Research on Power System Scheduling Improving Wind Power Accommodation Considering Thermal Energy Storage and Flexible Load

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Abstract. In the case of rapid development of wind power and heavy wind curtailment, the study of wind power accommodation of combined heat and power system has become the focus of attention. A two-stage scheduling model contains of wind power, thermal energy storage, CHP unit and flexible load were constructed. This model with the objective function of minimizing wind curtailment and the operation cost of units while taking into account of the total coal consumption of units, constraint of thermal energy storage and electricity-heat characteristic of CHP. This paper uses MICA to solve the problem of too many constraints and make the solution more feasible. A numerical example showed that the two stage decision scheduling model can consume more wind power, and it could provide a reference for combined heat and power system short-term operation.

1. Introduction
In the three northern regions of China, the phenomenon of wind curtailment is serious, which is caused by the rigid restriction of “determined power by heat” of the combined heat and power(CHP) unit, the low capacity of peak shaving of system, the insufficient local load and the weak power supply capacity of the power grid.

There have been a lot of references to prove that the installation of thermal energy storages [1], using wind power to provide heat [2], using demand response resources [3,4] can improve curtailed wind power accommodation. The [5,6] studied the specific implementation measures for installing the thermal energy storage in combined heat and power system, and compared the effect of wind power accommodation for installing the thermal energy storage on the heat source side and the heat load side. The [7] used multi-time scale scheduling method to reduce the effect of wind power prediction error, established a rolling scheduling model considering the resource of source and load, and achieve optimal wind power accommodation and maximum economic benefits.

But the existing studies have not considered the follow-up measures of the situation that wind power cannot be completely consumed after the thermal energy storage have been installed and the influence of the uncertainty of wind power on the operation strategy of the unit and the thermal energy storage. At present, the research and application of wind power accommodation considering the flexible load is more concentrated in the field of power system and is seldom used in combined heat and power system, just a preliminary study in theory.
Based on the above research, a two-stage scheduling method which includes thermal energy storages, CHP unit and flexible load is presented in this paper. At the stage of the day-ahead scheduling, units and thermal energy storage participate in the scheduling to consume short-term wind power forecasting. At the stage of the in-day scheduling, units and the flexible load participate in the scheduling to consume ultra-short-term wind power forecasting. The effect of energy-saving and emission-reduction, the output of the unit and the effect of wind power accommodation are analyzed, and the running characteristics of thermal energy storage are also analyzed. Finally, in order to solve the problem of too many constraint conditions of the model, the improved imperialist competitive algorithm (MICA) is used to solve the example. Example analysis shows that the scheduling model presented in this paper can consume more wind power compared with the traditional scheduling method, and can also reduce coal consumption and provide a reference for the short-term operation of the system.

2. The Principle of CHP unit with Thermal Energy Storage Improving Wind Power Accommodation

2.1. The Operating Characteristics of CHP unit with/without Thermal Energy Storage

In the heat-supply system, the thermal energy storage is usually installed on the heat source side, and between the heat and power plant and heating network. Thermal energy storage is a large heat storage tank for short-term storage of heat, and its medium is water. The major operation cost of thermal energy storage is its heat losses, and the daily loss is less than 1% [8], so it is not considered in this paper.

The coupling relationship between power generation and heating power of CHP unit is called “heat-to-electric ratio”, and it can well reflect the operating characteristics of CHP unit. Because the extraction steam unit is used more widely in China than the back-pressure unit, the extraction steam unit is used in this paper. The operating characteristics of CHP unit with/without thermal energy storage are shown in figure 1.

![Figure 1. Operation characteristics of CHP unit with/without thermal energy storage](image)

Before configuring the thermal energy storage, the operating interval of the unit is ABCD. After configuring the thermal energy storage, the operating characteristics of the unit have changed. For a specific power generation, such as $P_B$, the maximum extraction steam power of turbine is set as $H_{T,\text{max}}$, the maximum heating power of the whole can be increased from $H_{T,\text{med}}$ to $H_{T,\text{max}}$ through the thermal energy storage supplying heat, and the minimum heating power of the whole can be reduced from $H_{\text{med}}$ to $H_{H,\text{min}}$. Then the operating interval of the unit is changed to AGIJKL. $c_p$ is the heat-to-electric ratio when CHP unit run at the least condensing condition. $c_v$ is decrement of power generation when the heat is increased by one unit size under the condition of a certain amount of steam.
2.2. The Principle of Wind Power Accommodation for Thermal Energy Storage

As can be seen from Fig. 1, for the definite heating power $H_n$, the range of the generation power of the unit is $P_f \sim P_e$ when CHP unit is not equipped with thermal energy storage, and the range of the generation power of the unit is changed to $P_{f,i} \sim P_f$. Therefore, the peak shaving margin of the combined heat and power system can be increased by reducing the power generation of CHP unit while keeping the heating power constant. Thus more space can be provided for wind power integration when the output of wind power is large, and the amount of wind curtailment can be reduced.

3. The Principle of the Flexible Load Improving Wind Power Accommodation

The flexible load can be divided into two types: interruptible load and incentive load. Both of these two types of flexible loads are load management measures for peak-load regulation to improve the reliability and economy of the system. The flexible load response can realize the increase or decrease of electric energy under the condition of meeting the restriction of itself. The agreement which signed by the user and the power company requires the user to increase or decrease the amount of electricity during a fixed period of peak and valley period or at any time required by the power company. When the user reduces the electricity demand according to the agreement, the electric power company pays the certain cost to the user to make up for the loss. When the user increases the power demand according to the agreement, the electric power company reduces the user's electricity price as a reward.

Because the amount of response load is large and there are a lot of constraints for single response user, this paper introduces the concept of load agent to make grid scheduling easier [9]. In this paper, the flexible load response user specifically refers to the load agent.

The cost of flexible load response include that the compensation cost of interruptible load and the incentive cost of incentive load.

The compensation cost of interruptible load:

$$F_h(U_{i,t}, P_{i,t}) = \sum_{n=1}^{N_i} \rho_n U_{i,n,t} P_{i,n,t}$$  \hspace{1cm} (1)

Where $N_i$ is the number of the interruptible load user, $U_{i,t} = [U_{i,t,1}, \ldots, U_{i,t,n}, \ldots, U_{i,t,N_i}]$ is the state variable for the interruptible load user, $U_{i,n,t} = 0$ indicates load does not interrupt user, and $U_{i,n,t} = 1$ indicates load interrupt user, $\rho_n$ is the compensation factor, $P_{i,t} = [P_{i,t,1}, \ldots, P_{i,n,t}, \ldots, P_{i,t,N_i}]$ is the capacity of the interrupt load.

The incentive cost of incentive load:

$$F_h(U_{H,t}, P_{H,t}) = \sum_{i=1}^{N_h} \eta_i U_{H,i,t} P_{H,i,t}$$  \hspace{1cm} (2)

Where $N_h$ is the number of the incentive load user, $U_{H,t} = [U_{H,t,1}, \ldots, U_{H,t,n}, \ldots, U_{H,t,N_h}]$ is the state variable for the incentive load user, $U_{H,i,t} = 0$ indicates load does not increase user, and $U_{H,i,t} = 1$ indicates load increase user, $\eta_h$ is the incentive coefficient, $P_{H,t} = [P_{H,t,1}, \ldots, P_{H,t,n}, \ldots, P_{H,t,N_h}]$ is the capacity of the incentive load.

4. Two Stage Scheduling Method Considering Thermal Energy Storage and Flexible Load

At the stage of the day-ahead scheduling, the scheduling cycle is 24h, and the scheduling interval is 15min, the scheduling plan is updated every 24h. Units and thermal energy storage participate in the scheduling to consume short-term wind power forecasting at the stage of the day-ahead scheduling. The heating power of CHP unit and the storage capacity of thermal energy storage at each time will no longer
be changed at the stage of the in-day scheduling once determined at the stage of the day-ahead scheduling.

The in-day scheduling plan is based on the day-ahead scheduling plan, and the scheduling plan is updated every 15min to plan for the next scheduling period. At the stage of the in-day scheduling, units and the flexible load participate in the scheduling to consume ultra-short-term wind power forecasting. Therefore, the problem of wind curtailment and uneconomical operation of the unit caused by prediction error of short-term wind power can be solved.

The process of the two-stage scheduling is shown in figure 2.

![Figure 2. The Process of the Two-stage scheduling](image)

5. Comprehensive Model
In this paper, a model taking the minimum wind curtailment and system operating costs as target is proposed to optimize each link of the system. Because the cost of wind power generation is far less than the cost of thermal power generation, the cost of the wind power is not considered in the objective function.

5.1. Objective Function

\[
\min \left( \sum_{i=1}^{N} \sum_{j=1}^{N_W} \rho_i P_{W,i,j}^{\text{wor}} + \varepsilon \sum_{i=1}^{N} \sum_{m=1}^{N_{\text{CHP}}} \lambda_i \left( \sum_{n=1}^{N_G} \rho_{i,n} P_{i,n} + \sum_{k=1}^{N_{\text{INT}}} \eta_{i,k} P_{i,k} \right) \right) \]

Where \( N \), \( N_W \), \( N_G \), \( N_{\text{CHP}} \) represent the number of scheduling period, wind farm, pure condensing unit and CHP unit respectively. And the amount of wind curtailment is \( P_{W,i,j}^{\text{wor}} = |W_{i,j} - W_{i,j}^{\text{set}}| \). \( \varepsilon \) is penalty factor. And in order to make the wind power be dispatch preferentially by the system, \( \varepsilon = 10^3 \) in the simulation example. \( \lambda \) is the judgment parameter of whether the load response participates in the scheduling, and \( \lambda = 0 \) at the stage of the day-ahead scheduling, \( \lambda = 1 \) at the stage of the in-ahead scheduling.

The operating costs of units can be expressed as quadratic functions.

\[
f_j(P_{G,i,j}) = a_j P_{G,i,j}^2 + b_j P_{G,i,j} + c_j
\]
\[ f_m(P_{CHP,m,t}) = a_m P_{CHP,m,t}^2 + b_m P_{CHP,m,t} + c_m = a_m (P_{CHP,m,t} + c_v H_{CHP,m,t})^2 + b_m (P_{CHP,m,t} + c_H H_{CHP,m,t}) \]
\[ = A_m (P_{CHP,m,t})^2 + B_m P_{CHP,m,t} + C_m P_{CHP,m,t} H_{CHP,m,t} + D_m (H_{CHP,m,t})^2 + E_m H_{CHP,m,t} + F_m \]  

(5)

Where \( f_j(P_{G,j,t}) \) is the running cost of pure condensing unit, and \( f_m(P_{CHP,m,t}) \) is the running cost of CHP unit. \( P_{G,j,t} \) is the generating power of unit \( j \) at time \( t \). And \( P_{CHP,m,t} \) is power generation of CHP unit when CHP unit only provide power and not provide heat (which called pure coagulation condition), \( H_{CHP,m,t} \) and \( P_{CHPe,m,t} \) represent heating power and power generation of CHP unit in the heating conditions.

5.2. Constraints

(1) Power balance:
\[ \sum_{i=1}^{N_k} W_{G,i} + \sum_{j=1}^{N_G} P_{G,j,t} + \sum_{m=1}^{N_{CHP}} P_{CHP,m,t} = P_{LD,t} + \lambda \left( \sum_{k=1}^{N_k} U_{H,k,t} P_{H,k,t} - \sum_{n=1}^{N_n} U_{I,n,t} P_{I,n,t} \right) \]  

(6)

Where \( P_{LD,t} \) is the electric load of system at time \( t \).

(2) Heat balance:
\[ \sum_{m=1}^{N_{CHP}} H_{CHP,m,t} - (S_t - S_{1,t}) = H_{load,t} \]  

(7)

Where \( H_{CHP,m,t} \) is the heat output of CHP unit \( m \) at time \( t \), and \( H_{load,t} \) is the heat load at time \( t \). \( S_t \) is the heat storage capacity for the thermal energy storage at time \( t \).

The power output deviation of the unit in two stages:
Because the in-day scheduling is based on the day-ahead scheduling, the power output deviation of the unit in two stages can not be too large.
\[ |P_{\text{in-day},t} - P_{\text{day-ahead},t}| \leq \alpha P_{\text{max}} \]  

(8)

Where \( P_{\text{in-day},t} \) and \( P_{\text{day-ahead},t} \) indicate the output of the unit the in-day and day-ahead scheduling respectively. \( \alpha \) is constraint multiplier, \( \alpha = 0.2 \). \( P_{\text{max}} \) is the maximum power output of the unit.

Flexible load:
\[ P_{I,n}^{\text{min}} \leq P_{I,n,t} \leq P_{I,n}^{\text{max}} \]
\[ P_{H,k}^{\text{min}} \leq P_{H,k,t} \leq P_{H,k}^{\text{max}} \]  

(9)

Where \( P_{I,n,t} \) is the interruptible load of load agent \( n \) at time \( t \), and \( P_{H,k,t} \) is incentive load of load agent \( k \) at time \( t \).

Power limit of units:
\[ P_{G,j}^{\text{min}} \leq P_{G,j,t} \leq P_{G,j}^{\text{max}} \]
\[ \begin{cases} P_{CHP,m,t} \geq \max \left( c_m H_{CHP,m,t} + K_r P_{CHP,m,t,\text{min}} - c_H H_{CHP,m,t} \right) \\ P_{CHP,m,t} \leq P_{CHP,m,t,\text{max}} - c_H H_{CHP,m,t} \end{cases} \]  

(10)
0 ≤ H_{\text{CHP},m,j} ≤ H_{TJ,\text{max}}

W_{i,j} ≤ W_{i,j}^{\text{pre}}

Where $P_{G,j}^{\text{min}}$ and $P_{G,j}^{\text{max}}$ is lower limit and upper limit of power output of pure condensing unit, $P_{\text{CHP},m,j,\text{min}}$ and $P_{\text{CHP},m,j,\text{max}}$ is lower limit and upper limit of power output of CHP unit in pure coagulation condition, $W_{i,j}^{\text{pre}}$ is wind power forecasting.

Unit ramp rate limit:

$$-D_{R,j}^{\text{max}} \cdot \Delta t ≤ P_{G,j,i+1} - P_{G,j,i} ≤ U_{R,j}^{\text{max}} \cdot \Delta t$$

$$-D_{R,m}^{\text{max}} \cdot \Delta t ≤ P_{\text{CHP},j,i+1} - P_{\text{CHP},j,i} ≤ U_{R,m}^{\text{max}} \cdot \Delta t$$

(11)

Where $D_{R,j}^{\text{max}}$ and $U_{R,j}^{\text{max}}$ is the ramp-down rate limit and the ramp-up rate limit of pure condensing unit, $D_{R,m}^{\text{max}}$ and $U_{R,m}^{\text{max}}$ is the ramp-down rate limit and the ramp-up rate limit of CHP unit in pure coagulation condition.

Thermal energy storage:

$$S_{S,t} = S_{0}$$
$$0 ≤ S_{t} ≤ S_{\text{max}}$$
$$0 ≤ H_{in,j} ≤ H_{in}^{\text{max}}$$
$$0 ≤ H_{out,j} ≤ H_{out}^{\text{max}}$$

(12)

Where $S_{0}$ and $S_{t}$ is the storage capacity of thermal energy storage at the beginning of scheduling and at the end of scheduling, $S_{t}$ is the storage capacity of thermal energy storage at time $t$, $H_{in}^{\text{max}}$ and $H_{out}^{\text{max}}$ is the maximum input and output power of heat exchanger.

**Algorithm**

In order to solve the problem of too many constraints in the two-stage scheduling model, an improved imperialist competitive algorithm (MICA) based on dynamic clustering and fitness sharing proposed in [10] is used in this paper. The ICA algorithm is divided into three stages: creating the initial empire, assimilation and revolution. By introducing the dynamic clustering and fitness sharing, the fitness of similar individuals in groups and the probability of similar individuals being chosen in evolution can be greatly reduced, thus the occurrence of prematurity and local convergence can be avoided.

6. **Case study**

6.1. **Basic data**

The main parameters of the units of the case refer to [11]. The short-term wind power forecasting and the ultra-short-term wind power forecasting are based on [12], and a little modification is made. The day-ahead electric load forecasting and in-day actual load are based on [13], and a little modification is made. The specific values of wind power forecasting and electric load are shown in figure 3. It is assumed that the heat load remains unchanged, which is 1700MW, and there is no power exchange between this system and other systems.
The case includes 6 CHP units, 2 pure condensing units, 1 wind farm and some flexible loads. And 1~3 units belong to thermal power plant A, 4~6 units belong to thermal power plant B. Each thermal power plant has a thermal energy storage, and the storage capacity of each thermal energy storage is 1000 MW·h, the maximum power of thermal energy storage is 100MW. 7~8 units are pure condensing units. In the system, the installed capacity of pure condensing units is 700MW, the installed capacity of CHP unit is 1800MW, the installed capacity of wind farm is 600MW. The main parameters of load agent refer to [14], as shown in table 1.

### Table 1 Parameters of load agent

| load agent | $\rho_n$ | Upper limit of interruptible load/MW | $\eta_h$ | Upper limit of incentive load/MW |
|------------|---------|--------------------------------------|---------|----------------------------------|
| 1          | 4.53    | 15                                   | 3.96    | 12                               |
| 2          | 4.91    | 22                                   | 4.11    | 27                               |
| 3          | 5.24    | 25                                   | 4.23    | 30                               |

6.2. Analysis of wind power accommodation effect

In order to study the effect of thermal energy storage and flexible load on wind power accommodation of the combined heat and power system, 4 scenarios are set up for comparative analysis. After the two-stage scheduling, the schedule results of 4 scenarios are shown in table 2, and the effects of wind power accommodation of 4 scenarios are shown in Figure 4.

### Table 2 The schedule results of 4 scenarios

| Scenario | Thermal Energy Storage (the day-ahead scheduling,) | Flexible Load (the in-day scheduling,) | Coal Consumption /t | The Capability of Wind Power Accommodation / MW·h | The Capability of Wind Curtailment / MW·h | The Power-generating Capacity of CHP Unit and Pure Condensing Unit /MW·h | The Heat-generating Capacity of CHP Unit and Thermal Energy Storage / MW·h |
|----------|-----------------------------------------------|----------------------------------------|---------------------|--------------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|---------------------------------------------------------------|
| 1        | ×                                              | ×                                      | 15808               | 9838                                             | 840                                     | 37991                                                                     | 42500                                                          |
| 2        | √                                              | ×                                      | 15694               | 10272                                            | 406                                     | 37557                                                                     | 42500                                                          |
| 3        | ×                                              | √                                      | 15777               | 10038                                            | 640                                     | 37901                                                                     | 42500                                                          |
| 4        | √                                              | √                                      | 15614               | 10566                                            | 112                                     | 37306                                                                     | 42500                                                          |
Figure 4. The effects of wind power accommodation of 4 scenarios

As can be seen from Table 4, the introduction of thermal energy storage and flexible load can increase the capability of wind power accommodation while reducing the coal consumption of the system, and the economic and environmental benefits are better. From the comparison between scenario 1 and scenario 2, it can be seen that the introduction of thermal energy storage can reduce the capability of wind curtailment by 434 MW·h. And from the comparison between scenario 3 and scenario 4, it can be seen that under the condition of the flexible load has been introduced, the increases of wind power accommodation caused by the introduction of thermal energy storage is more, and the capability of wind curtailment is reduced by 528 MW·h. And from the comparison between scenario 2 and scenario 4, it can be seen that under the condition of thermal energy storage has been introduced, the increases of wind power accommodation caused by the introduction of flexible load is more, and the capability of wind curtailment is reduced by 294 MW·h. Therefore, if the thermal energy storage and flexible load are introduced into the system at the same time, the effect of improving wind power accommodation will be better than they are introduced into the system alone.

As shown in Figure 4, the phenomenon of wind curtailment mostly occurs between 2:00~9:00. In this period, the output of wind power is large, the electric load is small, the heat load remains unchanged, and the peak-load regulation ability of CHP unit is weak for the rigid restriction of “determined power by heat”, thus resulting in a large number of wind curtailment.

6.3. Comparison of Two-stage Scheduling Results
The in-day scheduling plan is based on the day-ahead scheduling plan. Flexible load with good response characteristics is dispatched in the second stage to reduce the effect of prediction errors of two-stage. In scenario 4, the electrical output of the units in two stages and the wind power accommodation situation, heat output of CHP unit and thermal energy storage and the use quantity of flexible load are respectively shown in Figure 5, 6 and 7.

Figure 5. The electric power of two-stage in scenario 4
Figure 6. Heat power of thermal power plant and storage capacity of thermal energy storage in scenario 4

(a) The heat output of CHP unit and thermal energy storage (b) The storage capacity of thermal energy storage

Figure 7. The use quantity of flexible load in different scenarios

(a) The use quantity of flexible load in scenario 4 (b) The use quantity of flexible load in scenario 3

As shown in Figure 5, CHP unit is also responsible for a large part of the electrical load while providing heat, especially in the peak load period during daytime. At the stage of the in-day scheduling, the power output of CHP unit and pure condensing unit are made a little adjustments on the basis of the in-day scheduling plan, the power-generating capacity of CHP unit and pure condensing unit is decreased from 38054 MW·h to 37306 MW·h. Part of the reduced power generation is to increase the amount of wind power accommodation, the other part is to balance the flexible load. On the basis of the increase in wind power accommodation, the coal consumption decreases from 15841 MW·h in the day-ahead scheduling to 15614 MW·h in the in-day scheduling.

As shown in Figure 6, the heat storage of thermal energy storage is the same at the beginning and the end of a scheduling cycle. The thermal energy storage releases heat from 0:00~9:00 and stores heat in other periods. In the peak load period during daytime, the excess heat output of the CHP unit after meeting the heat load is stored in thermal energy storage. In the evening, when the electric load is low and the wind power is large, the power output of units is reduced to provide space for the wind power, and the insufficient heat supply is provided by thermal energy storage.

It can be seen from Figure 7, during 0:00~8:00, the electric load is low and the wind power is large, the electric load of the system is obviously increased. During 9:00~20:00, the electric load is high and the wind power is small, the electric load of the system is obviously reduced. This indicates it that the flexible load played a role in peak load shifting and tracking wind power. From the comparison between scenario 4 and scenario 3, it can be seen that the use quantity of flexible load in scenario 4 is less, which means the compensation cost for the user is less. The result shows that the combination of thermal energy storage and flexible loads is more economical than using flexible loads alone.

7. Conclusion

(1) A two-stage scheduling method is proposed in this paper, the thermal energy storage is introduced into the day-ahead scheduling and the flexible load is introduced into the in-day scheduling. The influence of the forecasting error of wind power and electric load between two stages on system is greatly reduced, and the wind power accommodation level of the system is greatly improved.
(2) The introduction of thermal energy storage and flexible load can increase the capability of wind power accommodation while reducing the coal consumption of the system, and the economic and environmental benefits are better.

(3) The MICA proposed in this paper can deal with the problem of too many constraints in the model and get a more feasible solution.

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