Review of Optimal Dispatching of Combined Heat-Power System for Wind Power Accommodation

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Abstract. The contradiction between seasonal heating demand and large-scale wind power accommodation causes wind curtailment at nighttime during high heat load period. How to improve wind power accommodation has become a concern of the whole society. Aiming at this problem, the electrothermal characteristics of Combined Heat and Power (CHP) units are briefly reviewed, and then the relevant research results at home and abroad are summarized from the aspects of adding electrothermal coupling equipment and grid lean dispatching. The paper summarizes the principle and characteristics of adding electric boilers and heat storage devices to improve wind power accommodation, as well as the lean dispatching methods of the power grid for the CHP units. The practical application of decoupling thermoelectric coupling constraints at home and abroad is also expatiated. Finally, the next step work that needs carrying out in the power side and the grid scheduling side is pointed out.

1. Introduction

As a mature renewable energy generation method, wind power generation has become one of the strategic industries that all countries attach great importance to. It plays a vital role in environmental protection, and with the cost reduction and scale expansion, its alternative role of fossil energy has begun to emerge. Recently, China's new energy technology has developed rapidly and its installed capacity has been continuously improved, which has become the focus of China's energy development. In the first half of 2019, the installed capacity of new wind power was 9.09 million kilowatts, and the cumulative installed capacity of grid-connected power reached 193 million kilowatts.

However, due to its intermittent and anti-peaking characteristics, large-scale wind power integration will put great pressure on the peaking demand and stable operation of the power grid, which will cause difficulties in wind power accommodation. With the increase of wind power penetration rate, the regulation margin of thermal power and CHP units are limited, the flexibility of power grid is greatly reduced, and the wind curtailment is becoming more and more serious. It is becoming increasingly urgent to solve the problem of wind power dispatching in the operation stage.
In the first half of 2019, the national average wind-removal rate has reached to 4.7%, especially in the “Three North” (Northeast, North China, and Northwest) region of China.

The main reason for the wind curtailment is that the thermal power plant has a sharp decline in peaking capability during the heating period in winter [1]. Under the premise of ensuring the safety and stability of the power system, how to break through the electrothermal coupling constraint, reduce the high forced output caused by the mode of “power determined by heat” and improve wind power accommodation has become a research hotspot. This paper reviews the relevant research results at home and abroad from the power grid dispatching level, and summarizes the mainstream research results into two aspects: on the one hand, from the point of equipment, improve the peaking capability of the unit by adding electrothermal coupling equipment and on the other hand, from the perspective of dispatching, maximize peaking potential of the power system through the grid lean dispatching.

2. The electrothermal characteristics of CHP units

The coupling relationship between the output electric power and the external heating power of the CHP unit is called the “electrothermal characteristic”. The domestic CHP units mainly have two types: back-pressure type and extraction type. The electrothermal characteristic curve is shown in Fig.1.

![Figure 1. Thermoelectric characteristic curve](image)

For the back-pressure unit, the steam turbine back pressure exhaust gas exchanges heat with the hot network water through the steam-water heat exchanger, and the exhaust steam is all supplied to the heat user. The heating power and electric power of this type of unit are linearly related. After determining the heating power, the electric power is determined accordingly. The electric output \( P_{\text{chp}} \) is completely determined by its thermal output \( H_{\text{chp}} \), that is, the thermoelectric ratio of the unit is fixed, as shown in equation (1). In the heating period to meet the heat load demand in real time, this type of unit won’t have the adjustment capacity:

\[
P_{\text{chp}} = H_{\text{chp}} / K_{\text{hp}}
\]

(1)

Where \( K_{\text{hp}} \) and \( 1 / K_{\text{hp}} \) are the thermoelectric ratio of CHP unit and the slope of the line in Fig. 1(a).

The extraction unit is the main type in the thermal power plant. The steam from the intermediate pressure cylinder to the low pressure cylinder of the steam turbine is extracted from the intermediate pressure cylinder and the steam with high pressure and temperature as the heat source. Under the condition of meeting the operation requirements, the thermoelectric ratio can be adjusted by adjusting the amount of steam extraction. Its electrothermal characteristic can be described as:

\[
C_b H_{\text{chp}} \leq P_{\text{chp}} \leq S - C_v H_{\text{chp}}
\]

(2)

Where \( C_b \) and \( C_v \) are the slopes of the electric power lower limit and the upper limit corresponding line in Fig. 1(b), respectively, and \( S \) is the electric power maximum value.
When the heat load is high, in order to meet the cooling requirements of the turbine, the adjustment range of the output of the extraction unit is continuously reduced as the amount of steam extraction increases. If the wind power output is large during this period, in order to ensure that the wind power has sufficient space, the extraction unit is generally required to operate in the minimum condensing condition (Fig. 1(b) AB). At this time, the electric output is also determined by the heat load and it doesn’t have the flexibility of adjustment, as in equation (3):

$$P_{chp} = C_{h} H_{chp} = H_{chp} / K_{hp}$$

The area within the polygon in the fig. 1(b) is its working area. It can be seen from the figure that when the heating power is $P_{h}$, the electric power adjustment interval is $[P_{e,h,min}, P_{e,h,max}]$, and the ability of wind power accommodation is very limited. The higher the heat load, the smaller the power-conditioning power adjustment range and the worse the peaking capability.

A large number of thermal power units in northern China are CHP units. During the heating period in winter, the load is low at night, while the heating load is at a peak. The CHP unit with the mode of “power determined by heat” has a higher output level, the adjustment capacity of the unit is limited and the remaining space of the power grid is small, but this time is often a period with good wind resources, resulting in a large scale of wind curtailment. In order to eliminate large-scale wind power, it is necessary to break the operational constraints of “power determined by heat” and improve the peaking capability of the unit.

3. Adding electrothermal coupling equipment to decouple “power determined by heat”

At present, there are generally two ways to improve the peaking capacity of CHP units thus improving wind power accommodation: to transform the flexibility of the thermal power unit itself, such as bypass compensation heating, deep peak regulation technology, etc. [2]; to add electrothermal coupling equipment, such as electric boilers, heat storage devices, etc. The transformation of the former has less impact on the grid dispatching method. This article focuses on the latter.

3.1. Adding electric boiler for heating

In order for the CHP unit to reduce the forced output caused by the "power determined by heat", it’s necessary to compensate for the insufficient heating caused thereby. Adding an electric boiler on the power supply side or the load side can compensate for the heat supply, absorb the electric energy to generate heat energy and meet part of the thermal power demand. Meanwhile, it increases the electric load of the system, reduces the forced electric power of the" power determined by heat", decouples the thermo-electric coupling constraint and provides space for wind power accommodation. The principle of accepting wind curtailment is shown in Fig.2.

![Figure 2. Schematic diagram of wind power accommodation [3]](image-url)
From a macro perspective, the essence of the scheme is to use the wind curtailment power instead of the CHP unit for power and heat supply during the wind power abandonment period, thus reducing the coal consumption of the entire system and having obvious coal-saving benefits. The scheme is more suitable for wind power surplus, or electric boilers need to consume thermal power to supply heat, so that the system coal consumption increases.

The advantages of using electric boilers for compensation heating are as follows: Firstly, electric boiler equipment has a simple structure, low price, and high energy conversion efficiency [3]; secondly, electric boilers are flexible in operation, and the electric power consumed can be adjusted by adjusting the current magnitude or the heating rod group switching method; thirdly, for the electric boiler of the load side or the secondary heat network, the heat supply can be started and stopped at any time, and the heat load fluctuation can be well adapted.

A large number of studies have been carried out at home and abroad on taking use of electrothermal system dispatching with electric boilers to improve wind power accommodation. The analysis of the literature [4] shows that adding electric boilers to decouple its “power determined by heat” constraint, and then reduce the forced output to accept the wind power grid has a significant coal-saving effect and national economic feasibility. Literature [5] proposes a plan to add a peaking electric boiler to the secondary heating network, establish the start-stop control model of the peak-shaving electric boiler and the heat balance equation of the primary and secondary heating networks, increase the grid load valley while reducing the thermal load peak of the thermal power unit, thereby improving wind power accommodation. The literature [6] proposes a joint dispatching model for establishing electric heating boiler on the power supply side and the load side to receive wind curtailment. It’s found that the heating effect of electric boiler instead of the small coal-fired boiler on the load side is not as good as that of the power-side electric boiler. There are precedents in foreign countries that electric boilers and other heat sources cooperate with heat supply, and the technology is mature. For example, the Skagen Thermal Power Station in northern Denmark is equipped with an 11MW electric boiler which supplies heat combined with CHP units and other gas boilers.

3.2. Adding heat storage device for heating
Heat storage is a typical electrothermal decoupling technology. In electrothermal system, the application of large-capacity heat storage is similar to the peak-filling effect of pumping and storage energy. When the wind power output is small and the electric load is peak, use electric energy to store heat; when the wind power output is large, and the electric load is low, reduce the output of the CHP units. It can improve the flexibility of power system operation control, thereby improving wind power accommodation. The structure of the electro-thermal system is shown in Fig.3.

According to the coupling relationship between the power and the thermal system, the application location of the heat storage includes the CHP units and electric heating system, as shown in the dotted line in Fig.4. Applying large-capacity heat storage technology on the power supply side can break the rigid constraint of “power determined by heat”, effectively improve the adjustment capability of the CHP units. The wind power heating system with large-capacity heat storage on the load side takes use of the wind curtailment power to achieve clean heating. It can effectively improve the adjustment capability of the regional power system, and promote local consumption of renewable energy.

The heat storage device can increase the wind power receiving capacity and the maximum output of the heat-generator during the heating period. The coal-saving effect and peak-shaving efficiency are good, and the power grid dispatching and communication methods are not required to be adjusted greatly. It is one of the ideal solutions for wind power accommodation. However, there is an upper limit to the peaking capacity of the CHP units through the heat storage. When the thermal load assumed by the unit is too large or small, the effect of configuring the heat storage to increase the peaking capacity is not obvious; the investment of operating costs limit the application of heat storage devices; in addition, for the large amount of centralized heating in China, whether the scale of the heat storage device can meet the requirements of life, cost and efficiency needs further analysis.
At present, many studies have been carried out at home and abroad on heat storage devices to absorb wind power. Literature [7] constructed a dispatching model for CHP units and electric heating systems including heat storage, and incorporated heat storage into the active power dispatching system, and carried out the effects of different installation positions of the heat storage devices. The analysis verified the effectiveness of heat storage to improve wind power accommodation. Literature [9] analyzed the mechanism of heat storage tanks to increase the acceptance of wind power, established a comprehensive dispatching model including wind power, CHP units and thermal storage tanks, and compared the coal saved by cogeneration and wind power heating storage effect. Literature [10] proposes a dispatching mode in which the wind farm and the heat and power cogeneration with heat storage form a joint operation, and based on the dispatching model, a joint system optimization dispatching model considering wind power output uncertainty is proposed.

![Figure 3. Structure diagram of electro-thermal system with heat storage device [8]](image)

3.3. Multi-device combined heating

The combined application of two or more electrothermal coupling devices can greatly improve the adjustment capability of the CHP units, such as “electric boiler + heat storage”, or add some kind of electrothermal coupling devices on the power plant side and the load side to absorb wind power in a more flexible way. For example, installing heat storage devices on the side of the CHP unit, and electric boilers on the load side of the grid, the two can coordinate heating, the minimum power output can be achieved within a larger equivalent heating range, while increasing the maximum power generation, forming the system's spare capacity in order to achieve the purpose of heating and wind power accommodation.

![Figure 4. Application places of heat storage [7]](image)
The combined heating of the equipment can eliminate more wind curtailment and reduce the total dispatching cost of the system. In [11], heat pump heat is added to both the power supply and the load side. Through the joint coordinated dispatching of CHP unit, the centralized heat pump and the distributed heat pump, the peaking pressure of the system is reduced and the economics of the system operation is improved. Taking Denmark as an example abroad, the literature [12] jointly dispatches thermal power units, electric pumps and heat storage equipment to realize electrothermal decoupling to improve the peaking capacity and system economic efficiency of the thermal power unit. Through electrothermal coupling equipment and CHP units coordination joint heating, the characteristics of various types of equipment can be fully utilized, the adjustment space of the thermal power unit can be improved to a greater extent, and the peaking effect is remarkable. However, the high investment cost and complex operation need to be combined with the actual wind power accommodation.

4. Grid lean dispatching

In order to increase the peaking space of the power grid and reduce wind curtailment, in addition to adding electro-thermal coupling equipment to improve the equivalent output range of the CHP unit, it is also possible to promote electro-thermal coordination through lean dispatching, and to mine the peaking capability of the system under the current power supply and power grid structure. Based on the refined modeling of the dispatching system equipment, considering the power supply, power grid, and load characteristics, the power grid lean dispatching is realized by coordinating multiple types of power supplies, upper and lower level control mechanisms, and multiple timing dispatching cycles.

First of all, this paper reviews the multi-power joint dispatching. In order to break through the limitation of “power determined by heat” of CHP units, it is also possible to comprehensively consider the coordination of power supplies such as hydropower, thermal power, and pumping units with thermal power and wind power. Through the coordination of the start and stop of the CHP units, the peak shaving of the pumping unit and the hydropower units, the space for wind power accommodation is provided on the premise of ensuring heating. The literature [13] considers the forms of electricity and heat sources such as thermal power, thermoelectricity, wind power, hydropower, electric boilers, coal-fired boilers, etc., and improves wind power accommodation through multi-power supply and coordinated dispatching of power systems and thermal systems. Literature [14] established a cogeneration economic optimization model including photovoltaic, fan, gas turbine, fuel cell and other distributed power sources and electric energy storage unit. Through multi-power joint dispatching, the system economic benefits are improved on the basis of eliminating wind curtailment.

Then this paper reviews the multi-period rolling dispatching. Since the accuracy of wind power increases with the shortening of the forecasting time, the schedule of the remaining time period is rolling adjusted according to the latest wind power and load forecast at regular intervals through multi-time rolling scheduling, which can effectively reduce the impact of forecast uncertainty on the previous plan. Literature [15] proposes a joint optimization rolling scheduling algorithm considering wind power and other types of units. Considering the influence of thermoelectric coupling constraints, the current output value of the generator is taken as the initial solution to the optimization problem. Through rolling adjustment, the peaking potential of the system is mined and wind power accommodation is improved. Literature [16] establishes a joint dispatching model including wind power, thermal power units and electric boilers. Based on the previous dispatching plan, the rolling plan and real-time plan are added, and the daily dispatch plan is revised step by step according to the latest forecast data. The practical study verifies the proposed strategy can improve the electrothermal joint dispatching and improve power accommodation.

There are many other scheduling strategy optimizations. This paper will list some related literature. Literature [17], considering the heat storage inertia of the heat network, establishes a power dispatching system, solves the close relationship between power and heat supply, and improves the wind power accommodation capability. But in order to ensure the quality of residents' heating, the actual reduction of wind accommodation and energy saving is relatively insignificant [18]. In [19], the electric boiler consumes wind power to realize central heating of wind power, and a joint dispatching
model including wind power, thermoelectricity and heat load is established. The results of the example show that the central heating of wind power improves the ability of the system to absorb wind power. However, this kind of wind power central heating strategy must be realized by electric boilers, heat pumps and other equipment, and essentially the use of electrothermal coupling equipment for peak shaving. Literature [20] establishes a district secondary dispatching mode, which is based on the actual situation of the provincial power grids in the region, and organizes the fluctuations of the balanced wind power output of conventional units within the regional power grid to minimize the amount of wind curtailment to achieve effective and rational use of wind energy.

5. Economic dispatching algorithm for thermoelectricity and wind power

The economic dispatching problem of cogeneration with CHP units and wind power is a large-scale, non-linear, multi-constrained optimization problem. In addition to the cost of power generation, the objective function considered includes targets such as pollutant emissions, backup costs, and abandoned wind, as well as multiple targets with single targets; the constraints are considered in addition to basic constraints such as power balance, unit output constraints, and standby constraints, as well as thermoelectric characteristics of thermal power units, thermal balance, and operational constraints of electrothermal coupling components.

In the method of solving economic dispatch, it is mainly divided into traditional algorithm and heuristic artificial intelligence algorithm. At present, improved algorithms and combined algorithms based on various algorithms have become mainstream algorithms.

5.1. Traditional algorithm

Traditionally, Lagrangian relaxation and mixed integer methods are used more. The Lagrangian relaxation method decomposes the original problem into the main and sub-problems by relaxing the coupling constraint of the original optimization problem, and gradually approaches the optimal solution through the iteration between the main and sub-problems. The literature [21] used the Lagrangian relaxation method earlier in the economic dispatching problem involving thermal power units, and thereafter Lagrangian relaxation methods based on various improvements have been widely used. As in [15], a joint optimization rolling scheduling algorithm based on Lagrangian relaxation method and an adaptive iterative step size correction method are proposed to improve the convergence speed and optimization ability of the algorithm. The mixed integer programming method is very suitable for solving the unit combination and economic scheduling problems in the physical model. The solution sought is the global optimal solution, which can adapt to the modeling of complex logic. At present, large commercial software such as Cplex and Gams, etc. are commonly used.

5.2. Heuristic intelligent algorithm

As for heuristic intelligent algorithms, genetic algorithms and particle swarm optimization algorithms are commonly used. As a global search technique, genetic algorithm can be used to deal with optimization problems with non-smooth or non-convex functions as the objective function. Literature [22] adopted an improved genetic algorithm and introduced an elite retention strategy to improve the speed of optimization. The particle swarm optimization algorithm searches for the optimal solution through the cooperation among individuals. Particle swarm and its improved algorithms are also a class of effective and practical calculation methods for large-scale, non-convex, nonlinear and multi-constrained scheduling control optimization problems, such as HPSO, TVAC-PSO, IPSO-TVAC, etc [23]. It improves the particle convergence speed and calculation accuracy in the iterative process by algorithm improvement and avoids local optimization.

5.3. Combination algorithm

The combination algorithm can avoid the shortcomings of a single algorithm and improve the efficiency and accuracy of the solution. In [15], an immune genetic Lagrangian relaxation hybrid algorithm is proposed, which uses the immune genetic algorithm to solve the unit combination
problem. In the thermal and electrical load economic allocation problem, the Lagrangian relaxation algorithm is used to achieve wind power and thermoelectric optimization problem solving. In [24], the particle swarm optimization is embedded in the evolutionary programming process, and the evolutionary programming particle swarm optimization algorithm is proposed to solve the economic scheduling problem, which improves the efficiency and accuracy.

6. Practical application of electrothermal coordination

In foreign countries, in order to improve the peaking capacity of the power grid and improve wind power accommodation, the main strategies include the addition of electric heating coupling equipment and distributed heating, etc.

Taking the Nordic countries such as Denmark and Finland as examples, under the guidance of real-time electricity prices, the configuration of electric boilers and heat storage devices in thermal power plants has become an important means for their future consumption of renewable energy. Among them, Denmark is one of the leaders in the global wind power industry. The country's wind power ratio is very high, and the installed capacity of wind power accounts for about 30% of the total installed capacity. Denmark has a large number of unattended peak-adjusting boilers on the secondary heat network side after the heat exchange station. It can automatically adjust and start and stop according to user requirements and outdoor weather changes, further improving the ability to adjust the heat load. In the United States, Germany and other places, the research and application of the combined thermal power unit and heat pump system (CHP-HP) is extensive, and it is closely related to the heating of household houses, achieving the near-balance of thermal load [25].

In China, though there are many studies on electrothermal coupling equipment, there are not many practical applications. First, although in terms of overall social benefits, increasing the number of electro-thermal coupling devices can improve wind power accommodation, save energy and reduce pollutant emissions. However, for thermal power plants, increasing wind power consumption and reducing thermal power generation will affect power plant revenues. At the same time, the increase of heat storage, electric boilers and other equipment will increase additional investment. Due to the lack of effective incentive mechanism at present, thermal power plants lack the initiative to participate in wind power peak shaving, so the related technologies are less in practical applications.

7. Conclusion

Aiming at the difficulty of wind power accommodation during the heating period, this paper classifies and summarizes the related research results from the aspects of adding electrothermal coupling equipment and grid lean scheduling. The analysis shows that the addition of electro-thermal coupling equipment directly increases the peaking space of the system. The effect is obvious, but the investment needs to be increased. The lean dispatching focuses on the peaking potential of the mining system under the current power supply and power grid structure, but the effect is not as obvious as the former. On the power supply side, domestic power plants lack the enthusiasm for the thermal power unit to participate in peak shaving. In the future, it is necessary to construct a reasonable policy incentive mechanism and strengthen price guidance. On the grid side, it is necessary to construct a scientific and feasible electro-thermal joint dispatching model according to the actual situation. The ways of multiple power sources, multiple heat source joints, and multi-cycle rolling can mine system peaking potential further, improve the lean level of power grid dispatching and the level of wind power accommodation.

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