Calculation Model of Electric Load Adjustment Capacity of Low Vacuum Heat Supply Unit and its Application

Junshan Guo1,*, Jin Wang2, Ming Wang2, Yue Han1 and Wei Zheng1

1State Grid ShanDong Electric Power Research Institute, Jinan, 250003, China
2State Grid ShanDong Electric Power Company, Jinan, 250001, China

*Corresponding author

Abstract. Based on the thermal balance of steam turbine and condenser, the calculation model of electric load adjustment capability of low vacuum heating unit is established by iterative calculation method. Taking a low-vacuum heat supply unit in Shandong as the research object, the electric load adjustment capability is measured. Compared with the test results, the calculation model of this paper has higher precision.

Keywords: Low vacuum heating unit; electric load adjustment capability.

1. Introduction
The low vacuum heating technology of the thermal power unit is the technology that reducing the steam expansion and increasing the back pressure of the condenser by reducing the last few stages of the turbine. Thereby, the temperature of the circulating water is increased, and the circulating water is directly introduced to the heat network[1]. The low vacuum heating technology can make full use of the latent heat of vaporization of steam, thereby greatly reducing the heat rate of the unit. Taking the 135MW steam turbine as an example, the heat consumption rate of the low vacuum heating unit is about 3700kJ/kWh, while the heat consumption rate of the same type condensing unit exceeds 8000kJ/kWh[2]. In order to give full play to the good economic benefits of the low vacuum heating unit, the high back pressure unit at this stage basically maintains the rated power operation and does not participate in the peak shaving of the power grid. On the other hand, with the continuous improvement of UHV transmission networks, the transmission capacity of electric power across regions has been increasing. At the same time, the proportion of wind power generation, photovoltaic power generation, nuclear power generation and various new energy generations has been increasing, and the peaking pressure of power grids is huge[3]. It is difficult to meet the peaking demand of the power grid by relying solely on purely condensed and condensed fire power units. It is an inevitable trend for high back pressure units to participate in peak shaving. In order to ensure the effect of peaking operation of high back pressure unit, it is necessary to study the electric load adjustment capability of low vacuum heating unit and establish an accurate calculation model.

In this paper, a low vacuum heating unit is selected as the research object, and the electric load adjustment capability of this type of unit is calculated by establishing a simplified calculation model. And the field test is used to verify the model calculation results.

2. System Introduction
The target unit steam turbine is an ultra-high pressure, single-shaft, double-cylinder double-exhaust steam and condensing high-back pressure heating steam turbine designed and manufactured by
Shanghai Steam Turbine Works Co., Ltd., model C121-13.24/0.8/535 /535 type. The main technical parameters of the steam turbine and the main technical parameters of the rated high back pressure operating conditions are shown in Table 1.

**Table 1.** The main technical parameters of the target unit.

| Item                                      | Unit | Design Data |
|-------------------------------------------|------|-------------|
| rated power                               | MW   | 121         |
| Rated steam flow                          | t/h  | 428         |
| Rated steam pressure in front of main steam valve | MPa  | 13.24       |
| Reheating the rated steam pressure in front of the main steam valve | MPa  | 3.2         |
| Rated back pressure                       | kPa  | 54          |
| Exhaust steam temperature                 | °C   | 83.3        |
| Feed water temperature                    | °C   | 244         |
| Circulating water flow                    | t/h  | 7000        |

The rated evaporation of the boiler of the target unit is 435t/h. In the actual operation and test process, in consideration of the risk of leakage of the economizer, in order to ensure the safety of the boiler equipment, the operating personnel artificially control the evaporation amount to not exceed 400t/h.

Figure 1 is a simplified diagram of the heating system of the target unit. Under normal operation mode, the basic heat of residential heating is provided by the low vacuum exhaust of the target unit, and the return water of the heating network is heated to 80 °C by the low vacuum exhaust of the unit, and the heating network users heat. In order to ensure the heating quality, the heating company requires that the instantaneous heat flux of the heating and heating of the target unit is not less than 600GJ/h. When the high back pressure heating does not meet the requirements, the basic heater is turned on to extract and heat the hot water supply. The limiting factor for the electric load adjustment of the target unit heating system is: the instantaneous heat flow rate of heating is not less than 600GJ/h.

**Figure 1.** Heating system diagram of object unit.

### 3. Calculation Model

By assuming the unit exhaust steam temperature, calculates the exhausts heat of the turbine, and then calculates the new exhaust steam temperature according to the condenser heat balance, and iteratively assumes the temperature with the new exhaust steam temperature until the iterative calculation reaches equilibrium, and the calculated result is the actual output of the unit.

The power of the turbine generator is determined by the steam flow and steam enthalpy of the turbine. Within a certain load variation range, the power variation can be considered to be proportional to the product of the flow and enthalpy change, while the general load range of the low vacuum heating unit is
small. So the power generated by the low vacuum heating unit can be calculated by the following formula:

$$P = P_0 K_Q K_{sH} - D_{he} (h_{he} - h_{eh})$$  \hspace{1cm} (1)

Where, $K_Q$ is the main steam flow ratio, $K_{sH}$ is the total steam reduction ratio, $D_{he}$ is the heating extraction flow, t/h, and $h_{he}$ is the heating extraction, kJ/kg.

The ratio of the regenerative extraction steam flow to the main steam flow is defined as the total share of regenerative extraction, which can be calculated by the following formula:

$$\alpha = \frac{D_{re}}{D_m}$$  \hspace{1cm} (2)

Where, $D_{re}$ is the regenerative extraction steam flow, t/h. $D_m$ is the main steam flow, t/h.

In the case of variable working conditions, the total share of regenerative extraction can be calculated by the following formula:

$$\alpha' = \alpha \frac{\Delta H'_w}{\Delta H_w}$$  \hspace{1cm} (3)

Where, $\Delta H'_w$, $\Delta H_w$ are the increase in water supply enthalpy under rated and variable conditions.

The unit exhaust flow can be calculated according to the following formula:

$$D_{es} = D'_m (1 - \alpha') - D_{he}$$  \hspace{1cm} (4)

The external heat supply of the unit through the low vacuum circulating water can be calculated as follows:

$$Q = D_{es} (h_{es} - h_n)$$  \hspace{1cm} (5)

Where, $h_{es}$ is the enthalpy of the unit's exhaust steam, kJ/kg. $h_n$ is the enthalpy of the condensate water, kJ/kg.

Based on the heat balance of the condenser, the temperature rise of the circulating water can be calculated as follows:

$$\Delta t = \frac{Q}{D_{cw} \cdot C_{wh}}$$  \hspace{1cm} (6)

Where, $C_{wh}$, specific heat capacity of water; $D_{cw}$, circulating water flow.

Condenser end difference $\delta t$ can be calculated as follows:

$$\delta t = \frac{\Delta t}{A_c} e^{\frac{A_c}{K} D_{cw} - 1}$$  \hspace{1cm} (7)

Where, $A_c$ is the heat transfer area of the condenser, m$^2$; $K$ is the heat transfer coefficient.

The condenser exhaust steam temperature can be calculated as follows:

$$t_s = t_{s1} + \Delta t + \delta t$$  \hspace{1cm} (8)

Based on the above calculation model, combined with the actual situation of the target unit, the change of the unit's electric load under different steam extractions of the target unit is calculated in this paper. The calculation results are as follows:
Table 2. The calculation results of the model.

| Main steam flow | Heating extraction steam flow | Heat supply calculation result | Power generation calculation result |
|-----------------|------------------------------|-------------------------------|-----------------------------------|
| t/h             | t/h                          | GJ/h                         | MW                               |
| 265             | 0                            | 450                          | 78.8                             |
| 316             | 40                           | 528                          | 86.3                             |
| 325             | 70                           | 550.9                        | 85.9                             |
| 390             | 75                           | 661                          | 103.5                            |

4. Test Verification
In order to verify the accuracy of the model calculation results, the target unit conducted the electric load adjustment capability test in December 2018. The test results are as follows:

Table 3. The test results of the target unit.

| Power generation | Main steam flow | Heating extraction steam flow | Heat supply | Power error | Heat supply error |
|------------------|-----------------|------------------------------|-------------|-------------|------------------|
| MW               | t/h             | t/h                          | GJ/h        | %           | %                |
| 80.21            | 264.75          | 0                            | 459.88      | -1.75       | -2.15            |
| 85.19            | 325.35          | 70.63                        | 551.75      | 0.83        | -0.15            |
| 90.21            | 316.24          | 41.40                        | 538.27      | -3.11       | -1.91            |
| 105.63           | 388.86          | 74.11                        | 664.31      | -2.01       | -0.50            |

According to the comparison results, the model power calculation error does not exceed 3.5%, and the heat calculation error does not exceed 3%. The calculation model proposed in this paper can accurately calculate the output capacity of the low vacuum heating unit.

5. Conclusion
In the face of the increasingly tight peaking situation of power grids, it is an inevitable trend for low-vacuum heating units to participate in power grid peak shaving. In order to accurately evaluate the electric load adjustment capability of the low vacuum unit, this paper establishes a calculation model for the electric load adjustment capability of the low vacuum heating unit. In order to verify the accuracy of the model, this paper takes a low-vacuum heating unit in Shandong as the research object, calculates the output capacity of the unit under typical co-operation conditions, and designs the test to verify. The test results show that the calculation error of the calculation model proposed in this paper does not exceed 3.5%, which can accurately reflect the output level of the unit. The calculation model proposed in this paper is simple in calculation process and high in calculation accuracy, which is convenient for large-scale deployment.

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