study the allocation method of the distributed HPs, which is the task in our further work.

Table 2 Total integrated wind energy in different scenarios

	s1	s2	s3
Integrated wind energy/MWh	18229	18173	18366

4. CONCLUSION

In this paper, distributed HPs located at the HES are utilized to promote the flexibility of the CHP units for better wind power integration. Control strategies for the operation of the HPs are proposed in terms of start-stop states and running power considering the thermal inertia of the DHS. Furthermore, coordinated optimization model of the CHPS is conducted. The beneficial effects of the HPs are verified by case studies.

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