Optimal model for deviation penalty of electricity in joint operation of wind power retailer and heat storage electric boiler

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Abstract. Because of the randomness and fluctuation characteristics of wind power output, there is a deviation between the bidding output and the actual output of the wind power retailer, and it faces with a lot of penalty fees for deviated power. In order to promote clean heating in the northern heating area, the heat storage electric boiler (this article abbreviates as HSEB) have been gradually promoted. Based on the thermal storage capacity of the HSEB, the deviation of wind power output can be reduced to a certain extent. Considering the comfort range of the indoor human body, the indoor heat supply can fluctuate within a certain range, further increasing the regulation capacity of the HSEB. In this study, taking reducing the cost of deviation penalty as the objective function, and a joint operation model of wind power retailer and HSEB is established. By an example, the feasibility of using HSEB to reduce the cost of deviation penalty is verified.

1. Introduction

With the development of power market, it is an inevitable trend for wind power companies to participate in power market competition [1-2]. However, the characteristics of wind power's randomness and volatility makes a deviation between the bidding and actual output of wind power retailers. Deviation power will be penalized according to the penalty system, which will reduce the revenue of wind power retailers.

In order to reduce the impact of wind power output uncertainty on the operation efficiency, in [3] provides an idea for considering the consumption of wind power output uncertainty comprehensively by establishing a double-level robust interval economic scheduling model of wind-storage joint operation. In [4] considers the risk of load loss and wind abandonment in the joint operation of wind-storage system, and establishes a multi-objective optimal dispatching model of integrated power stations with wind and storage. All of the above studies are to reduce the wind power deviation, and do not involve the deviation penalty.

In [5], a multi-objective optimal scheduling model is established to maximize the revenue and minimize the voltage deviation. In [6] considers the demand response mechanism, and uses the interruptible load contract and the spread option contract to optimize the model of deviation penalty. In [7] uses two methods of real-time market power purchase and energy storage power station trading...
to establish an optimization model for the daily market deviation penalty. In [8], the electric energy storage and wind power retailers are jointly operated to build the model of deviation penalty of wind-storage system.

At present, electric energy storage is involved in reducing the deviation of wind power output and the cost of deviation penalty under the power market environment, while HSEB can also reduce the cost of deviation penalty to a certain extent due to its ability of energy storage. Based on this, this paper establishes a joint operation model of wind power retailer and HSEB, and verifies the feasibility of using HSEB to reduce the cost of deviation penalty through an example.

2. Model and Constraints

2.1. Deviation Penalty Model of Wind Power Retailer

Assuming that the bidding output is $Q_b(t)$ and the actual output is $Q_a(t)$, then the wind power retailer’s bidding output deviation $Q\Delta(t)$ is as follow.

$$Q\Delta(t) = Q_S(t) - Q_b(t)$$

(1)

The bidding deviation rate $Q\theta(t)$ is as follow.

$$Q\theta(t) = Q\Delta(t) / Q_b(t)$$

(2)

When $Q\theta(t) > 0$, the deviation is positive, the expression of the power to be penalized is as follow.

$$Q^+_{pe}(t) = \max\{Q_a(t) - \tilde{\vartheta}^+(t)Q_b(t), 0\}$$

(3)

$\tilde{\vartheta}^+(t)$ is the positive deviation exemption penalty coefficient, which is 5% in this paper.

When $Q\theta(t) < 0$, the deviation is negative, the expression of the power to be penalized is as follow.

$$Q^-_{pe}(t) = \max\{\tilde{\vartheta}^-(t)Q_b(t) - Q_a(t), 0\}$$

(4)

$\tilde{\vartheta}^-(t)$ is the negative deviation exemption penalty coefficient, which is -5% in this paper.

The dispatch cycle studied in this paper is 24 hours, with 1 hour as the unit period length. The actual revenue of wind power retailer in a dispatch period is as follow.

$$F = \sum_{t=1}^{24} [C(t)Q_h(t) + C(t)\beta^+ Q^+_{pe}(t) - C(t)\beta^- Q^-_{pe}(t) + C(t)(Q_a(t) - Q^-_{pe}(t) + Q^+_{pe}(t))]$$

(5)

$C(t)$ is the bidding price for the day-ahead market. $\beta^+$ is the penalty coefficient for the unit power of positive deviation. The value should be $\beta^+ \leq 1$, which means that the penalty cost for the unit power of positive deviation is not higher than the bidding price of wind power retailer, and 0.7 is taken in this paper. $\beta^-$ is the penalty coefficient for the unit power of negative deviation. The value should be $\beta^- \geq 1$, which means that the penalty cost for the unit power of positive deviation is not lower than the bidding price of wind power retailer, and 1.5 is taken in this paper.

From (5), it can be concluded that the reduction of revenue due to the deviation penalty of electricity is as follow.

$$M = \sum_{t=1}^{24} [C(t)(1 - \beta^+)Q^+_{pe}(t) + C(t)(\beta^- - 1)Q^-_{pe}(t)]$$

(6)

2.2. Objective Function

The HSEB has the capacity of energy storage. When the excess output of the wind power retailer needs to be penalized for positive deviation, the excess output can be accommodated by increasing the output of the electric boiler and storing heat. When the negative deviation penalty is needed for the
insufficient output of wind power retailer, the output deficiency can be reduced by reducing the output of electric boiler and increasing the heat release output.

The deviation of the wind power bidding output when the wind power retailer and the HSEB jointly operated is expressed as follow.

$$Q_{\text{w}}(t) = (Q_{\text{w}}(t) - Q_{\text{h}}(t)) - (P_{\text{t}}^b(t) - P_{\text{t}}^h(t))$$  \hspace{1cm} (7)

The output deviation after joint operation is expressed by $Q_{\text{w},r}(t)$. $P_{\text{t}}^b(t)$ and $P_{\text{t}}^h(t)$ are the day-ahead output and actual output of HSEB respectively.

To minimize the reduction of the revenue of wind power retailer is the objective function. That is expressed as follow.

$$\min M = \sum_{t=1}^{T} [C(t)(1 - \beta^+)Q_{\text{w},r}^+(t) + C(t)(\beta^- - 1)Q_{\text{w},r}^-(t)]$$  \hspace{1cm} (8)

$Q_{\text{w},r}^+(t)$ and $Q_{\text{w},r}^-(t)$ are the positive deviation penalty and negative deviation penalty after joint operation of wind power retailer and HSEB respectively.

2.3. Constraints

The constraints of the model are as follows.

1) The bidding output constraint of wind power retailer is as follow.

$$0 \leq Q_{\text{w}}(t) \leq Q_{\text{w}}^{\text{max}}(t)$$  \hspace{1cm} (9)

$Q_{\text{w}}^{\text{max}}(t)$ is the maximum bidding output of the wind retailer.

2) The electric power constraint of electric boiler is as follow.

$$0 \leq P_{\text{t}}(t) \leq P_{\text{t}}^{\text{max}}$$  \hspace{1cm} (10)

$P_{\text{t}}(t)$ is the power of the electric boiler. The maximum power of the electric boiler is expressed by $P_{\text{t}}^{\text{max}}$.

3) The constraints of storage and release rate of thermal storage tank are as follows.

$$0 \leq h_{\text{c}}(t) \leq h_{\text{c}}^{\text{max}} A_{\text{c}}(t)$$  \hspace{1cm} (11)

$$0 \leq h_{\text{d}}(t) \leq h_{\text{d}}^{\text{max}} A_{\text{d}}(t)$$  \hspace{1cm} (12)

$$A_{\text{c}}(t) + A_{\text{d}}(t) \leq 1$$  \hspace{1cm} (13)

$h_{\text{c}}(t)$ is the thermal storage tank's heat storage power, and $h_{\text{d}}(t)$ is the release power. $h_{\text{c}}^{\text{max}}$ is the maximum power of the thermal storage tank's storage (release). $A_{\text{c}}(t)$ and $A_{\text{d}}(t)$ are the introduced state variables, representing the state of heat storage and heat release respectively. $A_{\text{c}}(t) = 1$ means heat storage and $A_{\text{d}}(t) = 0$ otherwise. Similarly, $A_{\text{c}}(t) = 1$ means heat release and $A_{\text{d}}(t) = 0$ otherwise.

4) The capacity constraints of thermal storage tank are as follow.

$$S_{\text{c}}(t) = S_{\text{c}}(t-1) + (h_{\text{c}}(t)\eta_{\text{r,c}} - h_{\text{d}}(t)\eta_{\text{r,d}}) \Delta t$$ \hspace{1cm} (14)

$$0 \leq S_{\text{c}}(t) \leq S_{\text{c}}^{\text{max}}$$ \hspace{1cm} (15)

$$S_{\text{c}}(0) = S_{\text{c}}(T)$$ \hspace{1cm} (16)

$S_{\text{c}}(t)$ is the storage amount in the heat storage tank. $\eta_{\text{r,c}}$ and $\eta_{\text{r,d}}$ are the efficiency of heat storage and heat release respectively. $S_{\text{c}}(0)$ is the storage amount in the heat storage tank at the initial time.
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$S_{\text{max}}$ is the heat storage tank’s maximum storage capacity. $\Delta t$ is the unit period length. (16) indicates that there is margin left for the next dispatch cycle, and the initial state shall be restored at the end of one cycle.

5) The relationship between indoor heat supply and outdoor temperature on the user side is as follow.

$$\frac{dT_{\text{in}}(t)}{dt} = -\frac{1}{RC} T_{\text{in}}(t) + \frac{T_{\text{out}}(t)}{RC} + \frac{Q_{\text{in}}(t)}{C}$$  \hspace{1cm} (17)

$T_{\text{in}}(t)$ is the indoor air temperature. $R$ is the equivalent thermal resistance. $C$ is the indoor air heat capacity, and the thermal resistance parameter reference [9]. $Q_{\text{in}}(t)$ is the indoor heat supply. $T_{\text{out}}(t)$ is the outdoor air temperature.

6) The constraints of PMV and PPD are as follows [10].

$$\text{PMV}(t) = \begin{cases} 0.3895(T_{\text{in}}(t) - 26), & T_{\text{in}}(t) \geq 26 \\ 0.4065(T_{\text{in}}(t) - 26), & T_{\text{in}}(t) < 26 \end{cases}$$ \hspace{1cm} (18)

$$\text{PPD}(t) = 100 - 95\exp(-0.03353 \times \text{PMV}(t) - 0.2179 \times \text{PMV}(t)^2)$$ \hspace{1cm} (19)

$$\text{PPD}(t) < 10\%$$ \hspace{1cm} (20)

PPD is the user’s dissatisfaction with heating and the final evaluation index of heating comfort.

7) In order to ensure the heating quality, the average value of indoor temperature in a dispatch cycle is constrained.

$$\frac{1}{T} \sum_{t=1}^{T} T_{\text{in}}(t) = T_{\text{in}}^0$$ \hspace{1cm} (21)

$T_{\text{in}}^0$ is the temperature in comfort state.

8) The operation cost constraint of HSEB is shown as follow.

$$\sum_{t=1}^{T} P_{t}^{\text{h}}(t)C_{\text{load}}(t) \leq \sum_{t=1}^{T} P_{t}^{\text{h}}(t)C_{\text{load}}(t)$$ \hspace{1cm} (22)

$C_{\text{load}}(t)$ is the electricity price of the HSEB.

9) The constraint of heat balance is expressed as follow.

$$\eta_{\text{e}} P_{t}^{\text{s}}(t) - h_{\text{c}}(t) + h_{\text{d}}(t) = h_{\text{load}}(t)$$ \hspace{1cm} (23)

$\eta_{\text{e}}$ is the efficiency of the electric boiler.

3. Example analysis

In this paper, the heat is all supplied by the HSEB, and the heating area is 900,000 m$^2$. The curves of bidding output, actual output and outdoor temperature is shown in Figure 1. The day-ahead market transaction price of the wind power retailer adopts the peak valley electricity price. The price of peak period (10:00-15:00 and 18:00-21:00) is 0.8 yuan/kWh, the flat period (07:00-10:00, 15:00-18:00 and 21:00-23:00) is 0.5 yuan/kWh, and the valley period (00:00-07:00 and 23:00-24:00) is 0.25 yuan/kWh.
3.1. Operation Result Analysis

As the heat load is supplied by the HSEB, the day-ahead output of the HSEB is shown in Figure 2, and the actual output of the heat storage electric is shown in Figure 3. It can be seen from Figure 2 that since the electricity price at night is at a low level, the HSEB operate at full power in most periods, and the heat generated is used for heating and heat storage. Due to the high electricity price during the daytime, the heat storage electric boiler is mostly inoperative or running at low power in most periods. And mainly use the heat in the thermal storage tank for heating. In order to meet the demand of heat load during the period of peak electricity price, the HSEB is operated at full power during the period of flat electricity price in the afternoon for heating and heat storage.

Figure 2 Day-ahead output of HSEB

Figure 3 shows the output of HSEB after the joint operation of wind power retailer and HSEB. It can be seen from Figures 2 and 3 that the power of the electric boiler changes little in the periods of low load at night, but the heat storage power is different. This is to adjust the heat supply of the room based on the consideration of human comfort, so as to increase the output adjustment range of the HSEB when eliminating the deviation. Combined with the wind power curve in Figure 1, it can be seen that when the wind power output has a large deviation, the HSEB reduces the wind power output deviation by increasing or decreasing the power. For example, the wind power output from 07:00 to 08:00 is relatively large. By comparing Figures 2 and 3, it can be seen that the HSEB increases the
power, and the heat storage power also increases. From 16:00 to 17:00, the wind power output is relatively low. The HSEB reduces the power, and its heat storage power also decreases accordingly.

![Figure 3 Actual output of HSEB](image)

### 3.2. Economic Benefit Analysis

Table 1 shows the deviation rate of power output before and after the joint operation of wind power retailer and HSEB in each period. From table 1, it can be seen that the deviation rate in most periods before the joint operation is beyond the positive deviation exemption penalty coefficient.

| Period | Before  | After  | Period | Before  | After  | Period | Before  | After  |
|--------|---------|--------|--------|---------|--------|--------|---------|--------|
|        | 7.27%   | 5.93%  | 9      | 4.46%   | 4.13%  | 17     | -11.09% | 0.00%  |
| 1      | -14.30% | -14.30%| 10     | -10.79% | 0.00%  | 18     | 1.95%   | 1.95%  |
| 2      | -9.11%  | -9.11% | 11     | 8.24%   | 0.77%  | 19     | 6.22%   | 6.22%  |
| 3      | 4.82%   | 4.82%  | 12     | 15.20%  | 15.20% | 20     | -15.79% | -15.79%|
| 4      | 1.08%   | 1.08%  | 13     | -19.97% | -19.97%| 21     | -2.25%  | -2.25% |
| 5      | -9.35%  | -9.35% | 14     | -8.89%  | -8.89% | 22     | 7.11%   | 7.11%  |
| 6      | -5.16%  | -5.16% | 15     | 16.44%  | 16.44% | 23     | -1.00%  | -0.92% |
| 7      | 9.54%   | 0.00%  | 16     | -5.81%  | 0.00%  | 24     | -9.14%  | -9.14% |

By analyzing the deviation rate before and after the joint operation in Table 1, it can be seen that the reduction of the deviation rate mostly exists in the peak and flat periods of the transaction electricity price. And the deviation rate can be completely eliminated in individual periods. Combining Figures 2 and 3, it can be seen that HSEB is mostly operated at full power at night, and during the daytime mostly only uses the heat in the thermal storage tank for heating.

Before the joint operation, the reduction of the revenue due to deviation penalty is 21222 yuan. After the joint operation, the reduction of the revenue is 14373 yuan, and the cost of deviation penalty is reduced by 32.27%. In this paper, joint operation is carried out to reduce the deviation power without increasing the operation cost of the HSEB. The output adjustment period of the HSEB is restricted, so there is still a large deviation in some periods after joint operation.

### 4. Conclusion

In this paper, the revenue model for deviation penalty of electricity in joint operation of wind power retailer and HSEB is established. The energy storage capacity of the HSEB is used to reduce the
output deviation penalty of the wind power retailer, and the feasibility is verified based on an example. Based on this study, the following conclusions can be drawn.

1) The use of HSEB can reduce the deviation penalty of wind power retailer.

2) Constrained by the operating cost of HSEB after joint operation, the ability to reduce deviation penalty is limited.

Considering that the joint operation of this article is based on not increasing the operating cost of the HSEB, the regulation space is limited. In the future, the research will take the wind power retailer and the heat storage electric boiler as different benefit subjects to establish the joint operation model with the greatest benefit.

5. Acknowledgments
This work was financially supported by Science and Technology Project of State Grid Jibei Electric Power Co., Ltd. (52018K18001C).

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