Optimal dispatching strategy in the domain with energy storage and heat storage taking into account deep regulation of thermal power plants

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Abstract. In recent years, the installed capacity of wind power has been increasing, and the phenomenon of regional wind abandonment has become prominent. In order to improve the wind power accommodation, the domain definition is introduced, which stipulates that the periods without wind abandonment and load shedding during normal output of thermal power units are normal domains, the periods without wind abandonment or load shedding when thermal power units exert depth adjustment are abnormal domains, and the periods with wind abandonment or load shedding during depth adjustment of thermal power units are emergency domains. Give full play to the depth adjustment of thermal power units in abnormal and emergency areas, improve the accommodation of clean energy, and realize the coordinated and optimized scheduling of multiple energy sources including electricity storage and heat storage systems. To accommodate clean energy, an economic dispatching model including the cost of thermal power, the cost and benefit of power storage and heat storage system is constructed, and the optimal value of the model is solved by calling CPLEX with Matlab. The scheduling results not only ensure the safety and reliability of the whole network operation but also maximize the consumption of wind energy and realize the optimal clean energy scheduling.

1. Introduction
Wind power plays a dominant role in renewable energy power generation, and by the end of 2016, the cumulative grid-connected capacity of wind power has reached $1.49 \times 10^6$ kw [1]. The uncontrollability and volatility of wind power are serious, and the national average wind abandonment rate within one year is as high as 17% [2]. With the rise of ubiquitous power Internet of Things, it can better realize the joint operation of heat load and power grid [3]. Literature [4-5] puts forward that in the power system with a high proportion of wind power, energy storage is used to participate in power grid regulation, the uncertainty of wind power is analyzed, and the charging and discharging strategy of energy storage is arranged in the scheduling to absorb wind energy. Literature [6-7] puts forward a wind-fire-heat storage joint scheduling scheme including heat storage elements, analyzes the economic factors such as the income of the heat storage system and the penalty cost of abandoning wind, and
obtains a scheduling scheme with maximum income. Literature [8] adds a power storage system based on the wind-fire-heat storage joint scheduling model and solves the optimal solution by particle swarm optimization. Through the joint dispatching of power storage system and heat storage system [9], the peaking capacity and flexibility of the system are improved, the utilization rate of wind power is improved, and the operation cost is reduced.

Giving full play to the depth adjustment of thermal power units will increase the consumption of clean energy. In this paper, the wind-fire-storage-storage optimal operation of thermal power units in abnormal and emergency areas is mainly considered, and the wind power accommodation increases accordingly. This scheduling scheme can clearly see the change of utilization rate of clean energy in the scheduling process according to the division of domains. The three adjustment methods of power storage, heat storage, and depth adjustment of thermal power units are jointly scheduled, which makes the scheduling scheme more flexible and beneficial to environmental protection. Give full play to the depth adjustment of thermal power units in abnormal and emergency areas, improve the capacity of clean energy, and realize the coordinated and optimized scheduling of various energy sources such as power storage and heat storage systems.

2. Determination of the depth adjustment capability of thermal power units

2.1. The regulation capability of thermal power units

The depth regulation of thermal power units refers to the operating power is less than the minimum value of the normal operation, which will bring economic losses. To encourage the power plant to actively cooperate with the dispatching, the economic compensation should be made according to the depth adjustment of the dispatching of the generating set beyond its normal generating range. The unit shall be compensated at 50 yuan /MWh for the amount of electricity that is less than the rated minimum power when providing the depth regulation service. Set the compensation cost of depth adjustment as \( C_{pa} \).

The regulating capacity of thermal power units can be divided into three stages. The first stage is that the output power of the thermal power unit itself is between the maximum value and the minimum value, \( P_{\text{min}} \leq P_{\text{Gir}} \leq P_{\text{max}} \), which belongs to the normal regulation stage. The second stage is to make the output power smaller, where the power range is \( P_{\text{a}} \leq P_{\text{Gir}} \leq P_{\text{min}} \). The third stage is the stage of adjusting the depth of oil injection. This stage can minimize the output of the thermal power unit. At this time, the power range is \( P_{\text{b}} \leq P_{\text{Gir}} \leq P_{\text{a}} \), and the unit is not fully combusted. Oil injection is needed to support combustion to ensure the stable operation of the boiler and water circulation system.

2.2. In-depth adjustment cost analysis

The cost of the first stage is the normal coal consumption of thermal power units, as shown in formula (1); The cost of the second stage is based on the cost of the first stage, and the life loss cost of the unit needs to be considered. The life loss rate for the unit to rapidly reduce the load to 40% is 0.005%.

According to the Manson-Coffin formula, the life loss cost formula for depth adjustment is obtained in this paper. See formula (2); The cost of the third stage will lead to the instability of the system because the lower output limit of the thermal power unit is further lowered. At this time, the stability of the system needs to be maintained by oil injection. Therefore, the cost of oil will be increased in addition to the cost of the first two stages. The cost is expressed by Formula (3). In the third stage, thermal power units will increase the emission of gases harmful to the atmosphere [7]; The government will impose a fine when the emission is excessive. The cost caused by environmental pollution is shown in formula (4); See formula (5) for the additional cost of the third stage.

\[
C_f = \sum_{i=1}^{N}\sum_{j=1}^{n} u_i (a_{ij} P_{Gir}^i + b_{ij} P_{Gir}^j + c_{ij}) + \sum_{i=1}^{N}\sum_{j=1}^{n} u_i (1-u_{ij}) s_j
\]
In the formula, \( T \) is the total number of periods in a day; \( N_p \) represents the number of thermal power units; \( C_f \) is the output power of thermal power unit \( i \) during \( t \) period; \( a_i, b_i, c_i \) is the power generation cost constant of unit \( i \); \( s_i \) is the cost when unit \( i \) changes from shutdown to startup; \( u_i = 0 \) indicates that the unit is in a shutdown state and 1 indicates that unit \( i \) is in startup state. \( \alpha_i \) is the loss coefficient of thermal power units under depth adjustment; \( S_{\text{unit}} \) is the purchase cost of unit \( i \), with the unit being 10,000 yuan; \( N_p \) is the cycle number required for rotor splitting; \( C_o \) is the amount of oil used, in tons; \( S_{\text{oil}} \) is the oil price, the unit is RMB 10,000/ton; \( W_p \) is the penalty for using unit fuel in the third stage; \( S_p \) is a fine function when harmful gases are emitted excessively.

The generation cost of a thermal power unit when it is given full play to its depth regulation capacity is shown as follows:

\[
C_d = \begin{cases} 
C_f + C_{\text{unit}} + C_{p} - P_{\text{min}} \leq P_{\text{G}} \leq P_{\text{max}} \\
C_f + C_{\text{unit}} + C_{p} - P_{\text{min}} \leq P_{\text{G}} \leq P_{\text{max}} \\
C_f + C_{\text{unit}} + C_{p} - P_{\text{min}} \leq P_{\text{G}} \leq P_{\text{max}} 
\end{cases}
\]

(6)

3. Scheduling model

3.1. Objective function

The objective is to maximize the absorption of wind power. The objective function with the minimum operating cost is established to achieve the objective of maximizing the absorption of wind power with the optimal economy. The following objective function is established to ensure the safety and reliability meet the actual requirements after adding constraints:

\[
\min C_o = C_f + C_{\text{unit}} - E_{\text{dis}} - E_{\text{ess}}
\]

(7)

The formula: \( C_{\omega} \) represents the charging cost of the power storage system [8]; \( E_{\text{dis}} \) represents the discharged income of the power storage system; \( E_{\text{ess}} \) represents the heating revenue of the heat storage system [9].

3.2. Constraint conditions

Constraints include thermal power unit output constraint, system backup constraint, power balance constraint, thermal power unit runtime constraint, thermal power unit climbing constraint, unit power constraint, the state-of-charge constraint of electric storage device, electric storage power reduction, Electric storage operation state constraint, regenerative electric boiler power constraint, thermal storage constraint, regenerative electric boiler power fluctuation constraint.

3.3. Partition of operation domain

Stipulating that the periods without wind abandonment and load shedding during normal output of thermal power units are normal domains, the periods without wind abandonment or load shedding when thermal power units exert depth adjustment are abnormal domains, and the periods with wind abandonment or load shedding during depth adjustment of thermal power units are emergency domains. The division of domains can be further clarified through Table 1, where \( P_{\text{Lt}} = P_{\text{Lt}} + P_{\text{loss(t-1)}} \cdot (P_{\text{Lt}} \) is the total load of the system; \( P_{\text{loss(t-1)}} \) is the system line loss.
Table 1. Division of operation domain.

| Measure the amount | Control field | Heat storage and heat storage state |
|--------------------|---------------|------------------------------------|
| $P_{\text{min}} \leq P_{\text{f}} - P_{\text{e}} \leq P_{\text{max}}$ | Normal domain | 0                                  |
| $P_{\text{min}} + P_{\text{f}} > P_{\text{e}}$ | Abnormal domain | Storage charge, heat storage system storage |
| $P_{\text{min}} + P_{\text{f}} < P_{\text{e}}$ | Abnormal domain | Storage discharge |
| $P_{\text{min}} + P_{\text{f}} + P_{\text{wind}} \geq P_{\text{e}}$ | Emergency domain | Storage charge, heat storage system storage |

4. Example analysis

The example in this paper is based on IEEE-30-node system [9], and one thermal power unit with 200MW, 200MW, 100MW and 125MW is arranged at nodes 18, 21, 22 and 23 respectively, and the upper and lower limits of the output of conventional units are required to be $P_{\text{e, min}} = 0.5P_{\text{N}}$ and $P_{\text{e, max}} = 0.8P_{\text{N}}$. A wind farm with installed capacity of 270MW is respectively arranged at nodes 15 and 16, an electric storage system with maximum charging and discharging power of 50MW is arranged at node 7, and a heat storage system is arranged at node 6, with a maximum power of 40MW. The wiring diagram of the system is shown in Figure 1, taking a certain day in winter in a certain area of northeast China as a typical load day, the wind power output and load are predicted according to historical data, and then the power generation of thermal power units is reasonably arranged according to the output situation at each time of the day, taking into account the deep adjustment capability of thermal power units and ignoring the deep adjustment capability of thermal power units respectively, and calling CPLEX by Matlab to solve the optimal scheduling scheme.

4.1. Wind power generation and load prediction value

Based on the analysis of historical data and existing weather conditions, wind power prediction values, and load prediction values for 24 hours in the dispatching day can be obtained, as shown in Figure 2:

![Figure 1. Network structure of simulation system.](image1.png)

![Figure 2. Load and wind power prediction value.](image2.png)

4.2. Simulation results and analysis

According to the predicted results in Figure 2, when the depth regulation capacity of thermal power units is not taken into account, the optimal scheduling scheme within one day is shown in Figure 3. When the depth regulation capacity of the thermal power unit is taken into account, the optimal scheduling scheme within the same day is shown in Figure 4. When the depth adjustment capacity of
thermal power units is excluded and the depth adjustment capacity of thermal power units is taken into account, the periods of different domains are shown in Table 2. The output of each system on the day when the depth adjustment capacity of thermal power units and the depth adjustment capacity of thermal power units are taken into account is shown in Table 3.

**Figure 3.** Excluding depth adjustment in one day.  
**Figure 4.** Depth adjustment of unit output in one day.

Through analysis, the chart above, wind power output is more extreme in the abnormal domain, when introduced into storage systems for storing heat peak on wind power cut, either through the way of electric heating to earn profits, can also be adjusted reasonably call storage system, and the abnormal thermal power unit output in the domain are relatively stable, ease of scheduling. When considering the deep regulation capacity of thermal power units, eight emergency areas can be transformed into abnormal areas, which can absorb wind energy to a greater extent. According to the division of the domains, the reserve capacity can be reasonably used in the normal domain, abnormal domain, and emergency domain to ensure the safe and stable operation of the system and maximize the absorption of wind power.

**Table 2.** Time intervals for different domains.

|                  | Excluding depth adjustment of thermal power units | Including depth adjustment of thermal power units |
|------------------|-------------------------------------------------|-------------------------------------------------|
| Abnormal domain  | 1-4,13-19,24,25,65-82.95-96                     | 1-8, 13,25,65-82.95-96                           |
| Emergency domain | 5-12, 20-23,84,85                                | 9-12,84,85                                       |
| Normal domain    | Other time                                       | Other time                                       |

**Table 3.** System output under different conditions.

| System output | Excluding depth adjustment | Including depth adjustment |
|---------------|----------------------------|---------------------------|
| $kW\cdot h$   |                            |                           |
| The first stage of thermal power units | $7.8 \times 10^6$ | $7.4 \times 10^6$ |
| The second stage of thermal power units | 0 | $1.4 \times 10^5$ |
| The third stage of thermal power units | 0 | 1.3 |
| Wind power    | $5.6 \times 10^5$ | $5.7 \times 10^6$ |
| Storage system | $1.2 \times 10^5$ | $1.2 \times 10^5$ |
| The thermal storage system | $2.7 \times 10^5$ | $2.7 \times 10^5$ |
| Abandon the wind | $4.1 \times 10^5$ | $3.18 \times 10^5$ |
| Wind power utilization rate (%) | 93.2 | 94.7 |
5. Conclusions
Based on the wind power and load forecasting results, the dispatching period is divided into normal domains, abnormal domains, and emergency domains in advance, and the wind power consumption and wind abandonment period can be clearly and intuitively seen through the division of domains. In the abnormal domain and emergency domain, the power storage system and heat storage system are reasonably called, and at the same time, the depth adjustment ability of thermal power units is brought into full play to reduce the wind rejection rate. Matlab is used to call CPLEX to solve the optimal value of the model. When the depth adjustment of thermal power units is brought into play, some emergency domain periods can be converted into abnormal domain periods, which further increases the absorptive capacity of wind power.

(1) The definition of the domain is introduced, which is convenient for intuitive analysis of wind power consumption in each dispatching period. On this basis, the power storage system and heat storage system are reasonably called to improve wind power consumption. When necessary, giving full play to the deep regulation ability of thermal power units can reduce the time interval of emergency domains, increase the time intervals of abnormal domains, realize the transition from "wind must be abandoned" to "complete wind energy consumption", improve the wind power consumption ability, and facilitate dispatchers to predict the wind abandonment time in the dispatching stage in advance and make corresponding strategies in advance;

(2) Wind power enterprises are the direct beneficiaries of deep regulation, which is uneconomical for thermal power enterprises. However, if the deep regulation of thermal power units is not carried out, the penalty cost of wind abandonment stipulated by the government will be higher. Therefore, considering the deep regulation ability of thermal power units, more wind energy can be absorbed, and the overall economy is better;

(3) Based on the forecast and dispatching results, the wind abandonment or load shedding period on the dispatching day can be predicted in advance. In the continuous period of abnormal domains, it can be intuitively observed that the output fluctuation of thermal power units is very small and fluctuates around the maximum or minimum value, so thermal power units may not be able to provide rotating reserve capacity in abnormal domains. In future research, we can analyze the setting of reserve capacity in different domains, and optimize the reserve reasonably based on ensuring the safe operation of power system, to improve the operation economy of power system.

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