Coordinated Wind Power Accommodating Dispatch Model Based on Combined Electricity and Heat System

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Abstract. To solve the problem of wind power accommodation, this paper proposed a coordinated wind power accommodating dispatch model based on combined electricity and heat system with the perspective of decoupling thermoelectric coupling constraints and enhancing the adjustment capacity of the power system. Firstly, this paper introduced the working principles of wind power characteristics and combined heat and power (CHP), the basic operating principles of the consumption of wind power curtailment using thermal storage. Secondly, the coordinated wind power accommodation dispatching model was established due to the regulations mentioned above. Thirdly, the main problem was divided into two sub problems by Benders decomposition, which are power and thermal dispatching, and then the optimum solutions which meet the constraints of each sub problem was solved using Interior point. Finally, the whole dispatching planning of CHP was obtained. Case study verified that, the proposed model is effective.

1. Introduction

Energy and environmental crisis are the major challenges facing the world today. Taking the three major fossil fuels of coal, oil and natural gas as examples, according to the proved reserves, the ratio of production to storage is 153, 50.6 and 52.5 years, respectively[1]. The development and utilization of renewable energy is a realistic choice to ensure the sustainable use of energy. The ‘Energy Development Strategy Action Plan(2014-2020)[2] officially released by the State Council pointed out that it is necessary to vigorously develop renewable energy sources, in accordance with the output and the local utilization of both centralized and distributed development principle, accelerate the development of renewable energy.

As an effective way to deal with the energy crisis, wind power has been rapidly increasing in the world in recent years. The development of wind power in our country started relatively late but developed rapidly. In 2016, the installed capacity of wind power increased by 19.3 million kW and the total installed capacity reached 149 million kW, accounting for 9% of the total installed capacity of power generation,also the electricity of wind power integration reached 241.0 billion kwh. However, the wind power curtailment problem is still very serious. The total amount of wind power curtailment of China exceeded 49.7 billion kwh in 2016. The national average wind power curtailment rate was 17.1%. Among them, the rate of the ‘Three North regions’ ranked first in the country, the more serious areas are Gansu, Xinjiang and Jilin, the wind power curtailment rate reached 43%, 38%, and 30%[3]. The reason is that on the one hand, the wind power resources are abundant in the ‘Three North regions’, but the energy consumption is insufficient, so it is difficult to achieve large-scale wind power
by the local consumption while being restricted by transmission channels of the power grids. On the other hand, there is a natural contradiction between the stochastic volatility of wind power itself and the safe and stable operation of power grid. In order to meet the demand of heat load in winter, ‘the load level of CHP is restricted by the minimum heat demand’ production mode further reduces the space for wind power and exacerbates the phenomenon of wind power curtailment.

Energy storage technology has received extensive attention in recent years because of its good wind power complementarity. With the development of electric boiler heating technology, a system of combined heating by electric boilers and CHP units has begun to emerge in foreign countries. By using electric boiler heating to increase the load of electricity during the trough of low load, the space for wind power access has significantly increased. Although the development of these technologies has effectively alleviated the contradiction between wind and heat, however, most of the current studies separately consider the role of heat storage device and electric boiler for disposal of abandoned wind. Taking into account the close combination of future power system will be with the thermal system, it is very urgent and necessary to study how to coordinate the work of each unit in the energy system such as electric heating system to reduce the waste of energy loss and obtain the best economy.

2. Working principle

2.1. Wind power characteristics

Both wind power and conventional power supply convert primary energy into secondary energy. Conventional power supplies are based on natural water or fossil fuels as primary energy sources. These energy sources can be treated in a stable, sustainable and controllable manner. The energy source of wind power is wind energy in nature. Affected by factors such as season, climate and topography, wind energy can not artificially control the variation of wind energy even though some predictions of wind randomness can be made. After the wind power is connected to the grid, due to its randomness, fluctuation, intermittency and anti peak shaving characteristics, it will affect the state of supply and demand balance that the power system is completely controllable, dispatching and tracking the load forecast before the wind power is not connected to the grid. Therefore, the power grid may overestimate the risk caused by wind power fluctuations, thereby limiting the access scale of wind power, so as to ensure the safe and stable operation of the grid.

In summary, in order to improve the ability of the system’s wind power accommodation and solve the contradiction between wind power and heating units. Therefore, it is necessary to analyze the working principle of CHP units, which is now the main heating unit in the cogeneration system.

2.2. Working principle of the traditional CHP unit and CHP unit with thermal storage

The coupling relation between the generating power \( P_e \) and the heating power \( P_h \) of the CHP unit is the ‘electric heating characteristic’. The common CHP units can be divided into four types which are according to different electric heating characteristics. This paper takes the most common steam extraction CHP unit as an example to analyze its electrothermal characteristics as shown in figure 1.

As can be seen from the operation interval shown in figure 1, the power generation has a certain degree of adjust ability under a given heat load, such as the heating power \( P_h \). Power generation can be
adjusted between $P_H-P_F$, but the larger the heating power, the smaller the range of electric power can be adjusted. This is because, at a given extraction volume, such units can adjust the power output of the entire turbine by adjusting the amount of steam generated by condensing steam, but the larger the extraction volume, the smaller the proportion of condensing steam that can be adjusted. So the smaller the scope of regulation, abatement wind power capacity is very limited.

The traditional CHP unit in the configuration of the thermal storage device, the electric characteristics will be greatly changed, as shown in figure 2. Since the thermal storage device can perform heat storage and heat release operations, assuming that the heat release and storage powers are $P_{h,f\max}$ and $P_{h,c\max}$, the electrically feasible operating field AGIJKL containing the thermal storage CHP unit is actually the superimposed region formed by the translation of the original feasible operating domain ABCD to the right of the horizontal axis $P_{h,f\max}$ and to the left of the translation of $P_{h,c\max}$.

At the same heating power $P_h$, the power generation of the steam turbine can be allowed to be adjusted between $P_M$ and $P_H$, and the resulting steam turbine is under-heated or the remaining part of the heating is compensated by the thermal storage device for heating or heat storage to maintain a stable supply of heat load, thereby enhancing the peak capacity of the unit.

2.3. The operation principle of wind power accommodation with thermal storage

Thermal storage is usually built on the heat source side of the heating system and connected between the thermal power plant and the heating network. At present, the main heating units in China are large-scale coal-fired condensing bleeder units, and the start-up and shutdown costs of such units are very high. Therefore, after the heat storage device is configured, peak load can also be adjusted by using the low-load operation mode. The operation principle of wind power accommodation with thermal storage is: during daytime electric load waist load, increase steam turbine inlet steam power and steam extraction power for thermal storage; at electric load low troughs, while reducing the power generation and heating power for peak load down, the heating part of the supplement by the thermal storage.

2.4. Mechanism of wind power accommodation of the coordinated heating system

By arranging the thermal storage device on the side of CHP unit, not only the purpose of decoupling the thermoelectric coupling characteristics can be achieved, but also the power system can be closely connected with the heating system to form an integrated electric heating system to improve the power system optimal allocation ability and enhance the ability of consuming the abandoned wind. However, only the configuration of heat storage will still appear abandoned wind phenomenon, if the load side accesses electric boiler and CHP unit coordinated heating, the wind power accommodation space of the power grid can be further expanded. The electric boiler is used to increase the electricity consumption when the load is low, and the role of heat storage is to reduce the power output of CHP unit and improve the space of wind power network. The structure of the integrated system containing CHP units with thermal storage and electric boilers is shown in figure 3.

![Figure 3](image_url)

**Figure 3.** Structure diagram of combined heat and power system.

Integrated system access to electric boiler, on the one hand, CHP unit’s range will be more expanded through the electric boiler; on the other hand, electric boiler access while increasing the
electric load, and the role of the thermal storage device at the same time makes the power grid abatement wind power greatly enhance the ability to alleviate the problem of wind power curtailment.

3. Coordinated wind power accommodating dispatch model based on combined electricity and heat system

\[
\begin{align*}
P_{w,i,t} &= P_{w,i} - \Delta P_{w,i,t} \\
\Delta P_{w_ch} &= \Delta P_{w,eh} + \Delta P_{eh} \\
P_{w,i,t} &= \Delta P_{w,eh}
\end{align*}
\]

Where: \(P_{w,i,t}\) is the abandoned wind power of the system only containing CHP unit at time \(t\), \(P_{w,i}\) is the abandoned wind power of the system only containing CHP unit without heating at time \(t\), \(\Delta P_{w,i,t}\) is the space of \(P_{w,i,t}\) (maybe negative), \(\Delta P_{w,eh}\) represents the abandoned wind space which is produced by CHP with thermal storage and electric boiler in coordinated heating, \(\Delta P_{w,ch}\) is the abandoned wind space of CHP with thermal storage, \(\Delta P_{EB}\) is the abandoned wind space of electric boiler.

When the total heating load \(P_{he}\) is between point C and J in figure 2, for a system with a single electric boiler and CHP unit, the heat elimination combined heat and power unit can generate heat when the heat is removed. The space is expressed as a function of the heating power \(P_{het}\) of the electric boiler.

\[
\Delta P_{het} = \frac{c_e (P_{ht} - P_{ht}) - c_i (P_{ht} - P_{ht_{min}}) + c_i P_{ht_{med}} - c_i P_{ht_{max}})}{c_i \cdot P_{ht} + c_i (P_{ht_{med}} - P_{ht})}; \(P_{ht} \in (P_{ht_{med}} - P_{ht_{min}}) \cap (P_{ht_{med}} - P_{ht_{max}})\)
\]

Where: \(c_e\) is the elastic coefficient of electric and thermal power at back pressure, \(c_i\) is the reduction of power generation by multiple extraction of unit heat with constant intake of steam, \(P_{ht}\) is heating power of the unit under pure condensing conditions, respectively.

3.1. The objective function of scheduling model

Economic dispatch problems with wind power systems usually take the minimum system cost as the dispatch target. In order to test the effect of the heat storage device and the electric boiler to dissipate the wind power, the cost of abandoning the wind is added to the cost, so the objective function is:

\[
\min \left\{ F_1(P) + F_2(P_{cht,i}, P_{cht,i}, P_{cht,i} + \lambda \cdot P_{w,ef}) \right\}
\]

Where: \(P\) is the electric output of the conventional unit \(i\), \(P_{cht}\) is the electric output of the CHP unit \(i\) with thermal storage, \(P_{cht}\) is the total heating power of the CHP unit \(i\) with thermal storage, \(P_{cht}\) is the heat release and storage powers of the CHP unit \(i\) with thermal storage, \(P_{w,ef}\) is the system’s abandoned wind power, \(\lambda\) is the cost coefficient of abandoned wind.

(1) The costs of thermal power generation \(F_1\)

Wind power integration has an important influence on the power unit output size, the unit start stop plan and the start-up and shutdown of the unit during operation:\[8\]:

\[
F_1 = f_1(P) + f_2(u_i)
\]

Where: \(f_1\) indicates the operating costs of the thermal power unit, \(f_2\) indicates thermal power start-stop plan and start-stop peak-regulation costs, \(P_i, u_i\) are the power generated and operating status of unit \(i\).

\[
f_1 = \sum_{i=1}^{n} \sum_{i=1}^{u_i} [a_i P_{cht}^2 + b_i P_{cht} + c_i]
\]

\[
f_2 = \sum_{i=1}^{n} \sum_{i=1}^{u_i} [a_i (1 - u_i) S_i]
\]

Where: \(a_i, b_i, c_i\) are the quadratic fitting coefficient of the conventional unit operating costs, \(P_{cht}\) indicates the power output at \(t\) moment for conventional unit \(i\), \(u_i\) indicates the status of start or stop at \(t\) moment for unit \(i\), \(u_i=1\) indicates run, \(u_i=0\) indicates stop, \(S_i\) is the start-up cost of unit \(i\).

(2) The costs of CHP power generation \(F_2\)
\[ F_2 = \sum_{i=1}^{T} \sum_{t=1}^{K} \left( d_i \left[ P'_{el,i} + c_i \left( P'_{hr,i} + P'_{cr,i} \right) \right] + h_i \left[ P'_{el,i} + c_i \left( P'_{hr,i} + P'_{cr,i} \right) \right] + c_i \right) \]  

Where: \( a, b, c \) are coefficient of operating costs for CHP units, \( P'_{el,i} \) are respectively the power output, the total heating power, the heat storage device storage and the heat release power of the CHP unit \( i \) at the \( t \) moment.

**3.2. Running constraints**

The constraints on the scheduling model of dissipate the wind power for coordinated heating include the following two parts.

1. **Power system constraints**

   Load balancing constraints:

   \[ \sum_{i=1}^{N} \sum_{j=1}^{L} k_i P'_{el,i} + \sum_{j=1}^{K} P'_{el,j} - P'_{hr} - P'_{w,q} = 0 \]  

   Where: \( P'_{el,i} \) represents the power generation of the conventional thermal power or CHP unit \( i \) at the \( t \) moment, \( P'_{el,j} \) indicates the predicted output of the wind turbine \( j \) at the \( t \) moment, \( P'_{hr} \) is the heating power consumed that connected to the electricity boiler at the \( t \) moment, \( P'_{w,q} \) indicates the abandoned wind power at the \( t \) moment.

   Unit output constraints:

   \[ P_{el,min,i} \leq P'_{el,i} \leq P_{el,max,i} \]  

   Where: \( P_{el,min,i} \) is the minimum generation power of a conventional thermal power or CHP unit \( i \), \( P_{el,max,i} \) represents the maximum power generation of a conventional thermal or CHP unit \( i \). According to the above, the upper and lower limits of the power output for the CHP unit are a function of the heating power, while the conventional power is a fixed value.

   The ramp of unit constraints:

   \[ -P'_{u,i} \leq P'_{d,i} - P'_{d,i} - P'_{d-1,i} - P'_{d,i} \]  

   Where: \( P'_{d,i}, P'_{u,i} \) represent the ramp rate of upward and downward for unit \( i \) at the \( t \) moment, \( P'_{d,i} \) is the power generation of unit \( i \) at the \( t \) moment.

2. **Thermal system constraints**

   Operation constraints for thermal storage:

   \[ \left| S_i^t - S_i^{t-1} \right| = P'_{d,i} - P_{h,max,i} \]

   \[ S_i^t - S_i^{t-1} = P'_{u,i} \leq P_{h,min,i} \]

   \[ S_i^t \leq S_{max} \]

   \[ \sum_{j=1}^{L} P'_{hr,j} = 0 \]

   Where: \( S_i^t \) is the heat storage capacity of the thermal storage device \( i \) at the \( t \) moment, \( P_{h,max,i} \) \( P_{h,min,i} \) respectively represent the maximum heat storage and release power of the thermal storage device \( i \), \( S_{max} \) is the heat storage capacity of the thermal storage device \( i \), \( P'_{d,i} \) is the heat storage and release power of the thermal storage device \( i \) at the \( t \) moment.

   Heating balance constraints:

   \[ P'_{h,i} + \sum_{j=1}^{L} P'_{hr,j} = P'_{hc,i} \]

   Where: \( P'_{h,i} \) is the heating power of electric boiler at the \( t \) moment, \( P'_{hc,i} \) is the total heating power of the CHP unit with heat storage at the \( t \) moment, \( P'_{hc,i} \) is the heating load at the \( t \) moment.

**3.3. Solve the model**
The tric heating characteristic curve is shown in Figure 5, unit #4 is a pure heating unit, and unit #2 and #3 are CHP units, the electric heating characteristic curve is shown in Figure 5, unit #4 is a pure heating unit, and the system cost function is:

\[
\text{COST} = \text{cost}_1 + \text{cost}_2 + \text{cost}_3 + \text{cost}_4 \quad \text{unit: dollar}
\]

\[
\begin{align*}
\text{cost}_1 &= 50P_i \\
\text{cost}_2 &= 2650 + 14.5P_i + 0.0345P_i^2 + 4.2h_i + 0.03b_i + 0.031P_i^2 h_i \\
\text{cost}_3 &= 1250 + 36P_i + 0.0435P_i^2 + 0.6b_i + 0.027h_i + 0.011P_i^2 h_i \\
\text{cost}_4 &= 23.4h_i
\end{align*}
\]

Constraints include load balancing constraints, heat balance constraints, the ramp of unit constraints and the constraints of the unit output range. In order to find the nearest node from any coordinate distance, the initial value of low cost is taken as \(-\infty\), and then replace it constantly until the nearest node is found. \(\varepsilon\) is taken as 0.0001, when the \(|C_{up} - C_{down}| \leq \varepsilon\), that is, when the difference between low cost and high cost is less than \(\varepsilon\), the iteration stops.

Figure 4. Schedule flow chart of Benders decomposition interior point method.

4. Examples

4.1. Example conditions

The cost coefficient of abandoned wind \(\lambda\) is 100 USD/MW·h\(^9\). The example is based on the literature [10]. The electric heating system consists of four units, of which unit #1 is a conventional thermal power unit, and unit #2 and #3 are CHP units, the electric heating characteristic curve is shown in Figure 5, unit #4 is a pure heating unit, and the system cost function is:

4.2. Example results

Taking the first moment as an example, the iterative curve of Benders decomposition interior point method is shown in Figure 6. The best power output plan for each unit is shown in Figure 7 and the best heat output plan is shown in Figure 8.
According to the result of the scheduling, it is found that #1 conventional thermal power unit is not powered and #2 and #3 CHP units participate in the power supply arrangement as the best power output plan, #4 conventional thermal power unit does not heat, #2 and #3 CHP units to participate in the heating arrangement for the best heat output plan, with this scheduling arrangement, the system can achieve the best economy. The scheduling cost of each period of the system is shown in figure 9.

The total scheduling cost of the system is 250718.1767 dollars, at this time, the system does not abandon the wind, and the scheduling cost is reduced by 9.02% than that of not adding the thermal storage device and the electric boiler.

5. Conclusion
(1)By configuring the heat storage unit on the CHP unit side, not only to achieve the purpose of decoupling thermoelectric coupling characteristics, but also to connect the power system with the thermodynamic system. Thus forming a comprehensive electric heating system to improve the power system optimal allocation ability. However, it is still possible to abandon the wind only by configuring heat storage. At this time, if the load side access to electric boilers and CHP units coordinated heating. On the one hand, through the coordinated heating of the electric boiler and the heat storage device, the range of the electric power adjustment of the combined heat and power unit will be further expanded; on the other hand, electric boiler access while increasing the electrical load, with the heat storage device making the ability of eliminating wind power greatly enhance for the power grid at the same time, which can alleviate the problem of abandoning the wind.
(2)In this paper, Benders decomposition of interior point method can effectively solve the model.
(3)The example shows that the coordination scheduling model proposed in this paper is correct and effective. According to the scheduling results found that the scheduling of the pure heating unit is not heating and the pure power unit is not powered, the system can achieve the best economy.

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