Failure Analysis and Control Optimization of RB Test Due to Feed-water Excess Reducing for the 1000MW Ultra-supercritical Once-through Unit

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Abstract. As for the 1000MW ultra-supercritical unit of Beijiang Power Generation Co., Ltd, the FDF runback test (RB) is failed for the excess reducing of feed-water flow, and the reason is analized. In order to optimize the RB control logic, the method by using “slow-to-fast” pressure changing rate is applied during the RB process. Besides, the slowly interlock opening control logic of the motor-driven valve is added, which controls the inlet steam from auxiliary steam to feed pump steam turbine, in order to keep the inlet steam stable. In addition, the lag time of boiler to feed-water demand and the prohibit increasing time of fuel master are both increased, which benefit to the control effect of temperature. The test results show that, control logics after optimization can ensure the load reducing promptly and steadily during the runback process of the unit, and the transition of major parameters remains smooth.

1. Introduction

When one of the main auxiliary machine fault trips, and the maximum theoretical output of the unit is lower than the current actual load, runback is the measure to use coordinated control system to quickly reduce the unit load to the corresponding output that all auxiliary machines can actually achieve[1-2]. With the improvement of the automation level of the unit, the control method for the RB test is gradually improved. However, due to the different types of units and the combustion characteristics of the boiler, there are also differences in control strategy of RB. Besides, there are still a lot of optimization space for the control of main parameters such as steam temperature, steam pressure and feed water flow in RB process [3-5].

In this paper, aiming at the RB test of NO.3 unit of Beijiang Power Plant, the test failure is analyzed due to the low flow rate of the feed water and the excessive load drop, and measures including the automatic control of the steam supply of the feed water pump turbine and the inertia time of the variable pressure rate and the inertia time set value of the feed water master control, are taken to optimize the RB process. After optimization, a better control effect is achieved, and it has reference significance for the same type of unit.
2. Steam distribution mode and control characteristics analysis

Generally, in the control logic of RB test, the boiler master control in the coordinated control system is automatically cut off, and the (Turbine Follow) TF mode is used to control the steam pressure of the turbine. In the process of reducing load, the turbine adjusting valve will gradually close with the decrease of main steam pressure setting and the actual pressure in front of the turbine. As for the steam turbines supplied by three major steam turbine plants commonly found in domestic power plants, due to differences in structural design and manufacturing characteristics, there are also differences in the valve system of steam turbines. This also leads to differences in control characteristics in the RB process.

The STW ultra-supercritical 1000MW unit steam turbine valve system consists of two high-pressure main valves, two high-adjusting valves, two middle main valves, two middle-adjusting valves and one supplementary valve. The steam turbine adopts the single-flow + full-cycle steam inlet + supplemental steam valve to adjust the steam distribution mode. This steam distribution method can greatly reduce the end loss, improve the efficiency of the unit, and at the same time help eliminate the vibration source of the air gap [6-9].

As for the valve system of the 1000MW unit of DTW and HTW, it contains two high-pressure main valves, four high-adjusting valves, two middle main valves, and two middle-adjusting valves. And the steam distribution mode adopts the double flow regulation stage of the steam inlet mode.

For the DEH control of DTW and HTW, when the turbine is put into the remote control mode, the integrated valve position command sent by turbine master control in DCS is used. The pre-turbine pressure is controlled by assigning integrated valve position commands to four high-adjusting valves. The four-stage extraction steam source of the feed water pump turbine comes from the medium-pressure cylinder, and the reduction of the integrated valve position causes the closing of the high-adjusting valve to not have an excessive impact on the feed water pump turbine steam source.

For the DEH control of STW, after the turbine is put into the pressure limiting mode(load control) or the initial pressure mode(pressure control), DEH receives the load setting or pressure setting command sent from the DCS. And the integrated valve position command formed by the internal logic operation of DEH is simultaneously assigned to the high-adjusting valve and the middle-adjusting valve to control the unit load or the steam pressure in front of turbine. When the integrated valve position is closed from the full position, the high-adjusting valve is closed first, and the middle-adjusting valve is closed when the opening percentage is low. The closing of the middle-adjusting valve will cause the steam inlet of the medium pressure cylinder to decrease, which will affect the four-stage extraction sources of the feed water pump turbine.

In view of the characteristics of STW unit, the paper analyzes the RB failure caused by the shortage of the output of the feed water pump in the RB process, and proposes the optimization strategy in a targeted manner.

RB function design

2.1. RB trigger logic
The RB trigger condition is that the load is higher than 550MW, and any one (Forced Drafted Fan) FDF / (Primary Air Fan) PAF / (Induced Draft Fan) IDF /feed water pump turbine trips, triggering the unit RB action.

2.2. RB action logic
The RB trigger condition is that the load is higher than 550MW, and any one (Forced Drafted Fan) FDF / (Primary Air Fan) PAF / (Induced Draft Fan) IDF /feed water pump turbine trips, triggering the unit RB action.

1) After the RB is triggered, the coordination mode is cut off, and the DEH is switched from the pressure limiting mode to the initial pressure mode, and the pressure setting command sent by the DCS is received, and the pressure in front of turbine is adjusted by the adjusting valves.

2) The target load is converted into a target total coal quantity through the comparison with the current load, and is sent to the fuel master by the boiler master to control the coal feeder. The total coal
quantity command of the fuel master is converted into the feed water command according to the water-coal curve after different inertia time, and the feed pump turbine speed is controlled by the feed water master. The inertia time of the set value of the feed water master is 10 s for the IDF/FDF RB, 15 s for the PAF RB, and 20 s for the feed water pump RB.

3) The target load, load reduction rate, target pressure, and pressure drop rate after RB triggering are shown in Table 1. The target pressure value is given by the target load through the sliding pressure curve, and the pressure rate module generates a pressure set value and sends it to DEH. The pressure set inertia time is 35 s in the coordination mode and 25 s in the TF mode and RB mode.

4) The unit is equipped with six sets of mills. For normal operation, five mills are used and one mill is in backup. After the RB logic is triggered, the rapid reduction of the fuel amount and heat storage of the boiler are achieved by rapid tripping the mill, thereby achieving the purpose of rapid load reduction. After the RB action, the F-mill, E-mill, and D-mill are sequentially tripped in the order from the upper layer to the lower layer. The interval between the mill-tripping is 10 s, and the lower three mills are retained.

5) When IDF/FDF RB and PAF RB, overheating and reheating and desuperheating water adjustment valves close and keep off for 60 s, and automatically adjusting the temperature after 60 s

6) When PAF RB occurred, the furnace pressure will be instantaneously reduced due to the tripping of the primary air fan. Therefore, for the PAF RB, the design of the induced draft fan blade overrides one opening (the opening is 35% of the draft fan blade command), the closing rate is 100%/s when triggered, and the recovery rate is 0.001%/s. When the primary air RB triggers, it simultaneously closes the fan outlet valve, the primary fan outlet cold valve and the air preheater outlet hot valve.

Table 1. The target value during RB test

| RB type               | Target load (MW) | Load reduction rate (MW/min) | Target pressure (MPa) | Pressure reduction rate (MPa/min) |
|----------------------|------------------|------------------------------|-----------------------|---------------------------------|
| IDF/FDF RB           | 550              | 200                          | 15.17                 | 0.6                             |
| PAF RB               | 550              | 230                          | 15.17                 | 0.6                             |
| Feed water pump RB   | 550              | 200                          | 15.17                 | 0.6                             |

3. Analysis of failure reasons of RB test
12:30:06, local accident button was used to stop a FDF, and it triggered RB, and logically jumped a side IDF. At that time, five mills run, RB caused E, D mills tripped. The unit control mode was cut from the coordinated mode to the turbine follow mode and sliding pressure operation, the sliding pressure rate was 0.6 MPa/min, and the boiler command reduced coal and water at a rate of 200 MW/min. At 12:34:41, the total coal flow decreased to 195.6 t/h, and the feed water flow decreased to 1074.9 t/h, and the load was dropped to 375.6 MW. Load and feed water flow decreased too much, manual reset RB for intervention adjustment, RB test was failed. Figure 1 shows the process of load, feed water flow, turbine valve adjustment, feed pump control, etc. during RB test, and reasons for RB failure is analyzed below.
1-Actual load; 2-Feed water demand; 3-Feed water flow rate; 4-High pressure inlet pressure of feed pump turbine; 5-Turbine integrated valve position command; 6-Turbine high-adjusting valve command; 7-Turbine mid-adjusting valve command; 8-Feed pump turbine speed command; 9-Feed pump turbine actual speed; 10-Feed pump turbine integrated valve position

Figure 1. The failure process of FDF RB test

3.1. The closing of the middle-adjusting valve in the turbine caused the insufficient steam intake of the feed pump turbine

In the RB process, the boiler main control is automatically cut off, the turbine is cut to the initial pressure control mode, and the main steam pressure is controlled by the adjusting valve. As the fuel rapidly decreases, the main steam pressure decreases rapidly, and the turbine valve is gradually closed. When the integrated valve position of the turbine is high, the reduction of the integrated valve position will only close the high-adjusting valve, and the middle-adjusting valve opening will remain unchanged. When the turbine integrated valve position is reduced to 70%, the high-adjusting valve opening is closed to 20%, and the middle-adjusting valve start closing from 100% downwards. When the integrated valve position is reduced to 50%, the high-adjusting valves opening is closed to 15%, and the middle-adjusting valve is closed to 16%. As a result, the inlet pressure of the feed pump turbine is rapidly reduced, resulting in insufficient output of the feed pump turbine, and the actual speed cannot keep up with the speed command. In the RB process, the mid-adjustment valve opening is reduced from 100% to 16%, the feed pump turbine inlet pressure is reduced from 0.953 MPa to 0.419 MPa, the A-turbine speed command is 5014 rpm, but the actual speed is only 4435 rpm, resulting in feed water supply cannot keep up with the set value. Excessive drop in feedwater flow also led to an increase in late temperature, with the intermediate point temperature rising from 414.3 °C to 467.8 °C. Steam temperature control effect is not ideal during RB process.

3.2. Adjusting valves participate in the feed pump turbine inlet steam switching and acting repeatedly

The steam inlet mode of the feed water pump turbine includes the main adjusting valve and the steam inlet valve, and both of them can control the speed of the feed water pump turbine by adjusting the inlet flow of the valve. When the feed water pump turbine is put into the remote control, the MEH accepts the speed command sent by the DCS, and through the PID calculation in the MEH logic, forms a feed water pump turbine integrated valve position command, and configures the command of the main regulating valve and the supplementary steam valve through the valve flow characteristic curve.

The valve flow characteristic curve of the feed water pump turbine is shown in Figure 2. When the integrated valve position command of the feed water pump turbine is between 0-60 and the command
of the supplementary steam valve is 0, the integrated valve position only controls the speed by changing the valve position of the main adjusting valve; When the feed water pump turbine integrated valve position command is between 70-100, the main control valve command is 100, and the integrated valve position only controls the speed by changing the valve position of the supplementary steam valve; When the integrated valve position of the feed water pump turbine is between 60-70, the main adjusting valve and the supplementary steam valve are all open, and the integrated valve position acts on the main adjusting valve and the supplementary steam valve at the same time to control the rotational speed.

Figure 2. The value position distribution of feed pump steam turbine

Before the start of the RB test, the integrated valve position of the feed pump turbine was 60.74. During the RB test, the minimum was reduced to 30.35, and then increased to 100. The integrated valve position was reciprocated in the 60-70 range to cause the main valve and the supplementary valve to be greatly switched, affecting the control of the feed water pump turbine speed.

4. RB strategy optimization

4.1. Pressure setting optimization

After the RB triggers, the control mode is switched from the coordinated mode to the TF mode. The pressure is controlled by the steam turbine to adjust the pressure. The closing speed will affect the pressure in front of the turbine. On the other hand, the main steam flow caused by the opening or closing of the valve increases or decrease, and it will also have a greater impact on the main steam temperature. Therefore, the pressure change rate setting after RB triggering needs to take into account the influence on the main steam temperature[10-14].

In the original control logic, the rate of pressure change is 0.6 MPa/min. Because the rate of pressure change is too slow, the valve is quickly closed and the opening is too low, which causes the inlet pressure of the feed pump turbine to be too low, and the output of the feed pump is insufficient, resulting in water supply flow is too low. From the process of failure of the RB experiment, after the RB is triggered, the integrated valve position is reduced to 70 after 3 min 15 s, and the mid-adjusting valve starts to close from 100, and affects the output of the feed pump turbine.

Therefore, the control logic is optimized, and the variable rate adjustment is used to segment the pressure change rate. After the RB is triggered, the pressure change rate is set to 0.5 MPa/min in the first 85 s period. By setting the pressure change rate to a lower value, the valve can be quickly closed, achieving the purpose of rapid load reduction and reducing the heat loss of the boiler thereby slowing down the boiler side temperature reduction rate. And the pressure change rate after 85 s is switched to
2.4 MPa/min. In the late stage of RB, the rate of pressure change is greatly increased to slow down the closing rate of the turbine valve, so that the output of the water pump is not insufficient due to the closing of the mid-adjusting valve.

4.2. The steam source control of feed water pump turbine

The analysis of the process of the RB experiment shows the failure is mainly due to the low feed water flow caused by insufficient output of the feed water pump in the later stage. Therefore, in this case, in addition to changing the pressure change rate to ensure that the opening degree of the turbine valve is not too low, and also by optimizing the control logic, increasing the control of the auxiliary steam source after the RB is triggered to guarantee the steam supply of feed pump turbine.

The steam entering of the feed pump turbine is composed of four-stage extraction steam and auxiliary steam, as shown in Figure 3. The four-pumping steam supply pipeline is provided with four pumping to a turbine electric valve and four pumping to B turbine electric valve. The auxiliary steam supply steam line is provided with auxiliary steam for steam main pipe electric valve, and auxiliary steam valve to A feed pump turbine and auxiliary steam valve to B feed pump turbine. In the initial stage of steam turbine rushing and loading, steam is supplied from the auxiliary steam source to the feed pump turbine. After the unit is loaded with high load, the steam is mainly supplied by the four pumping steam. At this time, the auxiliary steam main valve is normally open. Steam to A, B small electric valve is generally closed.

After the RB trigger, in order to ensure the stability of the feed pump turbine steam source, the control logic is increased after the RB trigger, to open the auxiliary steam to the A, B turbine inlet steam electric valve. Since the auxiliary steam to the feed pump turbine electric valve is kept closed for a long time, the interlock opening logic of the RB needs to consider the heating problem of pipe behind the electric valve, and prevent the high temperature steam from directly entering the unheated pipe to cause damage to the equipment, so it needs to slowly open the electric valve. For the logic design of the auxiliary steam to the feed pump turbine inlet steam electric valve, it is necessary to ensure that there is sufficient opening degree of valve in the RB late period to ensure the feed pump turbine steam source, and to ensure that the pipeline has sufficient warming time.

The switching time control of the electric valve is realized by the interlocking open logic and the medium stop logic. After the RB is triggered, the electric valve is opened for 5 s and medium stopped for 5 s until the valve is fully opened, and the logic control strategy is as shown in Fig. 4. Since the full stroke time of the valve is about 2 min, in the logic design, after the RB is triggered, the valve will be interlocked and opened in the middle to the full opening time of 3 min 30 s, and will reach 70 % in 2 min 30 s. The opening degree, considering the flow characteristics of the valve, the 70% opening can basically guarantee the supply of steam source. For the previous RB test, the start and close time of the middle valve was around 3 min 15 s. Therefore, the logic modification of the auxiliary steam to the small electric valve can realize the effect of ensuring the steam inlet of the feed pump turbine.
4.3. Optimization of feed water setpoint inertia time

In the RB process, the control of the steam temperature is an important point, and the variation of the steam temperature is often too large due to equipment reasons and logic parameter settings. For a once-through boiler, the enthalpy expression for superheated steam is:

\[ h_{ss} = h_{fw} + \frac{Q_{net}\eta}{W} \]  \hspace{1cm} (1)

In the expression, \( h_{ss} \) and \( h_{fw} \) are the superheated steam outlet enthalpy and the feed water enthalpy, \( \text{kJ/kg} \); \( F \) and \( W \) are the total fuel amount and the total feed water flow, respectively, \( \text{kg/h} \); \( Q_{net} \) is the low heat of the fuel, and \( \eta \) is the efficiency of the boiler. It can be seen from equation (1) that if \( h_{fw} \), \( Q_{net} \) and \( \eta \) remain unchanged, then the value of \( h_{ss} \) is only related to the ratio \( F/W \) of fuel quantity to feed water flow. Therefore, as long as the water-fuel ratio changes, the superheated steam temperature will change. When the water-fuel ratio increases, the superheated steam temperature will increase. When the water-fuel ratio decreases, the superheated steam temperature will decrease. If the water-fuel ratio remains stable, the superheated steam temperature will remain stable. Therefore, the core problem of controlling the temperature of the main steam is to control the water-fuel ratio [15-17].

In addition, since the response of the fuel conforms to the third-order inertia link in the actual combustion process of the boiler, and the response of the feed water is faster, the setting of the inertia time is usually used for the set value of the fuel-to-water supply command in the actual logic design and delay the role of water supply to achieve better water and coal matching.

In the original control logic, the inertia time of the set value of the water supply master is 10 s for the FDF/IDF RB. From the process analysis of the RB experiment, the rate of decline of the feed water flow in the early stage is too fast, resulting in excessive temperature in the later stage. Therefore, it is necessary to delay the drop of the feed water, and the inertia time of the set value of the feed water in the logic is increased to 15 s.

4.4. Increase in the prohibition time of fuel master

In the original control logic, the fuel master control prohibition time after RB trigger is 40 s. It was found that during the RB test, due to the rapid tripping of the upper layer mills, and the coal supply command reduced the coal flow according to the load reduction rate. After 40 s, the fuel command was still higher than the actual coal volume, and the coal quantity reversed later. In order to avoid this phenomenon, the fuel master's prohibition time is changed to 60 s.

5. Results of RB test after optimization of control strategy

After optimizing the control strategy, the RB test is re-executed to verify the control effect of the optimized control strategy on the parameters in the RB process. The parameters in the test process are shown in Figure 5. At 11:19:50, FDF RB test was performed. B FDF trips, logic jumps B side IDF,
triggers RB. Five mills were running, and RB caused E and D to trip. The unit was cut from the coordinated control mode to the TF mode, and the sliding pressure operation is 0.5 MPa/min in the first 85 s, then switched to 2.4 MPa/min. The coal and water supply instructions are reduced according to the load reduction rate of 300 MW/min. At 11:29:23, the coal flow decreased to 214.93 t/h, the feed water flow decreased to 1667.98 t/h, the load fell to 578.50 MW, the parameters remained stable, and RB test was reset and successful.

The feed water flow rate is reduced from 2743.8 t/h to 1475 t/h; the main steam temperature is reduced to 567.3 °C and rises to 595.2 °C; the reheat steam temperature is reduced to 565.6 °C and rises to 580.5 °C. After 8 minutes, the main parameters of the unit are stable. Throughout the RB process, the unit can quickly reduce load and operate safely, coal and water are smooth and excessive, and parameters such as main steam temperature and reheat steam temperature can be maintained within a reasonable range. Optimized control strategy, showed a good control effect of main parameters of the unit in RB test.

![Figure 5. The FDF RB test after optimization](image)

6. Conclusion

In view of the failure of the RB test caused by the low water supply flow rate in the Beijiang Power Plant, the reasons for the test failure were analyzed. The logic is optimized. In the RB process, the variable pressure rate control strategy of “slow first and then fast” is adopted, and the steam inlet valve of the auxiliary steam to the feed pump turbine is slowly opened to ensure the stability of the steam inlet of the small machine. In addition, the inertia time of the boiler command to the feed water is increased during the RB process, and the prohibition time of the fuel in the RB process is increased to optimize the control effect on the temperature. By re-running the RB test, the results show that the optimized control logic can ensure that the unit can quickly reduce the load and operate safely during the test, and the controlled objects such as water and coal can be smoothly over-extended, and the control effect on the main parameters is good.

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