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Integrated Heat and Electricity Coordinated Dispatch Considering Multiple Time-Scale Flexibility of CHP Based on Thermal Energy Storage of DHS

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Abstract. With the large-scale installation of combined heat and power (CHP) units and wind farms in China, the amount wind curtailment and system frequency stability problems have arisen. In this paper, from the perspective of coordinated operation of electric heating system, the multiple time-scale operation mode of CHP unit is studied, and the flexibility of CHP unit is released, thus alleviating the pressure of power system dispatching and operation control. Based on the analysis of thermal energy storage of district heating system (DHS), coordination model of heating network system and CHP unit are proposed, which effectively unlock the multi-time scale flexibility of the CHP unit (MTF-CHP). Based on the framework of the combined heat and power coordinated dispatch, an adjustable robust heat dispatch model in DHS and a power system scheduling model based on the allowable heat range of CHP (AHR-CHP) are proposed to realize the coordinated configuration of CHP unit scheduling flexibility and regulating flexibility in power system output and reserve.

1. Introduction

More than 75% of the capacity of wind power (129GW by the end of 2015) is installed in Northern of China. Meanwhile, CHP units are supported by national policy [1] and account for 50~70% of the generation capacity from thermal generation units. The structure of power supply, consisting of high penetration of wind farms and CHP units, increases the need for the flexibility to satisfy different grid operating time frames, which is reflected in power system scheduling and operation control.

In power system scheduling, the combined dispatch of the integrated electrical and heating systems can improve the flexibility of CHP to reduce abandoned wind. The flexibility of CHP units can be enhanced by installing heat storage [2], electric heat boilers [3], and utilizing the characteristic of DHS [4]. In the operation control of power systems, The CHP unit can be used as a new AGC regulation resource by utilizing the characteristics of the CHP unit's electric heating output ratio that can be flexibly adjusted. In [5], a simplified nonlinear dynamic model of generating load-throttle pressure-extraction pressure has been proposed to study the method of utilizing the thermal energy storage of DHN to



increase the adjustment rate of CHP. Base on this, in [6], the controller of CHP units has been designed to respond the instructions of AGC.

However, the current research ignores the limited flexibility of the CHP unit and the problems caused by the difficulty of measuring the flexibility of CHP units. Based on this, this paper introduces the concept of multiple time-scale flexibility of CHP and outlines combined heat and power coordinated dispatch framework. Based on thermal energy storage of DHN, an adjustable robust heat dispatch model in DHS is proposed to unlock the multiple time-scale flexibility of CHP. Then, the power system dispatch model considering MTP-CHP is proposed to implement the optimal allocation of multiple time-scale flexibility of CHP. Finally, the case study that we conducted demonstrates the benefits and effectiveness of the proposed model.

2. Combined Heat and Power Coordinated Dispatch Framework with Multiple Time-scale Flexibility of CHP Unit

2.1. Introduction to Multiple Time-scale Flexibility of CHP

In this work we only consider extraction CHP units, which allow more flexibility for heat and electricity production. As shown in Fig. 1(a), the flexibility of CHP used in different operating time frames, is defined as MTF-CHP, which can be divided into the following two types. The heat and generation output are $Q_{g,t}$ and $P_{g,t}$. As shown in Fig.1 (b), in combined heat and power coordinated dispatch framework, the adjustable robust heat dispatch model in DHS and dispatch model considering MTF-CHP is proposed.

(1) The scheduling flexibility of CHP: In the scheduling phase, the CHP unit cooperates with the heat storage, the heating boiler, or the heating network system in the DHS to obtain a part of the power output space $FC = P_{g,t}^{driven} - P_{g,t}^C$, which represents the regulating flexibility of the CHP.

(2) The regulating flexibility of CHP: In the process of operation control, the CHP unit cooperates with the heat network system to obtain a part of the power output space $CK = P_{g,t}^C - \underline{P}_{g,t}$ existing in the standby form, which represents the regulating flexibility of the CHP.

(3)

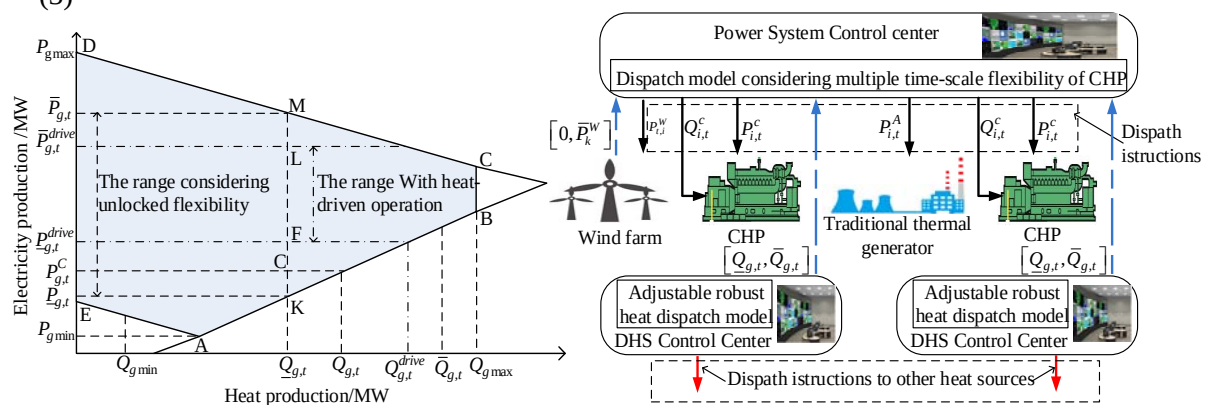


Figure 1. (a) The feasible operational region of extraction CHP unit (b) The coordinated dispatch framework for multiple time-scale flexibility of CHP units.

2.2. Coordination Model of Heating Network System and CHP unit

It can be seen from the above analysis that the heat characteristics of DHS can meet the coordination with MTF-CHP unit. Therefore, a coordination model of heating network system and CHP unit is proposed. The DHS consists of heat station (HS), heat-exchanger station (HES), and heat-network system (HNS). According to the analysis in [7], it is assumed that DHSs are operated with constant flow and variable temperature in this paper. When the CHP unit participates in the power system operation

and control, the actual heat production is defined as the $\tilde{Q}_{g,t}^C$ (the symbol“ $\sim$ ” placed above a variable indicates an uncertainty). The heat balance constraints of HSs are described in (1).

$$\tilde{Q}_{g,t}^C = c \cdot m_j^{hs} \cdot (\tilde{\tau}_{j,t}^{NS} - \tau_{j,t}^{NR}) = c \cdot m_g^{hs} \cdot (\tilde{\tau}_{j,t}^{NS} + \Delta \tau_{j,t}^N - \tau_{j,t}^{NR} - \Delta \tau_{j,t}^N) \quad (1)$$

$\tau_{j,t}^{NS}$, $\tau_{j,t}^{NR}$ are reference supply and return temperature of HS node j. $\tilde{\tau}_{j,t}^{NS}$, $\Delta \tau_j^N$ are the actual supply temperature and the actual temperature change of DHN. c is the specific heat capacity of water. m_g^{hs} is the mass flow rate of HS j.

The change in heat output will cause the heat system to be unbalanced, which will affect the temperature change of the whole heating network described by (2)-(4):

$$\tilde{\tau}_{j,t}^{NS} = \tau_{j,t}^{NS} + \frac{1}{c \cdot m_g^c} (\tilde{Q}_{g,t}^C - Q_{g,t}^C) \quad (2)$$

$$\Delta \tau_j^N = \sum_{i \in \Omega_{HES}} \eta_{ij} \left(\sum_{j=1}^{\Omega_{HS}^C} \lambda_{ji} \tilde{\tau}_{j,t-2\gamma_{ji}}^{NS} + \sum_{j \in 1}^{\Omega_{HS}^B} \lambda_{ji} \tau_{j,t-2\gamma_{ji}}^{NS} \right) - \sum_{i \in \Omega_{HES}} \eta_{ij} \frac{h_{i,t}}{cm_i^{hes}} - \tau_{j,t}^{NR} \quad (3)$$

$$\tilde{\tau}_{i,t}^{in} = \sum_{j=1}^{\Omega_{HS}^C} \lambda_{ji} \tilde{\tau}_{j,t-\gamma_{ji}}^{NS} + \sum_{j \in 1}^{\Omega_{HS}^B} \lambda_{ji} \tau_{j,t-\gamma_{ji}}^{NS}, \tilde{\tau}_{i,t}^{out} = \sum_{j=1}^{\Omega_{HS}^C} \lambda_{ji} \tilde{\tau}_{j,t-\gamma_{ji}}^{NS} + \sum_{j \in 1}^{\Omega_{HS}^B} \lambda_{ji} \tau_{j,t-\gamma_{ji}}^{NS} - \frac{h_{i,t}}{cm_i^{hes}} \quad (4)$$

The actual inlet temperature $\tilde{\tau}_{i,t}^{in}$, outlet temperature $\tilde{\tau}_{i,t}^{out}$ are adjusted according to the uncertainties. λ_{ji} is the temperature distribution shift factor for supply temperature of HS node j to inlet temperature of HES i. η_{ij} is the temperature distribution shift factor for outlet temperature of HES node i to return temperature of HS j. Ω_{HS}^B is the number of HS node connected by other heat sources. Ω_{HS}^C is the number of HS node connected by CHP. Ω_{HES} is the number of HES node. Equations (2)-(4) are coordination model of heating network system and CHP unit based on thermal energy storage of DHN.

3. Adjustable Robust Heat Dispatch Mode

This dispatch problem with CHP heat power uncertainties can be formulated as a robust optimization model as follows, determining the AHR-CHP, and dispatch instructions for other heat sources.

3.1. The Objective Function

The objective of the optimal operation is to minimize the total operation cost:

$$\min \sum_{t=1}^T \left[\sum f(Q_{g,t}^C) + f(Q_{l,t}^B) + f(Q_{s,t}^S) + g_1(\bar{Q}_{g,t}^C) + g_2(\underline{Q}_{g,t}^C) \right] \quad (5)$$

Where T is the number of dispatch periods. Ψ^C , Ψ^B , Ψ^S are the set of indices of CHP unit and heat-only production units and heat storage units. $g \in \Psi^C$, $s \in \Psi^S$, $l \in \Psi^B$, $t \in \{1, 2, \dots, T\}$.

To maximize the generation output flexibility of the CHP unit, the penalty cost of CHP units:

$$g_1(\bar{Q}_{g,t}^C) = \mu_g^+ (Q_{g,\max}^C - \bar{Q}_{g,t}^C)^2, g_2(\underline{Q}_{g,t}^C) = \mu_g^- (Q_{g,\min}^C - \underline{Q}_{g,t}^C)^2 \quad (6)$$

Where μ_g is the penalty factor for of CHP g . ς is the intermediate variable.

3.2. Constraints

To ensure security within allowable heat limits, robust heat dispatch is subject to the following constraints for all possible realizations of uncertain parameters within the allowable ranges, i.e., $\forall \tilde{Q}_{g,t}^C \in [\bar{Q}_{g,t}, \underline{Q}_{g,t}]$. For all the constraints, $g \in \Psi_{HS}^C, t \in [1, \dots, T]$.

(1) Heat characteristics of DHS constraints:

$$T_{j\min}^{NS} \leq \tilde{\tau}_{j,t}^{NS} \leq T_{j\max}^{NS} \quad (7)$$

$$\Delta T_{\min}^N \leq \Delta \tau_j^N \leq \Delta T_{\max}^N \quad (8)$$

$$T_{i\min}^{in} \leq \tilde{\tau}_{i,t}^{in} \leq T_{i\max}^{in} \quad (9)$$

$$T_{i\min}^{out} \leq \tilde{\tau}_{i,t}^{out} \leq T_{i\max}^{out} \quad (10)$$

(2) Heat production limit constraints: The heat productions of heat storage units and heat-only units are constrained by their technical limits. Please refer to [4] for detailed expressions.

(3) Allowable heat production of CHP constraints: The upper and lower limits of allowable intervals (AIs) of CHP are equal to or less than those of the corresponding maximum heat production intervals $[Q_{g\max}^C, Q_{g\min}^C]$.

$$\underline{Q}_{g,t} \leq Q_{g,t} \leq \bar{Q}_{g,t}, \quad \bar{Q}_{g,t} \leq Q_{g,\max}^C, Q_{g,\min}^C \leq \underline{Q}_{g,t} \leq 2Q_{g,\min}^C - \varsigma, 0 \leq \varsigma \leq Q_{g,\min}^C \quad (11)$$

3.3. Solution of Model

Equations (7)-(10) is the linear constrains related to the uncertain parameter $\tilde{Q}_{g,t}^C$ and the coefficient is constant. Therefore (7)-(10) is equivalent to the following (12).

$$\begin{cases} \min h(\mathbf{x}, \bar{\mathbf{y}}, \underline{\mathbf{y}}) \\ s.t. \mathbf{E}\mathbf{x} + \mathbf{F}\tilde{\mathbf{Q}}^C \leq \mathbf{D}, \forall \tilde{\mathbf{Q}}^C \in [\bar{\mathbf{y}}, \underline{\mathbf{y}}] \\ \mathbf{x}_{\min} \leq \mathbf{x} \leq \mathbf{x}_{\max} \\ \bar{\mathbf{y}} \leq \mathbf{Q}_{\max}^C, \underline{\mathbf{y}} \leq \mathbf{Q}_{\min}^C + \varsigma, 0 \leq \varsigma \leq \mathbf{Q}_{\max}^C - \mathbf{Q}_{\min}^C \end{cases} \quad (12)$$

Where $\mathbf{E}$, $\mathbf{F}$, and $\mathbf{D}$ are the coefficient matrix. $\mathbf{x}$ is the deterministic variable vector. Equation (12) is also equivalent to the following bi-level model.

$$\mathbf{E}_i \mathbf{x} + \sum_{i \in \Psi^C} \max_{\tilde{Q}_j^C} \{F_{ij} \tilde{Q}_j^C \mid \underline{Q}_j^C \leq \tilde{Q}_j^C \leq \bar{Q}_j^C\} \leq D_i \quad \forall i \quad (13)$$

Where $\mathbf{E}_i$ is the i th row of matrix $\mathbf{E}$, F_{ij} is the entry in the i th row and j th column of matrix $\mathbf{F}$, and D_i is the i th entry of vector $\mathbf{D}$. Then, we then have

$$\max_{\tilde{Q}_j^C} \{F_{ij} \tilde{Q}_j^C \mid \underline{Q}_j^C \leq \tilde{Q}_j^C \leq \bar{Q}_j^C\} = \begin{cases} F_{ij} \bar{Q}_j^C & F_{ij} \geq 0 \\ F_{ij} \underline{Q}_j^C & F_{ij} \leq 0 \end{cases} \quad (14)$$

Therefore, (13) is equivalent to the following expression:

$$Ex + \sum_{i \in \Psi^C, F_{ij} \geq 0} F_{ij} \bar{Q}_j^C + \sum_{i \in \Psi^C, F_{ij} \leq 0} F_{ij} Q_j^C \leq D \quad (15)$$

The adjustable variable $\tilde{\tau}^{NS}$ has been eliminated in (15). This means that the model is translated into a deterministic linearly constrained problem and nonlinearities are attributed to the objective function, which can be solved directly using well-developed nonlinear programming techniques.

4. Power System Dispatch Model Considering Multiple Time-scale Flexibility of CHP

The proposed model seeks the optimal dispatch of units that meet the load demand at minimum operation cost, while satisfying physical and security constraints of power grid. And, Based on the AHR-CHP ($\bar{Q}_{g,t}^C, Q_{g,t}^C$), the electrical decision variables include the generation dispatch ($P_{i,t}^A, p_{i,t}^w, ru_{i,t}^A, rd_{i,t}^A$) of the traditional thermal generators and wind farms. The decision variables ($Q_{g,t}^C, P_{i,t}^C, ru_{g,t}^C, rd_{g,t}^C$) of CHP include the CHP power production, heat production, and up/down regulation flexibility.

4.1. The Objective Function

The objective is to minimize the total operation cost

$$\min \sum_{t \in T} \left[\sum_{g \in \Psi^C} f_g^C(P_{g,t}^C, Q_{g,t}^C) + \sum_{i \in \Xi^A} f_i^A(P_{i,t}^A) + \sum_{j \in \Psi^C \cup \Xi^A} (S_j^u(ru_{j,t}) + S_j^d(rd_{j,t})) + \sum_{k \in \Xi^w} f_k^w(p_{k,t}^w) \right] \quad (16)$$

Ξ^A and Ξ^w are the set of indices of TTG and wind farms respectively. $\forall g \in \Psi^C, t \in T$. f_g^C is the quadratic function of TTG operation cost. The cost of CHP units f_i^A is expressed as a quadratic function of electricity and heat productions. The penalty cost f_k^w is proportional to the square of wind power curtailment. S_j^u and S_j^d are the reserve cost of TTG and CHP units.

4.2. Constraints

The model considering MTP-CHP is subject to physical and security constraints in electrical power system (EPS) and DHS, which include power balance constraint, reserve constraints of conventional units and the whole system, generation output constraints of wind farm. Those detailed expressions are refer to [8]. Feasible power operating region constraints of CHP units is expressed as follows:

$$E_g \leq \beta_g^h P_{g,t}^C + \beta_g^e Q_{g,t}^C \leq \bar{E}_g \quad (17)$$

$$-R_{i,dn}^C \leq P_{g,t}^C - P_{g,t-1}^C \leq R_{i,up}^C, \underline{Q}_{g,t} \leq Q_{g,t}^C \leq \bar{Q}_{g,t} \quad (18)$$

$$\max\{r_g \underline{Q}_{g,t}, Q_{g,t}\} \leq P_{g,t}^C + ru_{g,t}^C \leq \xi_{g,t}, \max\{r_g \underline{Q}_{g,t}, Q_{g,t}\} \leq P_{g,t}^C - ru_{g,t}^C \leq \xi_{g,t} \quad (19)$$

$$0 \leq ru_{g,t}^C \leq R_{g,up}^C, 0 \leq rd_{g,t}^C \leq R_{g,dn}^C \quad (20)$$

Where $Q_{g,t} = \min(E_g - \beta_g^e Q_{g,t} / \beta_g^h, P_{g,\min})$, $\xi_{g,t} = \min(E_g - \beta_g^e Q_{g,t} / \beta_g^h, E_g - \beta_g^e Q_{g,\min} / \beta_g^h)$, SR_t^{up} and SR_t^{dn} are system upward reserve and downward reserve capacity requirements.

5. Numerical Simulations

5.1. Description of the Simulation System

Fig.2a. shows the one-line diagram of an integrated system of a six bus EPS, a seven node DHS a, and a six node DHS b. The detailed operational parameters of CHPs are listed in Table 1. Fig.2-b shows the profiles of total electric loads, forecast heat demands of DHSs, and wind power forecasts, the upward/downward reserve system requirements is set to 60MW.

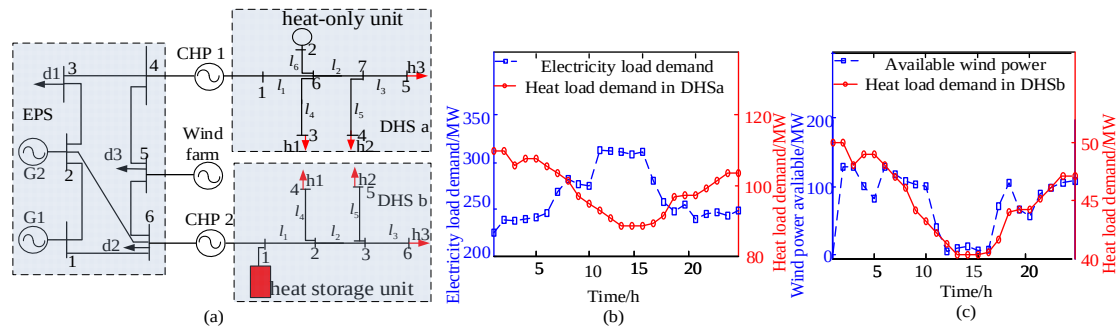


Figure 2. (a) one-line diagram of an integrated system (b) electric and heat load and (c) wind power forecast output.

Table 1. Operational parameters of CHP units

parameters	r_g	$\bar{F}_g$	$\bar{E}_g$	$Q_{g\max}^C$	$Q_{g\min}^C$	β_g^e	β_g^h
CHP1	0.85	240	50	60	15	2.4	0.95
CHP2	0.85	240	50	60	10	2.4	0.95

5.2. Results

(1) Case1: Integrated dispatch with scheduling flexibility of CHP

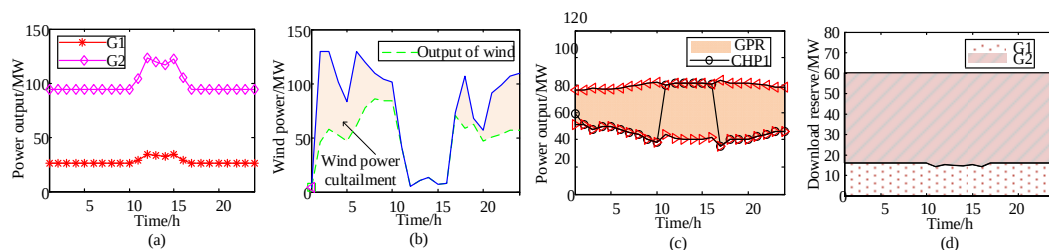


Figure 3. Hourly electric power dispatch of (1) G1 and G2 unit, (b) wind farm, (c) CHP 1 unit; (d) The downward reserve of electrical power system in Case1.

(2) Case2: coordinated dispatch with multiple time-scale flexibility of CHP

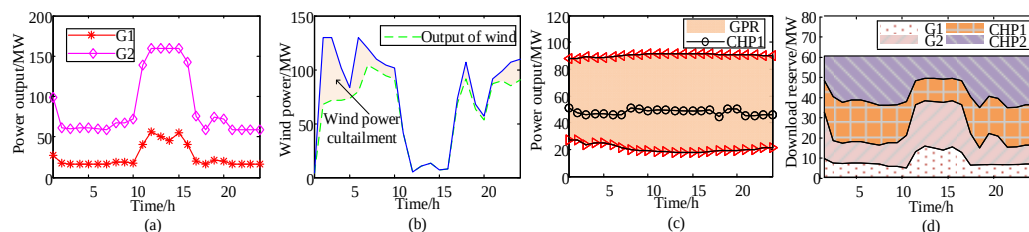


Figure 4. Hourly electric power dispatch of (a) G1 and G2 unit, (b) wind farm, (c) CHP 1 unit; (d) The downward reserve of electrical power system in Case 2.

From the above results, the influence of multi-time scale flexibility of CHP units on EPS and DHS is mainly reflected in the following aspects. The strategy of releasing the MTF-CHP proposed in this paper is coordinated with the DNS, so it has less impact on the output of other thermal equipment. (as shown in Fig3 and Fig4). The regulation flexibility of CHP units can replace downward reserve from G1 and G2 to improve the GOR of conventional units (as shown in Fig4-a); The strategy, taking into account the scheduling flexibility and adjustment flexibility of the CHP unit, can significantly reduce the wind power curtailments and can reduce the operating cost of the system (as shown in Fig4 b: the wind power curtailment capacity in Case1 and Case2 are 145.7MWh and 656.7MWh respectively. The operation cost in Case1 and Case2 are 7.8×10^5 yuan and 3.2×10^5 yuan respectively). Based on the AHR of Case2, the power system can make scheduling decisions for CHP units in a wider range, and improve the GOR of CHP units as shown in Fig4d.

6. Conclusion

This paper proposes the coordinated dispatch framework of combined heat and power with MTF-CHP units. Based on this, a robust heat dispatch model is proposed to provide the AHR-CHP for power system scheduling. Using the constraint equivalence method, the robust scheduling problem is transformed into a deterministic quadratic programming problem, which simplifies the solution process. Finally, the PSCC realizes the coordinated configuration of CHP units in scheduling flexibility and regulating flexibility in power system. The simulation results show that the proposed strategy can effectively increase system reserve capacity, reduce wind power curtailment and system operating costs.

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