The Design of Thermodynamic System Instrument & Control for the Daya Bay Turbine High Pressure Cylinder Retrofit

Yanjun Hu1*, Tian Wan2, Weiwei Pan3, Shengzhi Liu4 and Min Li5
1,2,3,4,5 Suzhou Nuclear Power Research Institute Co., Ltd., Shenzhen, Guangdong Province, 518000, China
*Corresponding author’s e-mail: jhon85@163.com

Abstract. Before the retrofit, the equipments of the turbine high pressure cylinder of the Daya Bay Nuclear Power Plant is of the old technology. The design of the leaf shape and the steam runner is not advanced, and the equipments are aged after more than 20 years' operation. From the point of increasing the power and improving the reliability of the equipments, it's decided to retrofit the turbine high pressure cylinder of Daya Bay Nuclear Power Plant unit 1 and unit 2. The retrofit relates to the design and modification of many secondary loop thermodynamic systems' instrument & control parameters, in order to match with the first loop reactor control systems, and also the mechanism and electric systems, it's necessary to verify and optimize these designed parameters of the units after the retrofit. This design and analysis method and experience of the secondary loop thermodynamic systems' instrument & control parameters can be referred by the similar retrofit of other nuclear power plants.

1. Introduction

Before the retrofit, the turbine high pressure cylinders in units 1 and 2 of Daya Bay Nuclear Power Plant were not sufficiently advanced in design and low in efficiency, and there was a lot of room to improve the output, and the units had been in operation for more than 20 years and some of the equipment was aging. Before the retrofit, the turbine high pressure cylinder in units 1 and 2 of Daya Bay Nuclear Power Plant was not sufficiently advanced in design and the steam flow path was low in efficiency, and the units had been in operation for more than 20 years and some of the equipment was aging, and there was more room to improve the output.

This retrofit involved the redesign and parameter modification of many of the instrumentation and control systems associated with the secondary loop thermal system to match the modified first loop reactor control system, mechanical and electrical systems.

The design and analysis of the instrumentation and control parameters of the secondary loop thermal system for the retrofit of the turbine high pressure cylinder in this nuclear power plant includes the following processes: mapping, calculation, analysis and demonstration during the project design phase; window arrangement and measurement and tracking, modification and verification of the parameters during the project implementation phase; analysis and summary of the final parameters and project acceptance. The methodology and experience of the design and verification of the instrumentation and control of this secondary loop thermal system is of great reference significance for the implementation of similar projects in nuclear power plants in the future.
2. Instrumentation and control analysis and design of secondary loop thermal systems

2.1. General analysis of the instrumentation and control of the secondary loop thermal system

The Daya Bay Nuclear Power Plant is a pressurised water reactor nuclear power plant. The instrumentation and control part of its secondary loop thermal system mainly includes: main steam system VVP, main feedwater flow control system ARE, turbine governing system GRE, turbine monitoring system GME, steam main feedwater pump system APP, electric main feedwater pump system APA, moisture separator reheater system GSS, condenser vacuum system CVI, etc.

This retrofit will change the structure and weight of the turbine's high pressure cylinder and rotor, which will directly lead to changes in the parameters of the turbine itself, ultimately affecting the instrumentation and measurement channels of the turbine monitoring system, including speed and overspeed, differential expansion, vibration and eccentricity, and thrust bearing wear, etc. Changes in the 1st stage steam inlet pressure and the efficiency of the turbine's high pressure cylinder will affect the pressure limit setting of the turbine governing system, steam demand and the opening of the governing valve, and will affect some of the parameters that use the 1st stage steam inlet pressure as a reference base for threshold setting.

2.2. Effect of turbine body parameters

2.2.1. Rotational speed measurement and overspeed analysis

This retrofit includes the replacement of the rotor and short shaft of the high pressure cylinder (including the speed measuring gear, overspeed flying hammer, main oil pump impeller, etc.), moving vane, spacer, spacer sleeve and other equipment in units 1 and 2 of the Daya Bay Nuclear Power Plant, where the replacement of the head speed measuring gear is directly related to the speed measuring channel of the turbine governing system (hereinafter referred to as GRE)/turbine monitoring system (hereinafter referred to as GME), as shown in Figure 1.

According to the analysis of the mechanical parameters and data of the equipment, as the size of the speed measuring gear after replacement remains unchanged, the original probe installation method and channel calibration method of GRE/GME001/002/003/004/005MC of the speed measuring channels of the GRE/GME system remain unchanged. However, during the stages of commissioning and run-up and grid connection after the retrofit, the measurement and display of the speed channels need to be closely monitored to ensure that the speed measurement and monitoring will not be affected after the replacement of the speed measuring gear.

After calculation, under full power load shedding, the peak turbine speed will increase by 6.69% under normal operation of the turbine governing system (0.07% more than the 6.62% before the retrofit, equivalent to 2.1 rpm); the peak turbine speed will increase by 16.23% under overspeed protection tripping (0.06% more than the 16.17% before the retrofit, equivalent to 1.8 (rpm). The increase in peak speed of around 2 rpm after the retrofit will not affect the existing overspeed protection settings and no modification of the relevant parameters is required.
2.2.2. High pressure cylinder differential expansion analysis

The differential expansion is the relative thermal expansion between the rotor and the cylinder. When the thermal growth differential exceeds the permissible clearance, friction may occur. During start up and shutdown, due to differences in rotor and cylinder mass, thermal expansion coefficients and thermal dissipation coefficients, the thermal expansion of the rotor and cylinder will not be the same, and if the difference in thermal growth exceeds the permissible clearance tolerance, friction will occur, which may cause accidents. The purpose of monitoring the differential expansion is to take the necessary measures to ensure the safety of the unit and equipment before friction occurs.

Regarding the installation and calibration of the high pressure cylinder differential expansion sensor, as the radial and axial dimensions of the short shaft of the rotor head did not change before and after the retrofit, and the bearing box cover where the sensor and its mounting bracket are located was not replaced in this retrofit, the installation method and calibration method of the high pressure cylinder differential expansion sensor did not need to be modified. The alarm set point before and after the retrofit and the recommended set point for manual trip are shown in Table 1.

| Table 1. HP differential Expansion Set Point Value before Retrofit |
|---|---|---|
| Meaning of set points | Unit | Before | After |
| Manual trip value for positive differential expansion | mm | +3.5 | +3.5 |
| Alarm value for positive differential expansion | mm | +3.0 | +3.0 |
| Cold set point | mm | 0 | 0 |
| Alarm value for negative differential expansion | mm | -3.5 | -3.5 |
| Manual trip value for negative differential expansion | mm | -4.2 | -4.2 |

2.2.3. Vibration and eccentricity analysis

The rotor will vibrate in operation, the amplitude of the rotor with the increase in speed and increase to a certain speed when the amplitude reaches a maximum (also known as resonance), more than this speed after the amplitude with the increase in speed gradually reduced, and stable in a certain range, the rotor amplitude of the maximum speed is called the rotor of the first-order critical speed. This speed is equal to the rotor's inherent frequency, when the speed continues to increase, close to 2 times the inherent frequency, the amplitude will increase again, when the speed is equal to 2 times the inherent frequency is called the second-order (level) critical speed, and so on, there are third-order and fourth-order, etc.
The first-order horizontal critical speed of Daya Bay Nuclear Power Plant Units 1 and 2 was 1283 rpm before the retrofit and has decreased to 1281 rpm after the retrofit; the first-order vertical critical speed was 2783 rpm before the retrofit and has decreased to 2742 rpm after the retrofit. The minor changes in the above two critical speeds do not result in a modification of the speed range in the critical speed zone during turbine ramp up.

With regard to the installation of the shaft vibration and bearing vibration sensors, it has been measured and verified on site that there is no effect. The eccentricity sensors are the same as the shaft vibration sensors. It mainly measures and monitors the bending of the rotor at low speeds (e.g. turning and ramp up). As is the case with the shaft vibration measurement channel, this retrofit has no effect on the measured values of the rotor eccentricity and its sensor installation.

2.3. Effect of increased inlet pressure of high pressure cylinders

2.3.1. Turbine governing system GRE inlet pressure limit
In addition to using advanced blade technology to improve the efficiency of the turbine's high pressure cylinder, this retrofit also increases the first-stage steam inlet pressure of the turbine's high pressure cylinder by reducing the flow area of the first-stage bulkhead, which increases the opening of the turbine governing valve and reduces throttling losses, thereby obtaining a power increase. The actual first-stage steam inlet pressure of the high pressure cylinder before the retrofit was 59.6 bar a and 60.2 bar a (absolute pressure) respectively for unit 1 and unit 2, and the first-stage steam inlet pressure of the high pressure cylinder after the retrofit was designed to be 60.8±0.6 bar a (absolute pressure).

Referring to the method of calculating steam demand after the synchronous grid connection of the turbine governing system GRE, it can be seen that the inlet pressure limit of the high pressure cylinder, Pmax, is one of the parameters involved in governing and control, and is item 30 of the adjustable parameters of GRE, as shown in Table 2. The original inlet pressure setting satisfies the maximum design pressure value after the retrofit, and after analysis it was decided that Pmax would remain unchanged.

| Item No. | Meaning of adjustable parameters                  | Minimum value | Maximum value | Initial set point | Unit |
|----------|---------------------------------------------------|---------------|---------------|-------------------|------|
| 30       | High pressure cylinder inlet reference pressure   | 0.00          | 75.00         | 60.86             | bar g|

2.3.2. Turbine high pressure cylinder governing valve opening
After the steam pressure of the first stage of the turbine is increased, the opening of the main steam governing valve of the turbine will be increased accordingly, which is expected to increase from about 45% before the retrofit to about 55%. According to the characteristic curve of the governing valve, its opening will be closer to the non-linear region, and the fluctuation of the valve opening with the change of steam demand will increase.

Taking Daya Bay Nuclear Power Plant Unit 1 as an example, the top black curve in Figure 2 shows the theoretical flow characteristics of the valve’s original design, the bottom purple curve shows the current actual flow characteristics of Unit 1, and the middle brown and green curves show the characteristic curves at the lower design pressure limit of 60.2 bar a and the upper design pressure limit of 61.4 bar a after the retrofit.
Figure 2. HP Governing Valve Flow Characteristic Curves

Table 3 shows that the actual operating characteristic curve of the governing valve has a slope of 2.2:1, which is smoother than the theoretical curve (slope of 6:1). The slope is 2.5:1 at a pressure of 60.2 bar a and 3.3:1 at 61.4 bar a. Although the characteristic curve is greater than before, but there is still a considerable margin compared to the theoretical curve. The slope can be judged that the actual operation of the governing valve will still be better than the theoretical design, although the fluctuation of the governing valve with the change of load will be slightly increased, but still within the acceptable range of the theoretical design, at the same time combined with the actual operation of the valve over a long period of time, there is no need to make additional adjustments to the valve in advance, and will be followed up during start up.

Table 3. Slope of Flow Characteristic Curves

| Characteristic curves                                | Slope  |
|-----------------------------------------------------|--------|
| Original theoretical flow characteristics           | 6:1    |
| Lower design pressure limit of 60.2 bar a           | 2.5:1  |
| Upper design pressure limit of 61.4 bar a           | 3.3:1  |
| Existing operating curve of unit 1                  | 2.2:1  |

2.3.3. Secondary loop steam feed pump load rejection and alarm set points

During daily power operation: If two of the three feed pumps in the secondary loop (steam feed pump APP1, steam feed pump APP2 and electric feed pump APA) are not running and the unit load is greater than 50% at this time, the unit will automatically reduce the load to 50% through the turbine governing system. If one of the two steam feed pumps (APP1 and APP2) trips/stops or if the electric feed pump (APA) is not available and the unit load is greater than 85% at this time, the APP001AA/001EC alarm in the main control room will be triggered to remind the operator to pay close attention to the status of the other two feed pumps and discuss whether it is necessary to reduce the load to 85%. Since there is an approximately linear relationship between the high pressure cylinder inlet pressure and the unit load, the above load signals are converted from the high pressure cylinder inlet pressure. As can be seen from Figure 3, since the deviation of the high pressure cylinder inlet pressure of Daya Bay units 1 and 2 before and after the retrofit is only 1.2 bar and 0.6 bar respectively, the corresponding pressure/load curve changes are very small, so the 50% and 85% load settings in the system will not be modified for the time being.
2.3.4. Drain water flow for moisture separator reheater system

After the retrofit, the efficiency of the high pressure cylinder was improved, the humidity of the high pressure cylinder discharge increased, and the total drain water flow of the two columns of moisture separator reheaters was expected to increase from 167.9 kg/s to 180.2 kg/s, an increase of about 7%. After analysis of the site data, before the retrofit of the drain water pump operation has not yet reached the rated power, the governing valve GSS103/203VL open for about 78%, there is still a certain margin. In addition, after calculating and evaluating the pipeline flow rate, drain water tank capacity, valve flow-through capacity and drain water pump capacity, it was confirmed that all parameters were within the design range and the current mechanical equipment configuration still met the requirements after the unit output was increased.

After the increase of the drain water flow of the moisture separator reheater, the drain water pumps and valves on site can speed up the transfer of condensate from the drain water tank through automatic adjustment and control loops within the scope of the design, and the current relevant instrumentation...
parameters and fixed values can achieve effective measurement and timely alarming of the high and low liquid levels of the existing tank.

3. Parameters tracking and verification of the unit up phase after retrofit

This retrofit project was first implemented in the D217 outage of Daya Bay Nuclear Power Plant Unit 2. After completing the equipment replacement and installation, the unit was started up, connected to the grid and ramped up in accordance with the previous normal start up procedures without any abnormalities during the period, and the instrumentation and control parameters of the secondary loop thermal system of the modified unit were within the scope of the preliminary design analysis and expectations.

The retrofit project team carried out a comprehensive follow-up and verification of the relevant parameters, including the differential expansion of the high pressure cylinder, vibration, thrust bearing wear, primary steam inlet pressure, governing valve opening and water level of the combined drain water tank as shown below.

3.1. High pressure cylinder differential expansion, vibration and thrust bearing wear

D217 outage after the turbine high pressure cylinder retrofit, the main operating parameters such as the differential expansion, vibration and thrust bearing wear meets the standard requirements during the turbine run up, grid connection and each load platform, and there is a small change after the retrofit with minimal impact, which is consistent with the analysis results. The measured and recorded values of the high pressure cylinder before and after the retrofit of the differential expansion at full power operation are shown in Table 4.

| DIFF. EXPANSION | D216 | D217 |
|-----------------|------|------|
| D2GME005MV (Unit: mm) | -2.55 | -2.16 |

3.2. High pressure cylinder primary inlet pressure

The actual pressure at full power in D215/D216 outage was about 60.0 bar a before the retrofit, and the measured pressure at maximum power of the unit after the D117 outage was 60.1 bar a. The actual pressure at full power platform before and after the retrofit was 0.1 bar.

The current setting value of Pmax in the GRE upper computer is 61.86 bar a, and the actual pressure value after the retrofit is 60.1 bar a. The original setting value meets the normal operation and effective governing of the unit, which verifies that the analysis results are correct.

3.3. High cylinder governing valve opening

As can be seen from section 3.2, the actual pressures at full power before and after the retrofit were very close, with a deviation of around 0.1 bar. According to the characteristic curves of the valves, the opening of the high pressure cylinder governing valves at full power after the three outage D215/D216/D217 are very close to each other due to the small deviation of the primary steam inlet pressure before and after the retrofit, as shown in Table 5. As can be seen from the data in the table below, the opening of the four high pressure cylinder governing valves are much closer after the retrofit of the D217 outage high pressure cylinder, and are very close to the valve position values of the D215/D216 outage, with minimal fluctuations and no significant changes compared to the operation before the retrofit.

| No. | Outage | D215 | D216 | D217 |
|-----|--------|------|------|------|
| D2GME005MM | 47.85% | 46.15% | 43.27% |
| D2GME006MM | 45.50% | 46.07% | 44.10% |
| D2GME007MM | 41.44% | 39.88% | 43.23% |
| D2GME008MM | 39.96% | 37.85% | 43.85% |
3.4. Moisture separator reheater drain water flow

Compared with the pre-retrofit period, there was no significant change in the control of the moisture separator reheater at each power platform, where the liquid level of the two combined tanks was controlled at around 0.75m at full power, and the opening of the normal drain water valve on site was maintained at around 78%, as expected by the analysis. The liquid level of the combined drain water tank in D216/D217 outage is shown in Figure 4 and Figure 5 respectively.

![Figure 4](image1.png)

Figure 4. Drain Water Tank Level of Moisture Separator Reheater in D216 Outage

![Figure 5](image2.png)

Figure 5. Drain Water Tank Level of Moisture Separator Reheater in D217 Outage

4. Conclusions

As the first large commercial nuclear power plant in China, the Daya Bay Nuclear Power Plant has been in continuous operation for more than 20 years since its commissioning in 1993, and some of its mechanical equipment is aging, resulting in potential operational problems. This project, as the first turbine high pressure cylinder retrofit for a megawatt nuclear unit in China, not only solves the problem of ageing equipment but also improves the efficiency of the turbine high pressure cylinder,
thus increasing the output power of the unit by several megawatts.

During the preliminary analysis and design stage, the project team combined the characteristics and parameters of the mechanical equipment before and after the retrofit provided by the equipment manufacturer, and through the collection of various operating parameters of the unit before the retrofit, analyzed and screened out the parameters that needed to be followed and optimized in the instrumentation and control part of the secondary loop thermal system, made theoretical evaluation of the possible working range of each parameter after the retrofit through relevant calculations and analysis, and prepared a detailed plan according to the analysis before the implementation. This laid a good foundation for the successful of the unit to the grid at one time after the retrofit, and can provide some reference for the subsequent retrofit of the turbine and high pressure cylinder of similar large nuclear power units.

References
[1] Huang, Z.J. (2014) Power Up-rates Analysis of 310 MW Unit in Qinshan NPP. Nuclear Power Engineering, 35: 83-87.
[2] Xiang, W.Y., Lv, Y.H. (2012) Power Uprate Approaches and Developments of Nuclear Power Plant. Power & Energy, 33: 263-270.
[3] Su, L.S., Yang, H.Y. (2005) Devices & Systems of 900 MW PWR. Atomic Energy Press, Beijing.
[4] Zang, X.N. (2010) Steam Power Conversion System of Nuclear Power Plants. Atomic Energy Press, Beijing.
[5] Liu, G.F., Guo, W.Q. (2010) Instrumentation and Control of Nuclear Power Plants. Atomic Energy Press, Beijing.