Treatment of abnormal vibration at the end of large air-cooled generator --The reference of operation and maintenance fault diagnosis of new type phase modifier

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Abstract: This paper introduces the abnormal natural frequency at the end of a large-scale air-cooled generator in a power generation company, analyzes the abnormal vibration frequency data at the end of the generator, and solves them successfully, which provides a reference for the state analysis of new high power phase modifier.

1. Introduction
In 2017, State Gird Corporation of China successively put into operation large capacity new synchronous phase modifier, improving the DC transmission power and the voltage stability of the power grid at the sending and receiving. Synchronous phase modifier is classified into air-cooled phase modifier, hydrogen cooled phase modifier and all water cooled phase modifier according to cooling mode. Currently, the new type of condenser put into operation mainly is water cooled phase modifier of Shangdian and Dongqi. Because compared with the other two phase modifier, air-cooled phase modifier has the characteristics of simple structure, less auxiliary equipment, easy installation, operation and maintenance, etc., and then it will take the air-cooled phase modifier as the mainstream.

In this paper, the end vibration of 330MW air-cooled generator unit is taken as an example to accumulate experience to solve such problems for large air-cooled phase modifier.

2. Unit overview
2.1. Basic information of unit
The 330MW Air-cooled Turbogenerator of a power plant of Huadian was produced by Jinan power generation equipment factory with the technology of ALSTOM (formerly ABB) Company of Switzerland, which reached a high international advanced level and filled in the domestic blank. The first one is in 2018 and the generator of this unit is in 2011. The closed-circuit cooling system of the generator consists of two axial-flow fans, six air cooler and cooling air trunk. Features of cooling air trunk: The fun of electric generator draws hot air from the generator and discharges it to the air cooler; Features of rotor with bypass air flue: (1) Unique wind path design: Short wind path; Fast velocity;
Sectional cooling; (2) Unique damped system (3) Unique inlay technology of rotor coil: The middle is fixed while both ends are free expansion; The wave spring is preset at the bottom of the groove.

The medium for cooling the stator and rotor is air, and the cooling mode is closed cooling mode with air-water heat exchanger. For the air cooled generator with double-layer arrangement, its air cooler is installed in the foundation. In order to effectively realize the cooling of the motor, an axial flow fan is installed on the rotor shaft, and a self-ventilation system is also on the rotor body. In addition, the wind path of electric generator is also designed as two wind paths symmetrical about the center. The stator core is cooled by radial ventilation slot; The stator winding is cooled directly. The heat generated by the winding is dissipated by stator bar and then taken away by the cooling air. The rotor winding is composed of hollow conductor, and its cooling mode is axial direct cooling. The rotor fun adopts high efficiency paddle fun. The blade angel of the fun can be adjusted according to different situations, and its main parameters are shown in Table 1.

Table 1: Parameters of 330MW air inner-cooled turbogenerator

| No. | Model     | WX25R—127 | Rated power speed 3000/min |
|-----|-----------|-----------|----------------------------|
| 1   | Rated capacity | 388.2MVA  | Insulation grade of stator winding Class F |
| 2   | Rated power  | 330MW     | Insulation grade of rotor winding Class F |
| 3   | Stator voltage | 22KV      | Number of phase 3 |
| 4   | Stator current | 10188A    | Connection mode of stator winding Y |
| 5   | Rotor voltage  | 385V      | Cooling mode Air cooling |
| 6   | Rotor current  | 1680A     | Critical speed |
| 7   | Off-load excitation voltage | 97V | First order 670/min |
| 8   | Off-load excitation voltage | 593A | Second order 1810/min |
| 9   | Rated power factor | 0.85 | Third order 4770/min |
| 10  | Rated frequency | 50Hz | Efficiency 98.73% |

2.2. The history of unit maintenance and fault
Since 2014, the problem of excessive vibration of bearing bush and end of #2 electric generator unit is highlighted. Since the construction of unit #2, the vibration of unit #2 is larger than unit #1. In the early stage of construction, it is built by Henan Electric Power Construction Co., Ltd., and in the middle stage, it is build by another power construction company. The vibration deterioration of the unit is mainly during the overhaul period. In order to solve the problem of large vibration of 2# bearing of steam turbine generator unit and 7# and 8# bearing bush of electric generator, the dynamic balance on site is needed. The progress is: After the field dynamic balance of the balance weight, the vibration of 2# bearing was well controlled, but the vibration of 7# and 8# bearing did not come down because of the balance weight quality and other reasons, and it even mass. After 1.5 hours of operation, the counterweights of 7# and 8# bearing were all removed and the vibration of the bearing 7# and 8# is maintained at about 100um when restart the machine.

The vibration of the end cover of the 8-bearing stator of the steam turbine generator unit exceeds the standard (see Figure 1), and the vibration is greater towards the axis side. The relationship between the end vibration and the load is that the higher the unit load, the greater the end vibration. Defect elimination record shows: Because the vibration of this place is quite big, it makes three bolts fixing the cover plate inside the electric generator in this place were broken and blades of the rotor cooling fan were damaged. After defect elimination, the power plant set up a point to point inspection here, where the vibration is measured and recorded every day (see Table 2). It can be seen that the end of the axial direction is the largest, especially the excitation side.
Table 2: The spot check list of vibration measurement on site

| Time      | Load   | Horizontal mm/s | Vertical mm/s | Axial direction mm/s | Horizontal um | Vertical um | Axial direction |
|-----------|--------|-----------------|---------------|----------------------|----------------|-------------|-----------------|
| Morning   | 2.2    | 4.1             | 22.3          | 19                   | 168            | 428         |                 |
| Afternoon | 3.2    | 5.1             | 27            | 30                   | 54             | 437         |                 |
| Morning   | 2.9    | 3.4             | 27.5          | 22                   | 69             | 362         |                 |
| Afternoon | 2.9    | 5.4             | 46.8          | 16                   | 156            | 487         |                 |
| Morning   | 180MW  | 2.8             | 5.7           | 48.2                 | 15             | 152         | 469             |
| Afternoon | 180MW  | 2.7             | 5.5           | 47.5                 | 32             | 168         | 385             |
| Morning   | 180MW  | 2.9             | 5.8           | 46.6                 | 35             | 179         | 397             |
| Afternoon | 180MW  | 2.7             | 5.7           | 47.2                 | 37             | 168         | 385             |
| Morning   | 180MW  | 2.8             | 5.5           | 46.2                 | 32             | 154         | 452             |
| Afternoon | 180MW  | 2.9             | 5.7           | 46.9                 | 34             | 165         | 388             |

| Time      | Horizontal mm/s | Vertical mm/s | Axial direction mm/s | Horizontal um | Vertical um | Axial direction |
|-----------|-----------------|---------------|----------------------|----------------|-------------|-----------------|
| 4.8       | 7.6             | 22.4          | 25                   | 204            | 355         |                 |
| 5.2       | 5.2             | 18.5          | 36                   | 140            | 280         |                 |
| 8.8       | 7.4             | 13.1          | 41                   | 141            | 222         |                 |
| 9.1       | 6.5             | 12.6          | 47                   | 158            | 240         |                 |
| 9         | 6.6             | 12.2          | 45                   | 162            | 227         |                 |
| 9         | 6.7             | 13.4          | 46                   | 166            | 259         |                 |
| 8.9       | 6.6             | 12.6          | 46                   | 134            | 188         |                 |
| 9.2       | 7.1             | 13.6          | 51                   | 142            | 205         |                 |
| 9         | 7.1             | 12.5          | 49                   | 136            | 195         |                 |
| 9.2       | 6.8             | 12.9          | 48                   | 137            | 198         |                 |
| 9         | 7               | 13.2          | 45                   | 141            | 207         |                 |

Figure 1: End cover
3. Field test
The test position is the end face of excitation side generator and its adjacent side, the end face of steam side generator and its adjacent side, vibration of bearing liner of 7# and 8# bearing, and Turbine side face of engine 1# (as the comparison of the same machine unit); Measuring points 1#, 2# and 3# are generator end face test, measuring points 1# is near axis side, measuring point 3# is far away from axis side, and measuring point 5# and 6# are on generator side, as shown in Figure 1.

3.1. Steam side electric generator test

3.1.1. Test of steam side end
The characteristics of vibration distribution are as follow: The closer the measuring point is to the axial side, the smaller the vibration is. The main character is that the vibration of the axial direction is large, and the characteristics are dominated by 100Hz. In the test parameters, the parameters such as waveform and impact demodulation parameters don't find abnormal conditions such as rubbing.

3.1.2. Test of 7# bearing bush of steam side
Test of 7# bearing bush of steam side is shown as Figure 2 and Figure 3.

3.2. Test of excitation side generator

3.2.1. Test of excitation side
The characteristic of distribution are as follow: The closer the measuring point is to the axial side, the bigger the vibration is. The main vibration is that the vibration of the axial direction and the characteristics of spectrogram is dominated by 1X(50Hz) No abnormality is found in the waveform, impact demodulation and other parameters.

3.2.2. Vibration test of bearing liner at excitation side of 8# bearing
The frequency spectrum of the vibration of bearing liner and end face of bearing bush are coincide, which is dominated by 1X (50Hz), with a smaller 1X harmonic distribution; The vibration in horizontal direction is the largest.

3.3. TDM on site about the spectrum waveform of 7# and 8# bearing bush of 2# electric generator is obtained, which is consistent with the field bearing test results; After checking the Bade diagram of start and stop and the balance record on site, shafting and support stiffness is normal, but the dynamic balance scheme can be optimized.
4. Fault analysis
The main external exciting force of electric generator end vibration is unbalanced centrifugal force of rotor and electromagnetic force of electric generator.

4.1. Resonance principle of electromagnetic force at the end of electric generator
When the generator works, there is current passing through the end winding, and the current and the rotating leakage magnetic field interact, which makes the end winding subject to the rotating magnetic pull. The spatial distribution of the stator end winding magnetic pull is very complex, including radial direction, circumferential direction and axial direction, in which the amplitude of radial component is bigger than the amplitude of other component.

The radial component of the magnetic pulling force rotates with the rotor as a whole, its distribution in the circumferential direction is periodic symmetry, and the line at the end of the magnetic pulling force vector is approximately ellipse. When the revolving speed of the rotor is 3000r/min, i.e. the rotating frequency is 50Hz, the frequency of the magnetic pull on the stator end winding will be twice of the speed, that is 100Hz.

The radial component of large bipolar generators' end winding magnetic pull force is distributed sinusoidal along the circumference of the winding:

\[ F_{γθ} = F_A \sin(ωt + 2θ) \]  

Wherein: The subscript γ means radial component; θ is the circumferential angle of end winding, and the value range is \([0, 2π]\); FA is the amplitude of the radial component of the magnetic pull; ω is the angular frequency of rotor rotation. At a certain time, for example, when \(t=t\), according to equation (1), the distribution of the radial component of magnetic tension along the circumferential direction is drawn, as shown in Figure 4. It can be seen that the radial component of the magnetic pulling force rotates with the rotor, its distribution in the circumferential direction is periodic symmetry, and the line at the end of the magnetic pulling force vector is approximately ellipse. When the revolving speed of the rotor is 3000r/min, i.e. the rotating frequency is 50Hz, the frequency of the magnetic pull on the stator end winding will be twice of the speed, that is 100Hz.

![Figure 4: Distribution of the radial component of magnetic pull along the circumference](image)

In order to obtain the complete radial component of the end winding magnetic pull, its axial distribution must be considered. According to the calculation results of Westinghouse, the radial component of the magnetic pull of the winding end is approximately linearly distributed along the axial direction, as shown in Figure 9. Therefore, the radial component of the magnetic pull of the end winding can be written as follow:

\[ F_γ = R_{F0}(z)F_A \sin(ωt + 2θ) \]  

Wherein: z is the axial coordinate of the end winding; R_{F0}(z) is the distribution function of the radial component of the magnetic pull along the axial direction.

4.2. cause analysis of generator failure
As mentioned above, the dominant frequency of the vibration at the end of the generator steam side is 100Hz, which is caused by electromagnetic force and the resonance frequency at the end is close to
100Hz, which caused the resonance.

The characteristic of the vibration frequency at the end of the excitation side is dominated by 50Hz fundamental frequency, and it is also the fault caused by resonance under the action of fundamental frequency excitation force when the end natural frequency is close to 50Hz.

According to the regulations of GB/T20140, the overall elliptical natural frequency at the end of stator winding should avoid 95-110Hz. The natural frequency of stator winding bars should be kept away from 95~106Hz. According to the regulations of DJ/T596, the natural frequency should not be within ±10% of fundamental frequency or frequency multiplication, that is 45~55Hz.

4.3. Solutions

(1) Reduce the excitation force and deal with the vibration source—The dynamic unbalance of the generator rotor is the excitation source, and doing well in the field dynamic unbalance of the generator rotor will help to solve the problem thoroughly; Checking machine halt BODE diagram of 7# and 8# landmark of generator unit from TDM of the unit, the third-order imbalance of the rotor can be seen basically; It is the key to choose a reasonable counterweight position, counterweight and phase;

(2) Reinforce the support of the end of diaphragm. It can be seen from the structure of the end that the excitation side has 4 diaphragms, the first layer is metal diaphragm (visual field measurements are about 4 to 5mm thick), and the last three layers are insulation diaphragms. The four layers of diaphragms are connected to each other by bolts, metal struts or similar I steel blocks. As a whole, the outer metal diaphragm is relatively thin. Though the inner three-layer partition is an insulating partition, its strength is close to that of the outer layer. Generally speaking, the support stiffness of the diaphragm is weak, In the existing operation stage, it can be considered to strengthen the stiffness of the outermost metal diaphragm, so as to improve the common stiffness of the four-layer diaphragm.

(3) Under the current condition of lacking of effective testing, the problem of diaphragm resonance cannot be ruled out. In the proper period (such as in the process of shutdown), the transient test of the diaphragm can be arranged to measure the resonance point of the diaphragm. If it is a resonance problem, then consider the solution of eliminating the resonance. It is mainly to strengthen or weaken the support stiffness of the steel plate—so as to change the resonance frequency of the diaphragm to achieve the goal of elimination the resonance. It is suggested that during the overhaul, the end condition of the stator at the steam side should be checked in detail to avoid large fault accidents caused by hidden faults.

5. Conclusions

The vibration of generator stator core and frame is the main cause of the fault of stator core and stator winding. As the same as other rotating machinery, generator may produce problems of unbalance, misalignment, mechanical looseness, bearing fault and resonance, which are all diagnosed by rotating machinery fault diagnosis methods. The new type phase modifier is a kind of large air-cooled synchronous generator, and fault diagnosis and treatment method of this kind of generator can be better used for reference.

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