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Analysis of the Increase in Generator Rotor Vibration after a Short Circuit in the Generator

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***Abstract*—The vibration of the generator has an important impact on the stable operation of the equipment and is directly related to the safe production of electrical power. There are many reasons for analyzing the factors affecting the vibration. Design, manufacturing, and installation may all cause the vibration of the generator. In this study, the factors affecting the vibration of generator rotor after short circuit is analyzed. The 210 MW steam turbine generator set of a private operator plant was produced by a private Group using the latest technology.**

The turbine generator is a six-mass structure connected by a steel shaft. The generator is water-hydrogen-hydrogen cooling. On January 26, 2018, the plant's No. 3 unit was connected to the grid for the first time. When the load reached 185 MW, the generator had a short circuit accident. After the short circuit, the different parameters and vibrations are measured and compared by different tests. The vibrations after the short circuit are also tested for different conditions, the rotor and stator winding resistances are checked after rewinding. Finally the found that the electrical, thermal, and mechanical stresses of the generator's three-phase short circuit adversely affect the rotor's balance.

***Index Terms*— Rotor Vibration, Multi-Mass Shaft, Onsite Testing.**

I. INTRODUCTION

The shaft system of the unit consists of a high-pressure rotor (HP), an intermediate-pressure rotor (IP), two low-pressure rotors (LP1, LP2), a generator rotor (G), an excitation shaft (EX) and eight support bearings. The shaft system structure of the unit is shown in Figure 1, and the critical speed of each shaft is shown in Table 1

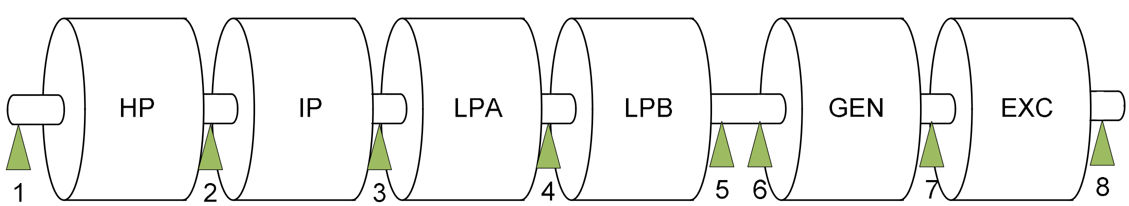

Figure 1. Multi Mass Shaft of Turbine-Generator

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On January 26, 2018, when Unit 3 was first connected to the grid with a load of 185 MW, a three-phase short circuit fault occurred in the generator stator outlet box, resulting in a ground fault in the rotor winding. Subsequently, the installation unit and the manufacturer handled the fault, with the stator part of the generator repaired on-site, the rotor part returned to the factory for repair, and all the wire rods replaced. After the fault was handled, Unit 3 began a 192-hour trial operation on April 25, 2018. During the trial operation, the generator rotor experienced abnormal vibration with an abnormal increase in load.

TABLE I. CRITICAL SPEED OF UNIT SHAFT SYSTEM (RPM)

	Multi mass shaft
Design Critical Speed	3000
Measured Critical Speed	2992

The vibration characteristics are mainly as follows:

- When the unit is at constant speed or no load, the maximum axial vibration of bearings 7 and 8 is about 70 μm;
- After the unit is loaded, the shaft vibration of bearings 7 and 8 increases rapidly with the increase of load when the load is above 200 MW, and the maximum shaft vibration values reach 220 μm and 130 μm, respectively. When the load drops below 150 MW, the shaft vibration begins to drop rapidly.
- When the load rises to a specific working condition, and the rotor current is constant, the shaft vibration of bearings 7 and 8 still shows an upward trend. It takes nearly 150 minutes for the vibration to be completely stable.
- The vibration of each bearing of the generator is small, and the change with load is small;
- The shaft vibration of each bearing of the generator is mainly composed of industrial frequency components;
- During the vibration amplitude fluctuation process, its phase changes little, and the vibration under various working conditions has good repeatability.

II. FAILURE CAUSE ANALYSIS

Generator vibration can be a critical sign of an unresolved problem that [1], if left unattended, could cause damage or accelerate the aging of your generator set. Causes of generator vibration include imbalance, misalignment, binding, looseness, or wear [2].

Unresolved generator vibration can have serious consequences for production operations and personnel health, ranging from costly unplanned downtime to life-threatening safety issues [3]. The vibrations in the rotor can also cause due to the loss of excitation [4]. After the unit is started, the axial and lateral vibration values of the AC synchronous generator under no-load conditions exceed specified limits, which can lead to a total loss of the generator unit. The generator rotor has a large fundamental frequency thermal variation according to the vibration characteristics.

Because the small excitation shaft was in good balance before the accident, the main reason for the large thermal variation of shafts 7 and 8 may be the thermal bending of the generator rotor. High oscillation of the multimass system due to sub-synchronous resonance leads to the vibration [5, 6]. However, because the generator had an internal short circuit accident and had undergone a lot of repair work, there is controversy about the cause of the rotor thermal imbalance vibration. Therefore, several common causes that may cause the thermal imbalance vibration of the generator rotor are analyzed.

A. Cooling system failure

The ventilation holes are the main air passages for hydrogen internally cooled generators for rotor heat exchange. Deformation of the ventilation holes, blockage by debris, etc., will cause the flow area of the ventilation holes to decrease [7], which will destroy the symmetry of cooling, make the temperature of the rotor cross-section asymmetric, and then cause thermal bending.

The characteristics of this fault are: as the hydrogen temperature increases, the cooling effect of the generator rotor will deteriorate, but the degree of asymmetric cooling of the rotor will be relatively reduced, which will eventually lead to a reduction in thermal imbalance vibration.

For this reason, a hydrogen temperature test was carried out, and it was found that the vibration of bearings 7 and 8 was not significantly correlated with the change in hydrogen temperature. In addition, when the unit was overhauled in February 2022, the generator rotor was returned to the factory for inspection again, and no deformation or blockage was found in the ventilation holes. Therefore, it can be judged that a cooling system failure does not induce the thermal imbalance vibration of the rotor.

B. Rotor coil expansion is hindered

The excitation current of the rotor winding establishes the generator's magnetic field [8]. The excitation current passes through the winding and heats the coil, which expands toward both ends after being heated. This expansion will not generate internal stress on the rotor if it is unconstrained. During the rotation process, the copper wire in the slot is subjected to substantial centrifugal force, which makes the coil close to the inner wall of the slot wedge and the retaining ring, resulting in considerable friction on the joint surface, which hinders the expansion of the coil; if the coil in some slots expands ultimately, the coil whose expansion is blocked will generate a reaction force, which acts on the rotor through the slot wedge and the retaining ring, causing the rotor to bend.

The characteristics of this fault are as follows: the coil expansion increases with the increase of rotor current, and this type of vibration is generally related to the current. However, due to the existence of inevitable friction, the coil expansion due to heat and contraction due to cooling will be hindered, and both can cause the rotor to bend. Therefore, when the rotor current increases, the vibration rises, but when the current returns to the initial state, the vibration will not fully recover and is often higher.

In addition, after a period of operation, this type of fault will slowly disappear as the coil expands and contracts many times. In this case, the rotor vibration has a good follow-up performance to the rotor current, and it still has good repeatability after nearly a year of operation. Therefore, it can be judged that the obstruction of coil expansion is not the leading cause of the thermal imbalance vibration of the rotor but the harmonics produced due to the nearby power electronics devices lead to the vibration [9].

C. Rotor winding turn-to-turn short circuit

Due to the generator's short circuit, the stator chamber is contaminated. The contaminants that have yet to be thoroughly cleaned may enter the rotor ventilation slots or other parts, causing a short circuit between turns. Through the following tests and comparison with the handover test of the rotor returned after repair, the results are as follows:

- The no-load characteristic curve is in good agreement with the handover test curve;
- The rotor direct resistance is within the qualified range compared with the factory value and is slightly larger than the factory value, as shown in Table 2;
- The static AC impedance test data of the rotor winding is normal;
- The rotor dynamic AC impedance test data is shown in Table 3;
- The dynamic rotor winding RSO pulse test shows that the positive and negative corresponding curves have mismatching parts, and the maximum voltage deviation of the mismatching part is close to 245 mV;
- The detection coil waveform method was used to diagnose that there was a suspected short-circuit fault in the No. 4 coil of electrode B;
- Pass the static RSO pulse test (static in the chamber);
- Pass the polar balance test (static state outside the chamber);
- The turn-to-turn voltage distribution test passed (static outside the chamber). The turn-to-turn voltage distribution data is shown in Table 4.

TABLE II. ROTOR DIRECT RESISTANCE TEST DATA

Test conditions	**Result (mΩ)**	**Value converted at 16°C (mΩ)**	**Error (Not More than 2%)**
Factory Test (19°C)	80.65	79.95	-
On-site Handover test (19.2°C)	79.62	78.83	-1.201
Field Test (35°C)	82.42	80.05	1.147

TABLE III. DYNAMIC AC IMPEDANCE TEST DATA

Item	**Speed (RPM)**	**Voltage (V)**	**Current (A)**	**Resistance (Ω)**	**Power (W)**
Handover Test	60	196.92	54.10	4.003	7270
	360	197.73	62.92	3.456	7803
	3000	197.64	63.73	3.411	7245
Field Test	60	197.82	47.73	4.562	7502
	360	198.27	60.59	3.589	8981
	3000	198.45	70.02	3.109	8956

TABLE IV. INTER-TURN VOLTAGE DISTRIBUTION DATA

Coil No.	Pole 1-upper screw (V)	Pole 2-lower screw (V)
1	10.22	9.937
2	23.04	22.62
3	36.68	36.21
4	50.92	50.54
5	65.45	64.88
6	80.0	79.61
7	94.92	93.57

The above test results show that the rotor winding has the characteristics of a dynamic inter-turn short circuit, and the rotor winding may have a dynamic inter-turn short circuit. In order to thoroughly find out whether there is an inter-turn short circuit in the rotor winding, the No. 3 generator rotor was returned to the factory for inspection again during the unit overhaul in 2022. During the removal of all the rotor windings, no overheating, blackening, damage, or blockage of the ventilation holes were found in the inter-turn insulation, and no apparent signs of overheating or discharge were found in the wire rods, proving that the rotor winding has not had a metallic inter-turn short circuit. In addition, from the perspective of mechanical vibration, the high temperature generated by the inter-turn short circuit will damage the sliding layer, affect the expansion of the coil, and may also produce uneven magnetic pull. Therefore, the vibration induced by the inter-turn short circuit has the characteristics of coil expansion vibration and a positive correlation with the excitation current. These are inconsistent with the vibration characteristics of the rotor, so the inter-turn short circuit is not the main reason for the abnormal shaft vibration of bearings 7 and 8.

D. Uneven rotor material

Uneven rotor material refers to the uneven radial fiber structure of the rotor due to air gaps, inclusions, bubbles, etc., in the rotor forgings, resulting in anisotropy in the material's physical properties. Defects in the production and heat treatment of forgings usually cause this problem. During the unit's operation, when the rotor with anisotropic material is heated, the shaft will produce uneven axial or radial expansion, causing thermal bending of the rotor, resulting in unbalanced vibration. The faults caused by uneven rotor material mainly have the following characteristics:

- The more significant the rotor current (positively correlated with the active and reactive loads of the unit), the greater the thermal bending of the rotor, and the greater the unbalanced vibration generated;
- Since the anisotropy of the physical properties of the rotor material is constant, the direction of its bending does not change when heated, so the phase of its vibration remains unchanged;
- Thermal bending caused by uneven materials is generally reversible, so the unbalanced vibration induced by it has good repeatability as the rotor current changes;
- Due to the large mass of the generator rotor, its response to heat has a certain lag, so the vibration change will also lag behind the change of the rotor current. It can be seen that the abnormal axial vibration of bearings No. 7 and 8 of the generator is consistent with the vibration characteristics of uneven rotor material. In addition, the original factory dynamic balancing test data of the generator rotor are listed in Table 5 and the factory dynamic balancing test results data after the generator short-circuit fault was repaired are listed in Table 6, it can be seen that after the No. 3 generator rotor was heated, the amplitude change of measuring point D reached 65"m, and there was apparent thermal bending. If the influence of the vibration phase is considered, its vibration thermal variable will be more significant. This also reflects that the generator rotor may have the problem of uneven original material.

TABLE V. ORIGINAL FACTORY DYNAMIC BALANCING TEST DATA OF GENERATOR ROTOR

Working Condition	Steam End Shaft Vibration (μm)		Excitation End Shaft Vibration (μm)	
	Measuring Point A	Measuring Point B	Measuring Point C	Measuring Point D
Before Heating 3000 RPM	47	25.38	92.12	113.74
After heating and keeping warm at 3000 RPM	26.32	21.62	75.2	188
After Dynamic Balancing 3000 RPM	46.06	31.02	43.24	43.24

TABLE VI. DYNAMIC BALANCING TEST DATA OF GENERATORS WITH SHORT-CIRCUIT FAULTS RETURNED TO THE FACTORY FOR MAINTENANCE BEFORE LEAVING THE FACTORY

Working Condition	Steam End Shaft Vibration (μm)		Excitation End Shaft Vibration (μm)	
	Measuring Point A	Measuring Point B	Measuring Point C	Measuring Point D
Before Heating 3000 RPM	86.45	23.75	57.95	57.95
After heating and keeping warm at 3000 RPM	105.45	63.65	57.95	131.1

E. Effect of Stator Three-Phase Short Circuit on Rotor Thermal Imbalance

This generator's three-phase short circuit accident occurred shortly after it was first connected to the grid. The generator had not been running at full load before the accident, and there was no relevant vibration data. However, the impact of the short circuit accident on the rotor material cannot be ignored. The unit load was 185 MW during the short circuit. Before the differential protection was activated and the GCB (Generator Circuit Breaker) was tripped, the power reversed by the grid was also very high (the maximum three-phase short circuit current at the generator end reached 204 kA), so extremely high temperatures were generated inside the generator, especially when the high-temperature arc directly impacted the excitation end rotor. After the rotor is subjected to instantaneous high-temperature impact, the internal structure of its local material may mutate, making its physical properties anisotropic, which leads to uneven axial or radial expansion of the rotor after heating, causing thermal bending.

III. ON-SITE HOT DYNAMIC BALANCING OF ROTOR

After confirming that the main reason for the abnormal shaft vibration of bearings No. 7 and No. 8 of generator No. 3 was uneven rotor material, the generator rotor was subjected to hot dynamic balancing. In calculating the hot dynamic balancing scheme, the vibration conditions under no-load and rated load conditions were considered, the vibration amplitude under constant speed and no-load conditions was appropriately increased, and the phase was reversed to compensate for the vibration thermal variables under high load conditions. On June 22, 2023, the on-site hot dynamic balancing test was carried out using the unit adjustment opportunity. 1006g was added to the excitation fan ring at 135 degrees, and 785g, 9406g, and 945g were added to the excitation wheel at 305 degrees, 319 degrees, and 345 degrees. After the hot dynamic balancing was implemented, the shaft vibration of bearings No. 7 and No. 8 reached an excellent level under various loads, and the vibration conditions under no-load conditions were also well considered. The shaft vibration amplitude and phase changes are shown in Table 7.

TABLE VII. AMPLITUDE VALUES AND PHASE CHANGES OF AXIS 7 AND 8 BEFORE AND AFTER WEIGHTING

Working Condition	No. 7 bearing shaft vibration (μm)		No. 8 bearing shaft vibration (μm)	
	X direction	Y direction	X direction	Y direction
Fixed speed and no load before aggravation	45∠46°	30∠225°	60∠65°	43∠215°
1000MW before weighting	190∠115°	108∠275°	172∠136°	112∠276°
Fixed speed and no load after aggravation	105∠290°	62∠156°	76∠345°	65∠66°
1000MW after aggravation	60∠92°	5∠33°	50∠235°	42∠6°

IV. CONCLUSION

- There are many reasons for the vibration of the generator rotor, which need to be comprehensively analyzed and eliminated one by one according to the vibration characteristics and relevant test conditions. When analyzing the thermally unbalanced vibration of the rotor, the focus is often placed on the existence of inter-turn short circuits in the rotor while ignoring the possibility of abnormal vibration caused by material defects in the rotor.
- After the rotor is returned to the factory for repair, a hot dynamic balance test (simulating the rotor operating temperature under full load conditions) must be performed on the manufacturer's rotor test bench.
- The generator rotor has a large original thermal bending due to uneven material. Although the original hot dynamic balance test was qualified when it left the factory, there was a large deviation in the actual operation. Therefore, for the generator rotor with large thermal bending, the hot dynamic balance test

method before leaving the factory needs further research and improvement to make it as consistent as possible with the actual working conditions.

- The electrical, thermal, and mechanical stresses of the generator's three-phase short circuit adversely affect the rotor's balance. Therefore, anti-accident measures to prevent generator short-circuits should be strictly implemented to prevent the occurrence of generator short-circuit failure.

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