Evaluation of Minimum Boundary Output Stability of Thermal Power Units

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Abstract. In order to improve the load regulation capability of the power grid, verification of the minimum boundary output characteristics of deep peak regulation of coal-fired units was carried out. Considering the safety, stability, environmental protection, and energy saving indicators, the minimum output stability evaluation method was discussed in a 300MW coal-fired unit, and the ultra-low combustion stability target of 25% of rated load was completed. This has important guiding significance for approving the output characteristics of units, carrying out precise load regulation, and expanding new energy consumption.

1. Preface

With the rapid development of wind power and photovoltaic power generation technologies in China, the proportion of new energy in the power structure is increasing. However, wind power and photovoltaics are intermittent, fluctuating, and random, which exacerbates the difficulty of peak regulation in the power grid. As the main component of China's power energy structure, coal-fired units are involved in in-depth peak shaving [1].

Beginning in 2018, in order to further improve the load regulation capability of Inner Mongolia Power Grid and ensure the flexibility, safety and reliability of load regulation, the autonomous region has carried out verification of the minimum boundary output characteristics of deep peak regulation of coal-fired units. Taking a 300MW coal-fired unit as an example, considering the safety, stability, environmental protection, and energy saving requirements, the evaluation method of the unit's minimum boundary output stability evaluation is discussed. This is important for approving the unit's output characteristics, performing precise load regulation, and expanding new energy consumption.

2. Overview of demonstration units

The 300MW unit boiler of a power generation company was designed by Harbin Boiler Co., Ltd. including sub critical parameters, intermediate reheat, four-corner tangential combustion, 5 medium speed milling systems. It is equipped with a 300MW steam turbine generator set with subcritical pressure [2]. Under the design coal type, the minimum stable combustion load of the unit is 44% of the rated electrical load. At present, the actual grid dispatch minimum load is 50% of the rated electrical load. According to the actual coal type, taking into account the requirements of safety, stability, environmental protection and energy saving, the unit starts to reduce the load from 50% of the rated load, and maintains stability at 45%, 35%, and 25% of the rated load. The minimum output characteristics of the unit are tested.
Table 1. The main design parameters of the boiler.

| Item                        | Load conditions | BMCR  | TRL   | 75%THA |
|-----------------------------|-----------------|-------|-------|--------|
| Unit load (MW)              |                 | 300   |       |        |
| Superheated steam flow (t.h⁻¹) | 1025           | 915.7 | 632.8 |
| Reheat steam flow (t.h⁻¹)   | 841.64          | 752.913 | 535.192 |
| Superheated steam outlet pressure (MPa) | 17.50          | 17.31 | 14.37 |
| Reheat steam inlet pressure (MPa) | 3.761          | 3.358 | 2.37  |
| Superheated steam outlet temperature (℃) | 540            | 540   | 540   |
| Reheated steam outlet temperature (℃) | 540            | 540   | 540   |
| Boiler efficiency (%)       |                 | 93.3  | 93.42 | 93.73  |

Table 2. Coal quality characteristics.

| Type           | Aᵣ (%) | Mᵣ (%) | Cᵣ (%) | Hᵣ (%) | Oᵣ (%) | Nᵣ (%) | Sᵣ (%) | Qₙₑₙ,ᵣ(MJ/kg) |
|----------------|---------|---------|---------|---------|---------|---------|---------|----------------|
| Design coal    | 16.6    | 50.6    | 2.7     | 7.42    | 0.61    | 0.82    | 18.63   |
| Actual coal    | 26.74   | 41.56   | 2.43    | 9.53    | 0.47    | 0.57    | 18.63   |

3. Evaluation of combustion stability

When the boiler is operated at a deep peak and low load, the volume of the furnace heat load, the cross-section heat load, and the center temperature of the furnace are greatly reduced due to the reduction in the amount of fuel sent to the furnace [1]. Therefore, ensuring the low-load flammability of the boiler is a core issue. The main sources of heat required for the ignition of pulverized coal gas flow are thermal convection from flue gas entrainment and heat radiation from the furnace. Under low load conditions, the heat obtained by convection and radiative heat transfer of the pulverized coal gas stream is significantly reduced, and a larger proportion of this heat is used to increase the primary air temperature. This has caused pulverized coal to be difficult to ignite, poor flame stability, easy to extinguish, and major hidden dangers such as furnace fire extinguishing and deflagration. In addition, during ultra-low-load operation, in order to meet the requirements of the flow field in the furnace and the drying output of the coal mill, the air-to-coal ratio of the burner in the furnace is much larger than the air-to-coal ratio under normal conditions. So increasing the temperature of the pulverized coal gas flow to the ignition temperature requires more heat. When the hot flue gas entrainment can no longer meet the requirements of pulverized coal ignition, ignition delay or difficulty will occur. In general, the stability of the furnace combustion is generally judged mainly by the negative pressure fluctuation, the fire detection intensity of the pulverizing system, the on-site flame combustion fullness and flame shape, and the furnace flue gas temperature field change.

3.1. Stability analysis of furnace pressure

Furnace pressure is the most intuitive parameter to characterize the combustion stability [3]. Pulverized coal is combined with oxygen in the furnace, and the combustion releases heat, CO₂ and other components. Stable pulsating combustion will release relatively stable heat and flue gas, and form a stable flue gas flow in the furnace with balanced ventilation, so that the furnace pressure fluctuates within a small range. If the combustion is unstable, the furnace pressure will form a wide range of fluctuations. Figure 1 shows the furnace pressure fluctuations data from DCS during the low-load stable combustion test. It can be seen that the maximum furnace pressure is -78Pa, the minimum value is -10Pa under each load. The average furnace pressure fluctuates around -40Pa, so the combustion is in a stable state.
3.2. Flame detection intensity analysis

The flame detection intensity is an important detection index for the operation of the unit's pulverizing system. The fire detection signal is divided into an analog value and an on-off value. The analog value shows the strength of the flame. The switching value is two states with or without fire. Fire detection analog indicators are mainly used to monitor the flame intensity and do not participate in thermal logic protection. The fire detection switch value is used as the logic protection of the pulverizing system and the main protection of the boiler MFT. If a single pulverizing system loses two of the four switch coal fire detections, it is considered that the flame layer combustion corresponding to this pulverizing system is unstable. The DCS system will issue a trip instruction for the pulverizing system. The corresponding coal mill and coal feeder will trip. The inlet cold and hot air isolation door of the coal mill will trip and close. When all the pulverizing systems determine that the flame is lost, the boiler main protection MFT logic is triggered, the furnace flame loss MFT protection is issued, all fuel systems of the boiler are cut off and primary fan trip is triggered[4]. During the unit's low-load steady-state combustion test, the test personnel closely monitored the fire detection intensity of the pulverizing system in operation. It was required that the switching fire detection should not cause short-term flash loss, and the simulated flame intensity should not be less than 90%. Once the fire detection instability occurs, the load reduction should be stopped immediately, and the wind coal ratio should be adjusted immediately. The test work can be carried out, only after the fire detection is stable. During this test, the unit started to reduce the load from 50% of the rated load, and remained stable at 45%, 35%, and 25% of the rated load, respectively. No instability occurred in the fire inspection of each milling system.

3.3. Analysis of in-situ flame patterns

The flame detection intensity signal is a thermal measurement original, which is affected by many factors such as the measurement principle, measurement accuracy, and installation position. Its accuracy should be checked regularly, and the combustion stability cannot be judged solely by the fire inspection. During the load reduction test of the unit, the test personnel observed the fire on the spot from time to time. Through the actual combustion conditions of the flame, the operating personnel are guided to carry out corresponding combustion adjustment and optimization to maintain the stability of the boiler parameters. Through the adjustment, the overall flame of the furnace is bright and full, and the single burner torch is scientifically shaped, regularly pulsed. The burner torch is divided into three areas: pulverized coal preheating zone, volatility analysis ignition zone, and burnout zone. The root of the burner outlet is a pulverized coal preheating zone, which appears as a black fire root, which not only ensures the pulverized coal airflow is fully preheated, but also protects the burner nozzle from
burning and deformation [5]; Subsequently, at the ignition zone the pulverized coal air flow rolled the flue gas heat, the volatiles were separated out, and the fire started. The fire looked golden and bright; Finally, at the burn-out zone outside the torch, with the pulverized coal gas stream continued to absorb heat, the flame temperature increased, and the fixed carbon in the pulverized coal began to burn out. All torch combustion is merged into the furnace, forming the furnace combustion power field.

3.4. Furnace Flue Gas Temperature Analysis
Furnace flue gas temperature is an important indicator to characterize the combustion stability of the boiler. A stable, high flue gas temperature can ensure good ignition performance of the pulverized coal gas flow and strong anti-interference stability characteristics. During the low-load stable combustion test, the furnace flue gas temperature test is performed for each load interval. The data are shown in Figure 2 and 3.

Figure 2. Furnace smoke temperature distribution 1

Figure 3. Furnace smoke temperature distribution 2

Figure 2 shows that the average flue gas temperature of the boiler is 990 to 1141°C under the five stable combustion conditions in the three load sections of 45%, 35%, and 25%, which maintains a good temperature level overall. The overall random group of flue gas temperature decreased and the load decreased. The flue gas temperature of the BCD mill group at 45% load is about 100°C higher than that of the ABC mill group. The average temperature of the flue gas at 25% load is 990°C. From the perspective of the smoke temperature distribution in the vertical section of the furnace, under the equal air distribution mode, the vertical smoke temperature distribution in the furnace is related to the operation mode of the mill group. The highest combustion temperature is in the CD and DE layers. The flue gas temperature is 1094 to 1236°C. The bottom A zone maintains a good bottoming
combustion effect. The flue gas temperature is 1029 to 1125°C. The concentration of pulverized coal in the burnout layer decreases. In the final burnout state, the minimum combustion temperature is 758-1010°C. Under the lowest 25% load condition, the AB mill group was put into operation, and the combustion-intensive area was concentrated between the A layer and the CD layer, and the furnace flue gas temperature remained between 1072 and 1172°C. At present, the mainstream burners in the industry mainly focus on stable and clean combustion technology, which can take into account the combustion stability and environmental protection at a relatively high temperature level. During this steady combustion test, the stable flue gas temperature ensured stable combustion organization.

4. Evaluation of environmental protection indicators

According to the national environmental protection policy, thermal power units need to meet full-load pollutant emission control requirements. Under low load of the unit, due to the requirements of stable combustion and the safe operation of auxiliary systems, the excess air coefficient control is often too large, which is not conducive to suppressing NOx generation. Lower flue gas temperature under load is also not conducive to the safe and efficient operation of the SCR denitration device. Figure 4 and Figure 5 show the NOx index and flue gas temperature of the SCR inlet during the low-load steady-state combustion test. As can be seen from Figure 4, the NOx value at the SCR inlet is lower at 45% rated load, especially the NOx at the ABC mill group. The value is stable around 172mg/m³, which reduces the pressure for the subsequent SCR denitration system. The NOx index of 35% and 25% rated load conditions is relatively high, about 482~655mg/m³, but it also meets the collaborative processing capacity of subsequent SCR denitration systems.

It can be seen from Figure 5 that at 45% and 35% and 25% of the rated load of the unit which is the BCD and ABC and AB mill group operation, the SCR inlet NOx values are maintained at 327°C, 323°C, 324°C, and 301°C respectively. At the rated load of 25%~45%, the SCR inlet smoke temperature is higher than 300 °C, and there is a certain margin, which can meet the requirements of denitration.

5. Evaluation of energy consumption indicators

Generally speaking, the high-efficiency operation section of the unit is often in the middle and high load condition. In order to meet the task of power grid safety peak shaving operation and new energy consumption, deep adjustment of peak energy consumption level directly affects the economic benefits of thermal power plants. As Figure 6 show, at 45%, 35%, 25% rated load of the unit, the boiler thermal efficiency is in the range of 92.25~93.69% [6]. The thermal efficiency of 45% load boiler is relatively high, the thermal efficiency of 35% and 25% load boilers is relatively low, and the thermal efficiency of ABC mills with 35% loads is 92.25% which is lowest.

The flue gas temperature has a decreasing trend with the unit load decreasing, and the variation range is 126.46~143.82°C. This is mainly because the unit load is reduced, the overall combustion of the boiler is weakening, and the flue gas volume is gradually decreasing. As shown in Figure 7, the content of combustibles in boiler fly ash is generally not large, showing a tendency of 35% load being too large, 45% and 25% load being small, and the variation range is 0.18 to 0.64%. The 25% load fly ash has a minimum carbon content of about 0.18%. The slag combustibles content is generally small.
and irregularly distributed, ranging from 0.41 to 4.22%. The slag combustible content of the 45% load ABC mill group is about 4.22%.

Figure 6. Boiler thermal efficiency

Figure 7. Combustible content.

6. Conclusions
Based on the tangential combustion mechanism of power plant boilers, the combustion optimization technology of power plant boilers is studied in depth, and the combustion stability mechanism is discussed. Considering the safety, stability, environmental protection, and energy saving indicators, the minimum output stability evaluation method was discussed in a 300MW coal-fired unit, and the ultra-low combustion stability target of 25% of rated load was completed. This has important guiding significance for approving the output characteristics of units, carrying out precise load regulation, and expanding new energy consumption.

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