The analysis and solution of contact rubbing fault for low pressure rotor of gas-steam combined cycle turbine unit

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Abstract. The contact rubbing fault mechanism for low pressure rotor of gas-steam combined cycle steam turbine unit is analyzed deeply in this paper. It is include that the high start and stop frequency of the gas turbine, the special operation mode of the long-time turning and the high designed turbine turning speed are the main reasons for the axial displacement to the inlet side of the fir-tree root and the contact rubbing fault of the low pressure rotor. At the same time, this paper presents a solution to the problem of contact rubbing fault of low-pressure turbine rotor, and analyzes the dynamic stress and vibration frequency of the new blade after technical improvement. The results show that the stress of root and groove of the new blade and the vibration frequency of the new blade can meet the requirements of safe and stable operation of the unit.

1. Introduction
With the development of power industry and the continuous strengthening of environmental protection requirements, large capacity and high parameter steam turbine units play a major role in the current generation units in China. With the continuous improvement of efficiency requirements for large units, the clearance between rotor and stator is reduced and the possibility of contact rubbing fault is increased. The rubbing of rotating and stationary parts of steam turbine unit is a common fault in operation. The contact rubbing fault will make the turbine rotor produce very complex vibration, the lighter will make the unit appear strong vibration, and the serious can cause the rotor to bend permanently, even the whole shaft system is destroyed. Therefore, the accurate analysis and diagnosis of contact rubbing fault and the research and analysis of contact rubbing fault mechanism will undoubtedly improve the safety and economy of unit operation and prevent major accidents. At present, the cases reported in the literature mainly focus on the shaft seal, oil baffle and the top steam seal of the moving blade of the steam turbine unit, while the cases of axial vibration rubbing between the moving and stationary blades are relatively few. In this paper, the causes and mechanism of steam gas combined cycle turbine vibration and contact rubbing fault are analyzed, which provides basis for subsequent analysis and treatment of similar problems.

2. Introduction to main equipment
The gas-steam combined cycle generation unit is F-class. The matching steam turbine of the gas steam combined cycle cogeneration unit is a combined cycle reheat, double cylinder double exhaust and extraction condensing steam turbine, which adopts the high and medium pressure combined cylinder and low pressure cylinder double flow arrangement. The low pressure last stage blade of steam turbine
unit is the whole circle loose-fitting type blade, and the blade root type is fir-tree blade root. The blade length is 800mm. The installation structure is as shown in the figure 1.

Figure 1. Installation structure of last stage moving blade.

3. Accident process and contact rubbing fault details

3.1 Accident process introduction
The process of the start-up and the grid connection of the gas turbine is smooth without any abnormality before the contact rubbing fault of the unit. The start-up parameters of the steam turbine are selected according to the warm start-up situation. During the start-up process of the steam turbine unit and reaching the working speed of 3000rpm, the operation parameters such as vibration, bearing temperature, shaft displacement and differential expansion are normal. After the turbine is connected to the grid and with initial load, the vibration of the unit suddenly increase, the vibration of No. 3 bearing reaches the protection action value in an instant, and the turbine unit trips. Through the analysis of TDM vibration data, the vibration characteristics accord with the characteristics of contact rubbing fault vibration. After further inspection, it was found that the axial displacement of the last stage blade of low pressure at the generator side of the turbine to the steam inlet side occurred, and the axial displacement distance had exceeded the dynamic and static installation clearance at this place, so it was confirmed that serious axial dynamic and static friction occurred.

3.2 Introduction of contact rubbing fault
After the disassembly inspection of the low-pressure cylinder, it was found that there were two significant characteristics of this contact rubbing fault accident. One was that some blade roots had axial displacement, and the axial displacement direction was the steam inlet side; the other was that further inspection found that the working-face and non-working face of the fir-tree root of the axial displacement blade and its adjacent blades had different degrees of wear. The details are as follows.

3.2.1 Axial displacement of blade root. Through further inspection, it is found that the moving blades that caused the contact rubbing fault accidents and their adjacent blades have shifted axially to the steam inlet side in varying degrees, with the maximum displacement of 25 mm. The designed axial clearance between the blade root of the last stage moving blade and the last stage stationary blade of the low-pressure rotor of the turbine is 19mm, and the axial displacement of the last stage moving blade to the steam inlet side has exceeded the clearance value designed by the unit. The axial locking plate on the outside of the last stage moving blade has been completely worn out, resulting in the friction between the root of the last stage rotor blade and the diaphragm of the last stage stationary blade. The detailed contact and wear conditions see figure 2.
3.2.2 Friction of fir-tree type blade root and blade root installation groove of last stage rotor blade. The designed installation clearance between the fir-tree type blade root and the blade root installation groove is 0.3mm, and that of the non working surface is 0.5mm. After returning the turbine rotor to the factory for accurate measurement, it is found that the blade root and blade root installation groove of the low-pressure last stage blade at the generator side and turbine side of the turbine unit are worn to varying degrees, and the blades with blade root and blade root installation groove wear are continuous (see Figure 3 and Figure 4). In the generator side, it was found that the number of blades with blade root and blade root installation groove wear is 26, which causes the clearance between the working surface and non working surface of blade root to increase, which resulted in the increase of the clearance between the working surface and the non working surface of the blade root. After detailed measurement, the maximum clearance of working surface of blade root is 0.6mm, and that of non working surface is 1.1mm. The blade root and blade root installation groove of 9 blades were found to be worn on the turbine side. The maximum clearance of working surface is 0.5mm, and that of non working surface is 0.7mm.

3.2.3 Blade top shroud and lacing wires damage. It was found that the clearance between the shroud on the top of some blades increased, and the shroud and the lacing wires on the top of the blades were damaged by serious collision. See Figure 5 and Figure 6.
4. Mechanism and cause analysis of the contact rubbing fault

The low pressure last stage blade of the steam turbine unit is fir-tree loosely installed blade root type, with mature design technology and wide application. The remarkable feature of the contact rubbing fault of the low-pressure rotor of the steam turbine unit is that the blade root of the last stage of the low-pressure blade moves towards the steam inlet side. In the past, the turbine units of different capacities have also experienced similar accidents of blade axial displacement. The phenomenon is that the blade root of the whole circle low pressure last stage or the whole circle low pressure second last stage basically has axial displacement, and the axial displacement direction is toward the steam outlet side, which is caused by the unqualified material of blade locating pin. In this accident, it is rare for some blades to shift axially, and the moving direction is toward the inlet side. Detailed analysis of the reasons for the wear and axial displacement of the blade root and the dynamic and static rubbing failure of the low-pressure rotor are as follows:

4.1 Design defect of the filler at blade root and the control of the installation clearance of the blade.

The designed installation clearance between the fir-tree type blade root and the blade root installation groove is 0.3mm, and that of the non working surface is 0.5mm. The installation of turbine blades is completed by manual work. It is very difficult to control the installation parameters of loose installed blades (such as the size of filler, the installation clearance between the working surface and non working surface of the fir-tree type blade root). Further inspection after the accident found that the installation parameters of the last stage blades of the unit had no data record. At the same time, the filler (see Figure 1) at the blade root completely depend on the elastic force of the metal itself to fix the blade radially. After long-term operation, with the extension of the operation time of the unit and the increase of metal fatigue, the effect of metal elastic force will gradually decrease and eventually fail. This may be the reason why the blade initially loosens and causes wear at the blade root.

4.2 Influence of design turning speed.

The turning gear of the unit is oil turbine driven, and the designed turning speed is 50 rpm, which is much higher than the turning speed (3-5 RPM) of the traditional turbine unit. After the initial looseness of the blade due to the installation and the failure of the packing parts, the centrifugal force caused by the rotating speed cannot lock the last loose blade when the unit is running at the turning speed. The wear of the working surface and the non working surface of the loose blade root, the wear of the filler and the locking pieces are dozens of times of the traditional turning speed. During the inspection overhaul of the unit in 2017, it was found that the maximum swing amplitude of the last stage blade of low pressure along the rotation direction was about 20 mm. After the event occurred, it is found that the swing amplitude of the low pressure last stage blade along the rotation direction was more than 80 mm, indicating that the blade looseness gradually increased over time and the wear rate
gradually increased. At the same time, when the turning gear is running at the rotating speed, there will be a strong impact between the blades, which is the cause of the damage of the blade top shroud and tie bar.

4.3 Operation characteristics of gas-steam turbine unit
The gas-steam combined cycle steam turbine unit belongs to the deep peak shaving unit. The unit not only starts and stops very frequently, but also is in the running state for a long time. According to the statistics of the power plant, the number of start-up and shut-down of the unit has exceeded four hundred times since it was put into operation, and the total turning time has exceeded ten thousand hours. At the same time, through the investigation and comparative analysis of the operation of the same type units, the number of starts and stops of the unit and the operation time of the turning state are far longer than that of other units of the same type, so the operation characteristics of the deep peak shaving gas steam combined cycle unit is the main cause of the blade root wear of the last stage loose blade of the unit at low pressure.

4.4 Analysis of the displacement of the axial inlet side of the low-pressure last stage blade
When the low-pressure last stage blade of the unit operates at the turning speed of 50 rpm, the centrifugal force at this time is not enough to make the blade lock. Under the condition of high-speed turning, the blade top shroud will collide violently with each other, and the stress condition of blade top shroud is as shown in the figure 7. And in the design, the assembly groove blade root inclines to the inlet side. The main reason for the displacement of the blade root to the axial inlet side and the contact rubbing fault of the low-pressure rotor is the operation characteristics of the long-term turning condition and the impact between the top shroud of the blade under the turning condition.

5. Treatment scheme and scheme safety assessment

5.1 Processing of root groove and blade configuration
As the wear groove on the generator side accounts for 27% of the whole circle groove, in order to keep the blades consistent and facilitate subsequent management and maintenance, the whole circle blade root assembly groove is processed according to the new profile. The new groove profile of the blade root assembly is determined according to the actual turning amount of the groove on the boring and milling machine, and the turning amount is determined by the existence of the wear-free surface of the maximum worn groove. The blade root of the whole circle is processed and configured according to the new blade root profile, and the other dimensions are consistent with the original blade. The blade
root assembly groove with wear condition on the turbine side shall be processed and equipped with blades uniformly according to the generator side. The comparison between the groove lines of new and old roots is shown in the figure 8.

Figure 8. Comparison between the groove lines of new and old roots.

5.2 Root strength and blade dynamic frequency evaluation
In order to ensure the safety and feasibility of the treatment scheme, the finite element method is used to evaluate the strength of blade root and blade root assembly groove, and check the dynamic frequency safety of the new blade. The blade model is calculated by applying the circularly symmetric boundary condition. The hexahedral mesh is used for the finite element analysis, and the element type is c3d8i. The contact boundary conditions are set for each contact surface of the fir tree type blade root and blade root assembly wheel groove, the bottom surface of the wheel groove is fixed, and the circular symmetrical boundary conditions are set for both sides of the circumferential direction. The centrifugal load of 3000 rpm was applied to the whole blade root groove. The blade root and blade root groove teeth are numbered from top to bottom according to the fir tree type root.

5.2.1 Average stress of blade root and blade root assembly groove. The calculation results of the average stress of blade root assembly groove and blade root is in table 1.

|                     | Root neck stress | Root tooth stress | Groove neck stress | Groove tooth stress |
|---------------------|-----------------|------------------|-------------------|--------------------|
|                     | Original blade  | New blade        | Original blade    | New blade          | Original groove   | New groove       | Original groove | New groove       |
|                     | root            | root             | root              | root               | root              | root             | root              | root              |
| First tooth         | 0.47            | 0.43             | 0.44              | 0.40               | 0.53              | 0.63             | 0.42              | 0.52              |
| Second tooth        | 0.48            | 0.44             | 0.44              | 0.40               | 0.51              | 0.56             | 0.42              | 0.52              |
After the root groove modification, due to the increase of the width of the root neck and the decrease of the width of the groove neck, the average stress of the root neck slightly decreased, and the average stress of the groove neck slightly increased, but the strength margin of the original blade root groove was large. The change of the average stress caused by the root groove modification did not affect the safe operation of the blade.

5.2.2 Peak stress of blade root assembly groove and blade root. The peak stress assessment calculation results of blade root assembly groove and blade root is in Table 2.

| Blade root assembly groove | Blade root |
|---------------------------|-----------|
| Original groove           | New groove|
| First tooth               | 0.51      | 0.43      |
| Second tooth              | 0.43      | 0.50      |
| Third tooth               | 0.43      | 0.50      |
| Allowable stress of root tooth: 1 | Allowable stress of groove tooth: 1 |

After the modification of the blade root groove, the change rule of the peak stress of each tooth of the blade root groove is similar to that of the average stress, that is, the peak stress of each tooth of the blade root decreases, and the peak stress of each tooth of the blade root assembly groove increases, but the change range is small. The strength margin of the original blade root assembly groove is large, and the change of the peak stress caused by the modification of the blade root assembly groove does not affect the safety of the blade.

5.2.3 Change of blade dynamic frequency at rated speed. The finite element method is used to calculate and analyze the change of dynamic frequency of low-pressure last stage moving blade at rated speed of 3000rpm after blade root modification, as shown in Table 3.

| First-order frequency | Second-order frequency |
|-----------------------|------------------------|
| 3rd nodal diameter    | 4th nodal diameter     |
| Original blade root   | New blade root         |
| 181.29Hz              | 186.28Hz               |
| 388.58Hz              | 390.72Hz               |
| 3rd nodal diameter    | 4th nodal diameter     |
| Original groove       | New groove             |
| 179.42Hz              | 184.44Hz               |
| 382.48Hz              | 384.62Hz               |

It can be seen from the calculation results that the modification of the groove profile of the blade root installation has little effect on the overall frequency of the blade and does not affect the safe operation of the blade.

6. Conclusion

6.1 In this accident, the worn of the working surface and non working surface of blade root and blade root installation groove of low-pressure last stage blade, the blade root moves to the steam inlet side
and finally causes the dynamic and static friction accident of low-pressure rotor of the unit, which is caused by the special operation condition of the gas steam combined cycle unit and the high designed turning speed. Therefore, if the type of loosely assembled blade is adopted for the low-pressure last stage blade of the gas-steam combined cycle unit with deep peak regulation, the special operation mode of the unit and the influence of turning speed on the blade root wear of loose blade should be fully considered.

6.2 Through the finite element analysis of the stress comparison between the root and the root groove after the modification, the average stress and the peak stress of the root have decreased, the average stress and the peak stress of the groove have increased, but the change range is not large, the strength margin of the original blade root groove is large, the change of the peak stress caused by the modification of the root groove does not affect the safety of the blade.

6.3 Through the finite element analysis, it is calculated that the dynamic frequency of the blade changes little under the rated speed condition after the blade root and the blade root groove are modified, which has no effect on the safe and stable operation of the unit.

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