The fault analysis for low pressure last stage blade of the deep load changing gas-steam combined cycle steam turbine unit

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Abstract. In this paper, the causes of the abrasion at the fir-tree type blade root of low pressure last stage which are loosely assembled and the axial movement of the blade root to the intake side of gas-steam combined cycle steam turbine unit are deeply analyzed, which are caused by the special operating conditions of long-term turning and the high-speed setting of turning gear of the deep peak load changing units. At the same time, through the analysis of the fracture of the broken blade, the damage of the top shroud and the vibration data of the accident process, it is concluded that the abrasion at the blade root results in loosening of the blade, the violent striking between the loose blades during the high-speed turning process, results in the damage of the top shroud and the blade. Under the action of centrifugal force of rated speed condition, a break first occurs, and the broken debris falls between the last rotor blade and the static blade, which causes severe impact damage to the blade body, thereby causing secondary tearing of the blade.

1. Introduction
With the aggravation of energy and environmental crisis in China, clean energy power generation technology is developing rapidly. Gas-steam combined cycle power generation system, as a kind of clean energy power generation, has also been developed. At present, the gas turbines in gas-steam power generation system in our country mainly rely on imports, and the matching steam turbines have been localized, which is due to the continuous improvement of the design technology and production level of steam turbines in our country. Accompanied by this is a sharp decline in the accident rate of the turbine itself. However, as an important part of the turbine, the blade design technology is still difficult to accurately evaluate the dynamic stress and vibration modes characteristics of the blade due to poor working conditions. Blade accidents still occur from time to time [1-8]. Taking the last stage blade fracture of a 350MW gas-steam combined steam turbine as an example, this paper analyses the cause and mechanism of the accident, and provides a reference for the design and fault analysis for the same type units.

2. Equipment overview
The gas-steam combined cycle generation unit is F-class, one-drag-one multi-axis arrangement. The matching steam turbines are three-pressure, reheating, reactionary, double-cylinder, double-exhaust and condensing steam turbines. The low-pressure final stage blade of the steam turbine is of whole-circle loose-fitting type, and the blade root type is of fir-tree type. It is manufactured, inspected and checked in accordance with STP SQB44.24. Specific blade parameters are as follows.
Table 1. Parameters of low pressure last stage rotor blade.

| Project                         | Parameter                                      |
|---------------------------------|------------------------------------------------|
| Rotor blade pitch diameter      | 2324.1 mm                                      |
| Rotor blade height              | 800.1 mm                                       |
| Blade type                      | Whole circle self-locking blade                |
| Rotor blade number              | 96                                              |
| Blade Material                  | 05Cr17Ni4Cu4Nb (Ⅱ)                            |
| Type of blade root              | Fir-tree root                                  |
| Working speed                   | 3000 rpm                                       |
| Water erosion measures          | Brazing stellite Alloy Sheet                   |
| Single blade weight             | 11.2 kg                                        |

3. Fault process and blade damage introduction

Before the accident, the gas turbine startup and grid-connection process were normal. Steam turbine is in the state of warm start-up. There are no abnormal operation parameters such as vibration, bearing temperature, axis displacement and unit expansion-difference during the whole start-up process and at rated speed. After three minutes of grid-connection, the unit load is 38MW, the vibration of the unit increases sharply, and the vibration of bearings 3 and 4 reaches the stop protection action value. The analysis of vibration data shows that there is a great imbalance at the moment of the unit stop protection action, and the rotor is unbalanced. Later, through hand-hole endoscopy, it was found that the low pressure last stage blade on the generator side was broken, and the low pressure cylinder of the unit was immediately disintegration for inspection. Inspection details are as follows:

3.1. Vibration analysis

Vibration data recorded by TDM during the whole accident process were collected. It was found that there were two peak value of the vibration during the process of unit tripping and speed reduction. Firstly, the vibration of the unit increases sharply after the unit is connected to the grid, which leads to the unit’s vibration protection action and unit tripping. The maximum vibration value of No. 3 bearing is 285.8 um. In addition, as the speed reducing, the vibration firstly decreases obviously with the speed. When the speed decreases to 2960 rpm, the vibration of No. 3 bearing suddenly increases to 290.3 um again, and then decreases gradually with the speed drop. Through the analysis of vibration spectrum and trend diagram, it is found that there were not only large unbalanced components but also some rubbing component in the two vibration increasing process.

3.2. Introduction of blade fracture

The disintegration inspection of the low pressure cylinder of the unit found that the last stage blade of the generator side number 50 was broken, and the fracture length was about 245 mm. As the fractured debris falls between the rotor blade and the stator blade, the intake edge of 96 blades in the low pressure last stage of the generator side is damaged, and the stellite alloy and the blade body are seriously damaged at the intake side of the blade. (figure. 1 and figure2).
3.3. Axial displacement of blade root and damage of tip shroud
Axial displacement of some blade roots to the intake side occurred. Fractured blade No. 50 and adjacent blade No. 49 have obvious axial displacement to the intake side, with offsets of 26 mm and 14 mm, respectively. The axial locking plates on both sides of the blade have all been lost efficacy (Figure. 3). The clearance of the top shroud of the rotor blades numbered 38-63 increased, and the defects caused by severe collision occurred in many parts of the top shroud (Figure. 4).

3.4. Abrasion of blade root and blade root installation slots
The blade root and the blade root installation slot of 26 blades numbered 38-63 at the generator side of the unit had been abraded, of which the installation slot of No. 51 blade are worn most seriously. The working surface clearance between the blade root and the blade root installation slots is 0.6 mm, and the non-working surface clearance between the blade root and the blade root installation slots is 1.1 mm. By examining the abrasion of the low pressure last stage blades of the steam turbine side, it was found that the blade root and the blade root installation slot of 9 blades were worn, numbered 37-45. No. 41 blades were worn most seriously. The working surface clearance between the blade root and the blade root installation slots is 0.5mm, and that the non-working surface clearance is 0.7mm.

4. Metal detection and fracture analysis

4.1. Chemical composition analysis.
The chemical composition of 2 samples near the fracture surface of the fractured blade was tested and analyzed. The results are shown in Table 2. From the test results, it can be seen that the chemical composition of the fractured blade meets the design requirements.
Table 2. Chemical constituents analysis of fractured blade.

|       | C    | Si   | Mn   | P     | S     | Cr     | Ni     | Cu     | Nb    | Ti    |
|-------|------|------|------|-------|-------|--------|--------|--------|-------|-------|
| Standard | ≤0.055 | ≤1.00 | ≤0.50 | ≤0.030 | 0.025 | 15.0-16.0 | 3.8-4.5 | 3.0-3.7 | 0.15-0.35 | ≤0.05 |
| Sample 1 | 0.036 | 0.27 | 0.44 | 0.021 | 0.001 | 15.46 | 4.42 | 3.37 | 0.2 | 0.005 |
| Sample 2 | 0.035 | 0.28 | 0.44 | 0.02 | 0.001 | 15.49 | 4.41 | 3.34 | 0.2 | 0.005 |

4.2. Mechanical properties testing.
The mechanical properties of three impact specimens were tested at the root of the fractured blade. The test results are shown in Table 3. The test results of metal mechanical properties of the blades show that the tensile properties, impact properties and hardness of the blades meet the requirements of the specifications.

Table 3. Mechanical properties testing of fractured blade.

|       | Rp0.2 | Rm   | A4   | Z     | HBW   | KV2   |
|-------|-------|------|------|-------|-------|-------|
| Standard | 900-980 | 950  | 18.0 | 55    | 293-341 | /     |
| Sample 1 | 947   | 1000 | 23.8 | 68.6  | 313   | 173 174 163 |
| Sample 2 | 932   | 991  | 23.3 | 69.8  | 313   | 177 174 176 |
| Sample 3 | 945   | 999  | 23.5 | 69.7  | 314   | 175 174 172 |

4.3. Metallographic examination of blades.
The results are shown in Table 4. The results show that the content and grain size of the ferrite meet the requirements of the specification.

Table 4. Metallographic examination of blades.

|       | δ-Fe   | Grain size | Inclusion |
|-------|--------|------------|-----------|
| Standard | ≤5%    | Not coarse than 4 level | Not more than 1.5 level |
| Sample 1 | ≤1%    | 6 level   | D:1.5     |
| Sample 2 | ≤1%    | 6 level   | D:1.0     |

4.4. Macroscopic examination of fracture surface.
Macroscopic analysis of the final fracture surface shows that the intake side of the blade fracture is obviously deformed, indicating that the blade body has undergone strong impact and the original fracture morphology has been destroyed, which brings some difficulties to the analysis of the cause of the accident. Macroscopic examination showed that the remaining fractured part had obvious tear morphology, which was an instantaneous fracture.

Figure 5. Fractured surface of the blade.
5.  Cause Analysis and Discussion of Accident

The low-pressure last stage blade of the unit is fir-tree loosely assembled blade root. In this accident, some of the blades moved axially, and the moving direction is toward the intake side, which is relatively rare. The causes of abrasion at the blade root, axial movement and displacement leading to contact rubbing and blade fracture are analyzed as follows:

5.1. Installation factors.

The designed clearance of the working surface between the blade root and the blade root installation slot is not more than 0.3 mm, and the designed clearance of the non-working surface between the blade root and the blade root installation slot is not more than 0.5 mm. In fact, the installation parameters of the last stage blade of the unit (such as the size of the filler, the installation control clearance of the blade root working surface and the non-working surface) were not recorded during the process of blade installation in the steam turbine manufacturing plant. In addition, it was found that a large number of fillers remained in the non-working surface of blade roots during the installation process, some of which had been prominent. Some blades have no filler in the non-working surface at the blade root, probably because the fillers had fallen off during the operation and turning or had been removed during the installation process (according to the assembly requirements of the manufacturer, the fillers were removed after the installation). As a result, there are differences in blade tightness during installation. In the process of unit turning, the blade root and the locking plate of loosely installed blades are more easily abrasive wear.

5.2. Design and operation characteristics of units.

The design turning speed of the unit is high to 50 rpm. Excessive turning speed will cause frequent friction at the root of the loosened blade, which will lead to the abrasion of the filler, the locking blade and the root of the blade. The clearance of the working surface and the non-working surface of the blade root will gradually increase, and the loosening of the blade will gradually expand. During the overhaul of the unit in 2017, it was found that the maximum swing distance of the low-pressure last stage blade along the rotating direction was about 20 mm. After the accident, the swing distance of the low-pressure last stage blade along the rotating direction was more than 80 mm. This shows that the blade loosening situation gradually increases, and the wear rate gradually increases also. At the same time, the unit belongs to deep load changing gas-steam combined cycle steam turbine unit. The unit’s start-up and shutdown are frequent, and is in a long-term turning state with a speed of 50 rpm. According to statistics, the number of starting and stopping of the unit has exceeded 400 times since putting into operation, and the cumulative turning time has exceeded 10,000 hours. Excessive turning speed and prolonged turning state are the important reasons for the wear of blade filler, locking blade and blade root, and the loosening of blade.

5.3. Stress between top shroud under turning state.

As shown in Figure 6. In the case of blade loosening, although the turning speed is relatively high (50 rpm), the centrifugal force is not enough to make the blades locked by centrifugal force, and the top shroud of the blades will collide with each other under high-speed turning conditions. This is verified by the obvious sound detected in the low-pressure cylinder during the turning of the unit since its commissioning. Loose blades collide with each other under the condition of turning will have two effects, firstly, it will cause the damage of the top shroud due to impact, secondly, it will cause the blade to be subjected to the force on the intake side (figure 6). At the same time, the blade root installation slot has an inclined angle to the intake side. These are the reason why the blade root moves axially towards the intake side.

5.4. Causes of blade fracture.

According to the analysis of the fracture of the broken blade, the damage of the top shroud and the vibration data of the accident process, the reason of the blade breakage is that the blade root is worn by
the long-term high-speed turning, and the blades collide with each other under the high-speed turning condition, resulting in the damage of the top shroud and the top part of the blade. The damaged parts of the blade top are firstly broken under the centrifugal force of the working speed. The broken debris falls between the last rotor blade and the static blade, causing further impact damage to the broken blade during the high-speed rotating process of the unit, and then causing secondary tearing under the action of centrifugal force.

6. Conclusion

6.1. From the metal test results of the fractured blade, it can be seen that the chemical composition, mechanical properties and metallographic examination of the blade meet the requirements of the design specifications, and have no direct impact on the blade fracture accident.

6.2. According to the analysis of the fracture surface of the broken blade, the top shroud damage of the blade and the vibration data of the accident process, the blade fracture should be divided into several stages. Due to the abrasion of loose blade root caused by long-term high-speed turning, loose blades collide with each other, and then damage the top shroud and the top part of the blade. The damaged part of the blade first breaks under the action of centrifugal force at rated speed. Fractured debris falling between the last stage rotor blade and the stator blade causes further impact damage to the fractured blade at the high speed of the unit. When the speed drops to about 2960 rpm, the blade will be torn twice. At the same time, the fractured debris also caused extensive damage to the intake side of the last stage rotor blade.

6.3. The abrasion of the blade root, the displacement of the blade root to the intake side, the damage of the blade top shroud and the dynamic and static rubbing are all caused by the long-term turning operating conditions of the unit and the high design of the turning speed. Therefore, for the deep load changing gas-steam combined cycle unit, if the blade root of the LP last stage of the steam turbine unit is designed with loosely assembled type, the effect of turning speed on the abrasion of blade root should be fully considered. It is suggested that turning speed should be 3-5 rpm.

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