Combined Heat and Power Optimal Dispatch Considering Wind Power Uncertainty

Chunlong Chen¹, Xueshan Han¹,a and Wenbo Li²

¹Key Laboratory of Power System Intelligent Dispatch and Control of Ministry of Education (Shandong University), Jinan, China
²State Grid Shandong Electric Power Research Institute, Jinan 250003, Shandong Province, China

Corresponding author: sduchen1994@163.com

Abstract. Large-scale integration of wind power is a clean alternative to power generation, but the uncertainty of wind power has become a huge dispatch challenge, which is much more serious in the northeast of China. For this reason, heat storage is configured to decouple thermoelectric constraint of CHP unit, releasing its flexibility and improving its peak-shifting ability. A random variable is introduced to represent wind power deviations firstly, then a chance constraint economic dispatch model of an aggregation unit containing wind power and CHP unit is established to explain the standby effect of heat storage on wind power uncertainty. Finally, a case study is conducted to verify the performance of the heat storage. The example results show that when configured with heat storage, the CHP unit have broadened its adjustable electrical output range, so more reserve capacity is released to cope with wind power uncertainty.

1. Introduction

Large-scale integration of wind power is a clean alternative to power generation, how to cope its uncertainty and ensure the economic and safe operation of power system has been a huge dispatch challenge. During heating period of northeast district, a time coincident with high wind power generation, the ability of the CHP unit to further reduce output is limited by its thermoelectric coupling constraint, causing insufficient peak-shifting capacity and much wind power curtailment. For this reason, a heat storage is configured to decouple thermoelectric constraint of CHP unit. The CHP unit external characteristics with and without heat storage are analysed in [1]. It is pointed out that the peak-shifting ability of CHP unit is determined by its heat load level. An economic dispatch containing heat storage was conducted in [2]-[5], showing that more wind power integration can be achieved owing to the existence of heat storage or/and electrical boiler, but they took no consideration to wind power uncertainty. Based on multiple wind power forecast scenarios, an optimal dispatch model for an aggregation unit with wind power uncertainty taken into consideration is proposed in [6], which can make full use of the flexibility provided by heat storage, but it made no explanation for the standby effect of heat storage on wind power uncertainty.

In this paper, based on random variable to represent wind power deviations, a chance constraint economic dispatch model of an aggregation unit containing heat storage is proposed to study the standby effect of heat storage responding to the wind power uncertainty. The model can conduct
scheduling operation strategy for the aggregation unit. Moreover, case is studied and analysed to verify the performance of the heat storage.

2. The Wind Power Output Model
In this section, based on the predicted value of wind power output, a random variable \( \Delta P_w \) is used to indicate the deviation between the actual output of wind power and the predicted value considering wind power uncertainty. The deviation obeys the normal distribution with variance of \( \sigma^2 \) \[ \Delta P_w \sim N(0, \sigma^2(\text{\(P_{\text{of}}\)))} \] (1)

where \( P_{\text{of}} \) is the predicted value of wind power (MW), and \( \sigma^2 \) is a function of \( P_{\text{of}} \).

The actual output of wind power at time \( t \) can be expressed as Equation (2)

\[ P_w(t) = P_{\text{of}} + \Delta P_w \] (2)

where \( P_w(t) \) is the actual output of wind power (MW),

3. Aggregation Unit Economic Dispatch Model
The general structure of the aggregation unit is shown in Figure 1.

3.1. Objective function
The system operator aims at minimizing the aggregation unit cost, so the objective function can be expressed as Equation (3).

\[ \min C = \sum_{t=1}^{T} \left[ a(P_{\text{chp}})^2 + bP_{\text{chp}} + cP_{\text{chp}}^2H_{\text{chp}} + d(H_{\text{chp}})^2 + eH_{\text{chp}} + f \right] \] (3)

where \( C \) is the total cost of the aggregation unit, representing the operation cost of the CHP where \( a, b, c, d, e \) and \( f \) are the cost coefficients of CHP; \( P_{\text{chp}} \) and \( H_{\text{chp}} \) are the electric power and the heat power of the CHP respectively (MW); \( t \) represents the discrete time index and \( T \) is the amount of periods.

3.2 Constraints
3.2.1 Power Equality constraints
An aggregation unit aiming at realizing distributed autonomy must satisfy the load demand firstly, in which the power equation constraints can be written as Equation (4)

\[ \begin{cases} P_{\text{chp}} + P_{\text{of}} = P_d \\ H_{\text{chp}} - Q_{\text{ch}} + Q_{\text{dis}} = H_L \end{cases} \] (4)

where \( P_d \) and \( H_L \) are local electrical load power and heat load power respectively (MW); \( Q_{\text{ch}} \) and \( Q_{\text{dis}} \) are charge power and discharge power of the heat storage device respectively (MW).
3.2.2 Thermoelectric coupling constraints for the CHP units
As the only coupling point of the two types of energy, the thermoelectric coupling relationship of the CHP unit makes multi-energy complementary be possible, which can be expressed as Equation (5)

\[
\begin{align*}
0 & \leq P_{chp}^{min} - c_v H_{chp}^{i} - P_{chp}^{i} \\
0 & \leq H_{chp}^{i} - (P_{chp}^{max} - P_{chp}^{min} + (c_v + c_a)H_{chp}^{max})/c_a
\end{align*}
\]

(5)

where \(c_v\) and \(c_a\) are the characteristic parameters of CHP unit.

3.2.3 Reserve capacity constraint
For the purpose of coping with wind power uncertainties, sufficient reserve capacity must be provided in the aggregation unit, which is determined by unit ramp rate or the flexibility of unit release by heat storage. The reserve capacity constraints can be presented as Equation (6)

\[
\begin{align*}
R_{up}(H_{chp}^{i}) & = \min \{P_{chp}^{max} - c_v H_{chp}^{i} - P_{chp}^{i}, r_{up}\Delta t\} \\
R_{dw}(H_{chp}^{i}) & = \min \{P_{chp}^{min} - c_v H_{chp}^{i}, c_a H_{chp}^{i} + P_{chp}^{max} - c_v H_{chp}^{max} - c_a H_{chp}^{max}\}, r_{dw}\Delta t\}
\end{align*}
\]

(6)

where \(R_{up}\) and \(R_{dw}\) represent reserve capacity expressions with \(H_{chp}^{i}\) as variable; \(r_{up}\) and \(r_{dw}\) are the ramp rate of CHP unit (MW/h).

3.2.4 Wind power uncertainty probability constraint
The wind power uncertainties can be featured by wind power fluctuation. Due to the existence of prediction errors, the actual wind power may be lower or higher than the forecast value. In order to balance the reserve capacity economics and the safety of power system, reserve capacity must be able to cope with wind power fluctuations at high probability. A probability constraints is established as Equation (7) by introducing chance constrained programming to deal with randomness of the wind power, which can be transformed into an equivalent deterministic problem\[8\].

\[
\begin{align*}
f_1 & = P_{chp}^i (P_{chp}^i - p_{chp}^i > R_{up}(H_{chp}^{i})) \leq \mu_1 \\
f_2 & = P_{chp}^i (P_{chp}^i - p_{chp}^i > R_{dw}(H_{chp}^{i})) \leq \mu_2
\end{align*}
\]

(7)

where \(P_{chp}(\cdot)\) represents the occurring probability of event (\(\cdot\)). \(\mu_1\) and \(\mu_2\) are the probability value.

4. Case Study
In order to illustrate the standby effect of heat storage responding to wind power uncertainty, a case study is conducted in this section and the parameters used in the model are listed in Table 1.

The model is solved by Visual Studio 2010 and the optimization results are shown as Figure (3)-Figure (5). The following is the analysis of optimization results.

| Table 1. Values of the Parameters |
|----------------------------------|
| Parameters | Value | Parameters | Value |
| \(a\)      | 0.000171$/MW^2 | \(P_{chp}^{max}\) | 150MW |
| \(b\)      | 0.2705$/MW    | \(H_{chp}^{max}\) | 350MW |
| \(c\)      | 11.537        | \(E_{sE}^{max}\) | 200MWh |
| \(c_v\)    | 0.15           | \(Q_{dis}^{max}\) | 80MW/h |
| \(c_a\)    | 0.75           | \(r_{up}/r_{dw}\) | 70MW/h |
| \(P_{chp}^{max}\) | 300MW |

As Figure 2 shows, when configured with heat storage, the CHP unit can broaden its adjustable electrical output range, releasing its flexibility and improving its peak-shifting ability. During the periods in which wind generator has high power output, for example period 0-5 and period 20-24, the
CHP unit can further reduce its electrical power to accommodate more wind power under the premise of satisfying the load demand.

Figure 2 the output of CHP unit and wind power

The comparison of CHP unit’s thermal output and thermal load power in the aggregation unit is shown in Figure 3.

Figure 3 the comparison of CHP unit’s thermal output and thermal load power in the aggregation unit

The thermal output of CHP unit is no longer limited by thermal load power owing to heat storage, as shown in Figure 3. The equality constraint of real-time power balance is broken, causing flexible adjustment of thermal power with corresponding operation mode of heat storage shown in Figure 4.

Figure 4 the output and state of heat storage
Figure 4 can better reflect the standby effect of heat storage responding to wind power uncertainty. The green line represents the adjustable electrical output range with heat storage configured and the black line represents the range without heat storage.

As can be seen from the figure above, in the period of high wind power output, in order to cope with the strong uncertainty of wind power, the heat in the heat storage is consumed to meet the demand of heat load which can be seen in Figure 4, decoupling thermoelectric coupling constraint, releasing more flexibility and thereby providing more wind power reserve capacity. When the wind power is low, the required spare capacity is small, it is necessary to supplement the heat in the heat storage device, preparing for the next heat release.

5. Conclusion
An aggregation unit chance constraint economic dispatch model is presented in this paper, in which the standby effect of heat storage on wind power uncertainty is considered. A random variable is introduced to represent wind power uncertainty. The optimization results show that when configured with heat storage, decoupling thermoelectric coupling constraint to some extent, the CHP unit can broaden its adjustable electrical output range, so more reserve capacity is released to cope with wind power uncertainty effectively, ensuring active power coordination with electrical network.

Acknowledgment
This work is supported by the Science and Technology Foundation of SGCC(SGSDDK00KJJS1600061).
References
[1] Q. Li, T. Y. Chen, H. X. Wang, et al. Analysis on Peak-load Regulation Ability of Cogeneration unit with Heat Accumulator, Automation of Electric Power Systems. 38(11), 34 (2014)
[2] Y. Cui, Z. Chen, G. G. Yan, et al. Coordinated Wind Power Accommodating Dispatch Model Based on Electric Boiler and CHP With Thermal Energy Storage. Proceedings of the CSEE. 36(15). 4072(2016)
[3] L. Chen, F. Xu, X. Wang, et al. Implementation and Effect of Thermal Storage in Improving Wind Power Accommodation. Proceedings of the CSEE. 35(17). 4283(2015)
[4] Q. Lv, T. Y. Chen, H. X. Wang, et al. Combined Heat and Power Dispatch Model for Power System With Heat Accumulator. Electric Power Automation Equipment. 34(5). 79(2014)
[5] J. Yu, H. B. Sun, X. Y. Shen, Optimal Operating Strategy of Integrated Power System With Wind Farm, CHP Unit and Heat Storage Device, Electric Power Automation Equipment. 37(6). 139(2017)
[6] Y. H. Dai, L. Chen, Y. Min, Optimal Dispatch for Joint Operation of Wind Farm and Combined Heat and Power Plant With Thermal Energy Storage, Proceedings of the CSEE, 37(12). 3470(2017)
[7] Y.P. Li, N. Feng, Y. Cui, et al. Security Constrained Unit Commitment Problem Considering Wind Power Uncertainty and Flexible Load, Electric Power Construction. 38(2), 129, (2017).
[8] P. Yan, Combined Optimization Scheduling of Wind and Fire Power System Considering the Feasibility of the Results [D]. (2016)