Optimized operation of micro grid electric heating integrated system based on PMV

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Abstract. The characteristics of wind power, such as peak inversion, lead to serious wind abandonment in heating season. With the implementation and use of the heat storage electric boiler (HSEB), the utilization rate of wind power can be effectively improved by establishing the electric heat combined operation system with the HSEB. When the thermal comfort of human body is considered, the heat load will be changed into elastic range, and the regulation range of heating unit will be increased. Based on the analysis of the heat transfer state of the house on the user's side, the relationship model between the outdoor temperature and the indoor heat supply is established in this paper. On this basis, the micro grid electric heating comprehensive system with the HSEB is constructed. Taking the minimum operation cost of the system as the objective function, the economic optimal operation model of the micro grid electric heating system based on PMV is established. The feasibility of the four schemes is verified by an example. The results show that the micro grid electric heating system based on the PMV contained HSEB can accommodate the abandoned wind power, reduce the fuel cost and reduce the environmental pollution on the premise of ensuring the indoor comfort, which has a good application prospect.

1. Introduction

With the gradual depletion of fossil energy and the increasingly serious environmental pollution, China will face a mixed energy model of complementary fossil energy and new energy in the future. In 2018, the wind curtailment was 27.7 billion kWh, mainly concentrated in the three northern areas. The main reason was that the heating season was constrained by the traditional “following the thermal load” mode, the operation peak shaving was restricted, coupled with the volatility and anti-peaking of wind power increased the severity of wind curtailment.

In order to achieve the consumption of wind power, the literature [1] comprehensively introduces existing energy storage methods such as compressed air energy storage, capacitor energy storage, battery energy storage and pumped storage. Due to the limitation of technical means, most of the energy storage methods have the disadvantages of insufficient economy and limited storage capacity, only the pumped storage technology is widely used [2]. Considering the complementarity between electric heating systems, many scholars have proposed the use of electric boilers and thermal energy storage to achieve the consumption of wind power. Literature [3] takes the national economy and coal saving benefits as the goal, and concludes that the use of wind power for heat storage and heating can...
transform electric energy into heat energy and achieve a large amount of storage. Literature [4] consume wind power by adding a peak-regulating boiler in the heating network, and studies the effects of different electric boiler capacity and heat load peak-shaving schemes on system coal consumption and abandoned air volume. In the above study, the thermal load curve is often used to analyze the thermal collaborative scheduling, without considering the impact of user side thermal comfort on the thermal load curve.

The user side thermal comfort can change the traditional thermal load curve into the thermal load range, and increase the regulating space of the thermal power unit. Based on the consideration of human thermal comfort, the literature [5] proposes a user-side electric heating equipment load adjustment capability evaluation method based on weather forecast. In reference [6], the user thermal comfort index is introduced into the load side to change the thermal load into an elastic range. The objective function of the minimum total coal consumption is to study the wind power consumption, but the cost of environmental pollution caused by thermal power units is not considered. Aiming at user comfort and system operation economy, the optimal thermal scheduling time scale is sought by establishing an electric-thermal time-scale balance optimization model in [7].

The current research situation is lack of consumption of wind power based on thermal comfort index. Based on the user's thermal comfort, aiming at the minimum system cost, this paper establishes an optimized operation model of micro grid electric heating with HSEB. Through the analysis and comparison of four different operation schemes, the feasibility of using the HSEB to consume the wind curtailment and reduce the system operation cost based on the user's thermal comfort is verified.

2. Load side model

2.1. Heat user model

According to the heat balance theory, the indoor and outdoor temperature is in a dynamic process when the indoor heat supply and the heat dissipation of the enclosure are different. An equivalent thermal parameter model [8] is used for the hot user house to describe the temperature change of the room under the action of indoor and outdoor cold heat sources such as outdoor temperature and indoor equipment, as shown in Figure 1 [9].

![Figure 1. Equivalent thermal parameter model of heating room](image)

The thermodynamic process can be characterized by a first-order equivalent thermal parameter model [10], and the first-order differential equation is as follow.

\[
\frac{dT_{in}(t)}{dt} = -\frac{1}{RC} T_{in}(t) + \frac{T_{out}(t)}{RC} + \frac{Q_{in}(t)}{C}
\]

\( T_{in}(t) \) is the indoor air temperature in the \( t \)-th period. \( R \) is the equivalent thermal resistance. \( C \) is the indoor air heat capacity, and the thermal resistance parameter reference [5]. \( Q_{in}(t) \) is the indoor heat supply at time step \( t \). \( T_{out}(t) \) is the outdoor air temperature in the \( t \)-th period.
2.2. User comfort

The comprehensive thermal comfort index PMV is the cold and hot feeling of human body to the external environment temperature. The relationship between the PMV value and the feeling of human body is shown in Table 1, and the state of PMV = 0 is the most ideal thermal comfort environment.

| Comfort | PMV |
|---------|-----|
| Cold    | -3  |
| Cool    | -2  |
| Slightly cool | -1 |
| Neutral | 0   |
| Slightly Warm | 1 |
| Warm    | 2   |
| Hot     | 3   |

Table 1. PMV and thermal comfort

User comfort is represented by PMV index. The closer it is to 0, the better the user's comfort is. The literature [11] gives the PMV value at different temperatures when other factors are at comfort level, and obtains the relationship between PMV value and indoor temperature $T_{in}$.

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

(2)

3. Model construction of electric heating system

The electric heating system of the micro grid in this paper is shown in Figure 2, which is mainly composed of wind turbine (WT), gas turbine (GT), heat recovery steam generator (HRSG) and HSEB. The load side mainly includes electric load and heat load.

Figure 2. The electric heating system of Micro grid

3.1. Objective function

The economic optimization of micro grid system requires the least total operating cost of the system. The costs in the operation of the electric heating system mainly include the power purchase cost from the grid, the gas purchase cost from the natural gas network and the gas emission control cost of GT. The optimal scheduling cycle studied in this paper is 24 hours, with 1 hour as the unit period length. Its objective function is as follows.

$$F = \min \left( \sum_{t=1}^{T} \left( c_e(t)P_{grid}(t) + c_g(t)G_{net}(t) \right) + \sum_{k=1}^{K} \alpha_k \times \lambda_k \times \sum_{t=1}^{T} P_{GT}(t) \right)$$

(3)

$F$ is the system operation cost. $c_e(t)$, $c_g(t)$, $P_{grid}(t)$ and $G_{net}(t)$ are the electricity price, natural gas price, electric power purchase from the grid and gas purchase from the natural gas network in the $t$-th period. $\alpha_k$ is the external discount cost of emission type $k$. $\lambda_k$ is the emission factor of GT when the emission type is $k$. $K$ is the total number of emission types. The values of $\alpha_k$ and $\lambda_k$ of GT are determined by the parameters in reference [12].
3.2. Equipment model and constraints

There are the constraints of the equipments in the system.

(1) Upper and lower limits of WT output is as follow.

\[ 0 \leq P_w(t) \leq P_w^{\text{max}}(t) \]  

(4)

\( P_w(t) \) is the output of the WT sent to the micro grid in the \( t \)-th period. \( P_w^{\text{max}}(t) \) is the predicted maximum output of the WT in the \( t \)-th period.

(2) The constraints of GT are as follows.

\[ P_{\text{GT}}(t) = \eta_{\text{GT}} H G_{\text{GT}}(t) \]  

(5)

\[ P_{\text{GT}}^{\text{min}} \leq P_{\text{GT}}(t) \leq P_{\text{GT}}^{\text{max}} \]  

(6)

\[ -\Delta P_{\text{GT}}^{\text{down}} \leq P_{\text{GT}}(t) - P_{\text{GT}}(t-1) \leq \Delta P_{\text{GT}}^{\text{up}} \]  

(7)

\( P_{\text{GT}}(t) \) is the output power of GT in the \( t \)-th period. \( H \) is the calorific value of natural gas, taking 9.7kwh/m³. \( G_{\text{GT}}(t) \) is the gas consumption of GT in the \( t \)-th period. \( \eta_{\text{GT}} \) is the generating efficiency of GT. \( P_{\text{GT}}^{\text{min}} \) and \( P_{\text{GT}}^{\text{max}} \) are the minimum and maximum electrical power of GT respectively. \( \Delta P_{\text{GT}}^{\text{down}} \) and \( \Delta P_{\text{GT}}^{\text{up}} \) are the downward and upward Ramp rate of gas turbine in unit period.

(3) HRSG is to use the high temperature flue gas discharged from GT for power generation, which plays the purpose of waste heat utilization. The heating efficiency of HRSG is related to the temperature of flue gas inlet and outlet [12].

\[ Q_{\text{boiler}}(t) = \frac{P_{\text{GT}}(t)(1 - \eta_{\text{GT}} - \eta_{r})}{\eta_{\text{boiler}} \nu(t) \eta_{\text{rech}}} \]  

(8)

\[ \eta_{\text{rech}} = \frac{T_{b1} - T_{b2}}{T_{b1} - T_{w}} \]  

(9)

\[ Q_{\text{boiler}}^{\text{min}} \leq Q_{\text{boiler}}(t) \leq Q_{\text{boiler}}^{\text{max}} \]  

(10)

\( Q_{\text{boiler}}(t) \) is the heat output of HRSG in the \( t \)-th period. \( \eta_{\text{boiler}} \) is the heating efficiency of HRSG in the \( t \)-th period. \( \eta_{\text{rech}} \) is the heat recovery efficiency of flue gas. \( \eta_{r} \) is the heat loss efficiency. \( \nu(t) \) is the proportion of flue gas flow into HRSG in flue gas emission of GT in the \( t \)-th period. \( T_{b1} \), \( T_{b2} \) and \( T_{w} \) respectively represent the flue gas inlet and outlet temperature of HRSG and ambient temperature. \( Q_{\text{boiler}}^{\text{min}} \) and \( Q_{\text{boiler}}^{\text{max}} \) are the minimum and maximum power of HRSG respectively.

(4) The constraints of HSEB are as follows.

\[ 0 \leq P_r(t) \leq P_r^{\text{max}} \]  

(11)

\[ 0 \leq h_{r,c}(t) \leq h_{r,c}^{\text{max}} A_{c}(t) \]  

(12)

\[ 0 \leq h_{r,d}(t) \leq h_{r,d}^{\text{max}} A_{d}(t) \]  

(13)

\[ A_{c}(t) + A_{d}(t) \leq 1 \]  

(14)

\[ S_r(t) = S_r(t-1) + (h_{r,c}(t)\eta_{r,c} - \frac{h_{r,d}(t)}{\eta_{r,d}}) \Delta t \]  

(15)

\[ 0 \leq S_r(t) \leq S_r^{\text{max}} \]  

(16)
\( S_i(0) = S_i(T) \) (17)

\( P_t(t) \) is the electric power of the electric boiler in the \( t \)-th period. \( P_{\text{max}}^t \) is the maximum electric power of the electric boiler. \( h_{r,c}(t) \) is the heat storage power of the thermal storage tank in the \( t \)-th period, and \( h_{r,d}(t) \) is the heat release power. \( h_{\text{max}}^t \) is the maximum storage (release) power of the thermal storage tank. \( A_c(t) \) and \( A_d(t) \) are the introduced state variables, representing the state of heat storage and heat release respectively. It is 0 when it is "No" and 1 when it is "Yes". \( S_i(t) \) is the heat storage amount of the heat storage tank in the \( t \)-th period. \( \eta_{r,c} \) and \( \eta_{r,d} \) are the efficiency of heat storage and heat release respectively. \( S_i(0) \) is the heat storage amount in the heat storage tank at the initial time. \( S_{\text{max}}^t \) is the maximum heat storage capacity of the heat storage tank. \( \Delta t \) is the unit period length. Equation (17) indicates that there is margin left for the next scheduling cycle, and the initial state shall be restored at the end of one cycle.

(5) PPD is the user's dissatisfaction with heating and the final evaluation index of heating comfort.

\[
\text{PPD}(t) = 100 - 95 \exp(-0.03353 \times \text{PMV}(t)^4 - 0.2179 \times \text{PMV}(t)^2) 
\]

(18)

(6) In order to ensure the heating quality and avoid the phenomenon that the indoor temperature is always at the lowest limit during the optimization, the average value of indoor temperature in a scheduling cycle is constrained. \( T_{\text{in}}^0 \) is the temperature in comfort state.

\[
\frac{1}{T} \sum_{t=1}^{T} T_{\text{in}}(t) = T_{\text{in}}^0 \tag{19}
\]

(7) The balance constraints of electricity and heat are as follows.

\[
P_{\text{GT}}(t) + P_{\text{w}}(t) + P_{\text{grid}}(t) = P_{\text{load}}(t) + P_t(t) \tag{20}
\]

\[
Q_{\text{boiler}}(t) + \eta_r P_t(t) - h_{r,c}(t) + h_{r,d}(t) = h_{\text{load}}(t) \tag{21}
\]

\( \eta_r \) is the efficiency of the electric boiler.

4. Example analysis

![Figure 3. Electric load, wind power ultimate output and outdoor temperature](image)

In this paper, the typical daily curves in winter of electric load, the maximum output of WT and outdoor temperature in this micro grid area are shown in Figure 3. This paper uses CPLEX to solve the
problem. It is noted that the thermal load index method does not add the HSEB as the scheme I, the thermal load index method adds the HSEB as the scheme II, the PMV method does not add the HSEB as the scheme III, and the PMV method adds the HSEB as the scheme IV. The heat load index is 28.38 w/m² for energy-saving building design in a heating area, the heating area is 40,000 square meters.

4.1. Operation result analysis

![Figure 4. Changes of PMV](image)

Figure 4 shows the fluctuation curve of indoor human thermal comfort under four schemes. When scheme I and II are adopted, it is necessary to ensure that the heat input in each time period is the same, so the PMV curve is the same before and after the HSEB is added. It can be seen from Figure 4 that when the thermal load index method is adopted, indoor personnel feel cool when the outdoor temperature is low at 03:00-06:00. While when the outdoor temperature is high at 12:00-20:00, the indoor have partial heat feeling. The warm and hot feeling occur when the outdoor temperature reaches the highest value at 14:00-16:00. When scheme III and IV are adopted, the indoor temperature is kept within the comfort range of human body.

![Figure 5. Electric & thermal output of scheme I and II](image)

Figure 5 shows the fluctuation curve of indoor human thermal comfort under four schemes. When scheme I and II are adopted, it is necessary to ensure that the heat input in each time period is the same, so the PMV curve is the same before and after the HSEB is added. It can be seen from Figure 4 that when the thermal load index method is adopted, indoor personnel feel cool when the outdoor temperature is low at 03:00-06:00. While when the outdoor temperature is high at 12:00-20:00, the indoor have partial heat feeling. The warm and hot feeling occur when the outdoor temperature reaches the highest value at 14:00-16:00. When scheme III and IV are adopted, the indoor temperature is kept within the comfort range of human body.

It can be seen from Figure 5(a) and Figure 5(b) that in case of adopting the heat load index method, since the same heat demand to be guaranteed at any time in the room, the heat all comes from the HRSG without adding the HSEB. Therefore, the electric output of GT is limited, so that GT operates at a constant power. Only during the daytime peak load period, the electric power needs to be purchased from the grid. At night, due to the large output of GT, there is a large amount of wind curtailment (12.9 MW·h, about 34.3%). When scheme II is adopted, due to the low electricity price and large amount of wind curtailment at night, the electric power demand of electric load and electric boiler is mainly met by the wind power and the grid, which makes GT operate at a low power. In the
peak load period at noon, due to the high electricity price, increasing the output of GT is adopted to meet the system electric load demand. During the period of flat electricity price in the daytime, due to the relatively high gas price, the electric power purchased from the grid is adopted to meet the demand of electric boiler and electric load at this time. From Figure 5(b), it can be seen that the electric boiler operates at maximum power in multiple periods at night. The most of the heat generated is used for heating, a small amount is stored in the thermal storage tank and released in the daytime.

Figure 6. Electric & thermal output of scheme III and IV

According to the output curve of GT in scheme III in Figure 6(b), it can be seen that the heat demand in the room changes with the change of outdoor temperature when PMV method is adopted. When the outdoor temperature is high at noon, in order to ensure comfort, the indoor heat demand is low. The output of GT is low and can not meet the electric load demand, so it needs to purchase electric power from the grid. When the outdoor temperature is low at night, the heat demand is large. Due to the high output of GT, there is a large amount of wind curtailment (13.16 MW·h, about 35%). When scheme IV is adopted, the demand of electric load and electric boiler is mainly met by wind power and the grid, the GT is operating at a low power. Due to the high electricity price during the peak load period at noon, the system's electrical load demand is met by increasing the output of GT. It can be seen from Figure 6(b) that when PMV method is adopted, the heat demand is relatively large at night. And the heat is jointly provided by electric boiler, heat storage tank and HRSG. During the period of flat electricity price in the daytime, electricity is purchased from the grid to meet the electric demand of the electric boiler. The heat generated by the electric boiler is stored in the thermal storage tank except for heating, and is released when the heat demand is high at night.

4.2 Economic benefit analysis

It can be seen from Table 2 that when scheme I and scheme III are adopted, the power purchase cost is far less than scheme II and scheme IV, while the gas purchase cost and gas emission control cost are far higher than scheme II and scheme IV. All the heat comes from the HRSG, resulting in the GT in a high output for a long time. The electric load demand of the system is mainly met by the GT, and the electric power purchased from the grid only exists in the peak load period. After adding the HSEB, the excess wind power is used for heat storage at night, which reduces the operation output of GT and the gas purchase cost. Because of the capacity of heat storage, the HSEB can be used to store heat and supply heat to reduce the operating cost of the system by purchasing electric power from the grid when the electricity price is in the flat period during the day. The gas purchase cost is reduced when PMV method is used compared with that when heat load index method is used. Because the heat demand of the system changes with the change of outdoor temperature when PMV method is used, it only needs to meet the indoor thermal comfort, reduce the heat waste and save the cost of gas purchase. Due to the reduction of the output of GT when the PMV method is adopted, the cost of electric power purchase from the grid increases.
### Table 2. Operation cost in different schemes

| Scheme | Power purchase (yuan) | Gas purchase (yuan) | Gas emission control (yuan) | $F$ (yuan) |
|--------|-----------------------|---------------------|-----------------------------|------------|
| I      | 2831.49               | 36560.74            | 853.75                      | 40245.98   |
| II     | 12871.04              | 17133.40            | 400.00                      | 30404.53   |
| III    | 4952.35               | 34385.64            | 802.95                      | 40140.94   |
| IV     | 13988.67              | 15772.46            | 368.31                      | 30129.44   |

5. Conclusion

This paper studies the optimal operation of the micro grid electric heating system based on PMV. The feasibility is verified by the analysis of an example, and the following conclusions are obtained.

1. The utilization rate of wind power can be improved, the consumption of natural gas can be reduced, and the gas emission control cost can be reduced by using the HSEB.
2. The heat is no longer only from the HRSG after the adoption of the HSEB, which makes the output of the gas turbine more flexible.
3. When the PMV method is adopted, the indoor heat needs to change according to the change of outdoor temperature, so that the indoor is always in a thermal comfortable state.

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