Optimal capacity allocation of thermal storage system considering peak regulation ancillary services

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Abstract. Limited by the operation mode of ‘heat-set’ is one of the main reasons for the large amount of wind abandonment in Northeast China. Reasonable allocation of electric heat storage system is an effective means to improve the wind power absorption capacity of regional power grid. In this paper, an optimal capacity allocation model of electric heat storage system considering peak regulation auxiliary services is proposed, and the optimal capacity of electric heat storage system is solved based on game theory. Firstly, the economic benefits of each stakeholder participating in peak regulation ancillary service market are analyzed by allocating electric heat storage equipment in thermal power plants. Secondly, a bi-level programming model for optimal capacity allocation of electric thermal storage system is established. Finally, the model is optimized by particle swarm optimization and Cplex hybrid optimization method. The optimal configuration scheme of the electric heat storage system is obtained by solving the optimization problem. The example shows that the model is reasonable and effective.

1. Introduction
In recent years, the problem of wind abandonment in the "Three North" area of China has become more and more serious. According to the statistics of the national energy administration, in the first half of 2017 alone, the abandoned wind power reached 23.5 billion kW•h, with an average abandoned wind rate of 13.6% [1]. However, in the winter heating period in Northeast China, the thermal power unit is limited by the operation mode of "power by heat", which further reduces the system regulation capacity, which is the main reason for wind abandonment [2-3].

In order to break the traditional operation mode of "thermal power generation", reduce abandoned wind and promote wind power consumption, the existing research has carried out a lot of work in improving the regulation capacity of combined heat and power (CHP) units. Literature [4] analyzes and models the electric heating operation characteristics of large-scale extraction units before and after heat storage, discusses the flexible operation mode of thermal power units after heat storage; literature [5] establishes the operation optimization model of the electric heating energy integrated system under the complex power and heat source structure, and verifies that the proposed model can improve the overall peak load regulation capacity of the system, and provide more absorption space for wind power.

Based on the above problems, this paper proposes a two-level optimal allocation model of electric heat storage system capacity under the peak load regulation market trading mode: the lower level
optimization model takes the minimum penalty cost of wind farm as the optimization objective function, and optimize the generation power of wind farm, the output value of conventional thermal power unit and the output value of thermal power unit; based on the variable value optimized by the following layer optimization model, the upper layer optimization model takes the maximum benefit of wind farm, thermal power plant, thermal power plant and power grid as the objective function to obtain the optimal capacity configuration of the thermal storage equipment. An example shows that the proposed model is reasonable and effective.

2. Cost benefit analysis of all subjects participating in peak shaving market transactions

2.1. Cost benefit analysis of all subjects participating in peak shaving market transactions

The total revenue of a thermal power plant participating in peak shaving auxiliary service market is:

$$E_{TF} = \sum_{i=1}^{n} P_{H,TF,i} \cdot P_{TF,i}$$  \hspace{1cm} (1)

In the formula: $E_{TF}$ is the total income of participating in peak load adjustment auxiliary service; $P_{H,TF,i}$ is the paid peak load adjustment power of the $i^{th}$ level; $P_{TF,i}$ is the clearing price of the $i^{th}$ level.

2.2. Economic benefits of wind farm participating in peak load regulation auxiliary service market

According to literature [6], it can be seen that wind power is temporarily considered as not having peak load regulation auxiliary service capacity. Therefore, the wind farm needs to share all the profit expenses of the seller of the paid peak shaving auxiliary service with other buyers.

$$C_W = \frac{P_{W,Actu}}{P_{W,Actu} + P_{T,Modi}} \cdot E_{TF} \cdot P_{W,Corr}$$  \hspace{1cm} (2)

Where: $C_W$ is the apportionment amount for peak load regulation of the wind farm; $P_{W,Actu}$ is the actual power generation of the wind farm; $P_{T,Modi}$ is the corrected power generation of the thermal power plant; $P_{W,Corr}$ is the correction coefficient.

2.3. Economic benefits of thermal power plant participating in peak load regulation auxiliary service market

Thermal power plants that fail to fulfill their duty of peak load regulation need to purchase deep peak load regulation services. The allocated peak shaving auxiliary service cost is:

$$C_T = \frac{P_{T,Modi}}{P_{W,Actu} + P_{T,Modi}} \cdot E_{TF}$$  \hspace{1cm} (3)

$$P_{T,Modi} = \sum_{i=1}^{2} P_{T,Actu,i} \cdot k_{T,Corr,i}$$  \hspace{1cm} (4)

Where: $C_T$ is the apportionment amount for peak load regulation of thermal power plant; $P_{T,Actu,i}$ is the actual power generation of the $i^{th}$ grade of thermal power plant; $k_{T,Corr,i}$ is the correction factor.

3. Capacity optimization model of electric heat storage system based on double-layer optimization

In this paper, the double-layer model of capacity optimization of thermal storage system is built. The relationship between the participants of the regional power grid is shown in figure 1.
3.1. Lower level optimization model
The lower level optimization model takes the minimum penalty cost of wind farm as the optimization objective function. The mathematical model is shown in equation (5):

$$F_d = \sum_{i=1}^{M} \sum_{t=1}^{T} (P_{WF,ij,t} - P_{W,i,t})r$$

Where: $M$ is the total number of wind farms; $T$ is the total scheduling time of heating season; $P_{WF,ij,t}$ is the predicted generation power of wind farms $i$ at time $t$; $P_{W,i,t}$ is the generation power of wind farms $i$ at time $t$; $r$ is the penalty cost of wind farms' abandoned wind power.

The following constraints need to be met.

(1) Wind power output constraint:

$$0 \leq P_{W,i,t} \leq P_{WF,i,t}$$

(2) Heating balance constraint:

$$\sum_{t=1}^{T} H_{H,i,t} = H_{load,i}$$

Where: $H_{H,i,t}$ is the heating power of the thermal power unit $i$ at time $t$; $H_{load,i}$ is the heat load during the period $t$.

3.2. Upper level optimization model
The upper optimization model aims to maximize the total revenue of wind farms, thermal power plants, thermal power plants and grid companies on the premise of improving the wind power consumption capacity.

$$F_u = \max(f_w + f_T + f_H + f_G)$$

Where: $f_w$ is the annual net income of the wind farm; $f_T$ is the annual net income of the thermal power plant; $f_H$ is the annual net income of the thermal power plant; $f_G$ is the annual net income of the power grid.

$$E_w = \sum_{i=1}^{M} \sum_{t=1}^{T} P_{H,i,t} (p_w - d_s)$$

$$E_T = \sum_{i=1}^{N} \sum_{t=1}^{T} P_{T,i,t} - \sum_{i=1}^{M} \sum_{t=1}^{T} \left( a_t P_{T,i,t}^2 + b_t P_{T,i,t} + c_t \right)$$


Figure 1. Relations among participants in regional power grid.
\begin{equation}
E_H = \sum_{i=1}^{K} \sum_{j=1}^{T} P_{H,i,j} + \sum_{i=1}^{K} \sum_{j=1}^{T} P_{\text{heat}}H_{H,i,j}
\end{equation}

\begin{equation}
E_G = \sum_{i=1}^{M} \sum_{j=1}^{T} \left( p_{gw} - p_w \right) P_{gw,i,j} + \sum_{i=1}^{N} \sum_{j=1}^{T} \left( p_{gt} - p_t \right) P_{gt,i,j} + \sum_{i=1}^{N} \sum_{j=1}^{T} \left( p_{gh} - p_h \right) P_{gh,i,j}
\end{equation}

In the formula: \( p_w \) is the price of wind power on grid; \( d_w \) is the operation and maintenance cost of wind power generation; \( p_t \) the price of thermal power generation on grid; \( a \), \( b \) and \( c \) are the coal consumption coefficient of thermal power generation; \( p_{gw} \), \( p_{gt} \) and \( p_{gh} \) are the unit price of electricity of wind farms, thermal power plants and thermal power plants sold by the grid.

4. Case analysis

In this section, the simulation analysis is carried out based on the above-mentioned optimal configuration model of electric heat storage system wind, and the rationality and effectiveness of the above-mentioned electric heat storage capacity planning model are verified by an example. The typical daily power / heat load data curve and wind power prediction curve of a certain area in Northeast China are shown in figure 2.

![Figure 2. The typical curve of electric / thermal load and forecast wind power.](image)

In this paper, the measured electric load data and wind power prediction data of a certain area in Northeast China are analyzed, and the optimal configuration model of electric heat storage system is solved. The experimental results are shown in Table 1. Figure 3 shows the electricity trading in the electricity peak shaving market.

|                         | Annual income / Billion yuan | Heat storage capacity /MW-h | Peak shaving ancillary service revenue / Billion yuan | Annual net income / Billion yuan |
|-------------------------|------------------------------|-----------------------------|-----------------------------------------------------|---------------------------------|
| Wind farm               | 10.1475                      | -4.4865                     | 5.6610                                              |                                 |
| Thermal power plant     | 3.4080                       | -2.9870                     | 0.4210                                              |                                 |
| CHP power plant         | 2.3920                       | \( S_{St}: 1810 \)          | 7.4735                                              | 9.8655                          |
|                         |                              | \( S_{Ph}: 1790 \)          |                                                     |                                 |
| Power Grid Corp         | 15.0814                      |                              | 15.0814                                             | 31.0289                         |
| Total revenue           | 31.0289                      |                              |                                                     |                                 |
According to the experimental results in Table 1, the optimal capacity of the electric boiler with thermal storage is 1810MW•h, and the optimal capacity of the phase change thermal storage system is 1790MW•H. According to the results in Figure 3, the free and paid peak load regulation capacity provided by the thermal power plant are 22269MW•h and 10832MW•h respectively. The free peak load regulation allocated to thermal power plants and wind farms is 8900MW•h and 13369MW•h respectively, and the paid peak load regulation purchased by thermal power plants and wind farms is 4329MW•h and 6503MW•h respectively. After the thermal power plant is equipped with heat storage system, the revenue from participating in the peak shaving auxiliary service market is 74735 million yuan, and the peak shaving auxiliary service cost shared by wind farm and thermal power plant is 44865 million yuan and 2987 million yuan respectively. The total annual net income of each entity is 310289 million yuan.

Figure 3. Electricity peak-shaving market trading situation.

5. Conclusion
In this paper, based on the current northeast electric power peak shaving auxiliary service market, a capacity optimization model of electric heat storage system under the peak shaving market trading mode is proposed, and a typical example of the northeast electric / heat load data is analyzed to verify the rationality and effectiveness of the model. Considering the optimal allocation of the capacity of the electric heat storage system under the peak load regulation market trading mode, the thermal power plant can obtain additional economic benefits by allocating the heat storage system, so that the thermal power plant can allocate sufficient heat storage capacity to decouple the operation mode of "power by heat", improve the regulation capacity of the thermal power unit, promote the consumption of wind power, and effectively alleviate the wind abandonment in Northeast China Problems.

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