The Analysis of a Generator Shaft Crack Cause by Torsional Vibration due to SSR

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Abstract. This paper introduces the serious crack accident of the rotor of a 600 MW turbo-generator unit in Vietnam, which leads to the rotor scrapped. After excluding the material and design reasons, it is considered that the electrical torque is the possibility. Through the operation parameters and theoretical calculation of the unit, the fault reason is positioned as Sub-synchronous resonance. The most important criterion is that the vibration of Unit 1 increases simultaneously with that of Unit 2, which is physically isolated from Unit 1. Further theoretical calculation shows that the natural frequencies of torsional vibration are 13.74 Hz, 26.23 Hz and 30.30 Hz, which are complementary to the grid frequency at that time cause of the change of grid structure.

Keywords. Torsional vibrations, cracks, sub-synchronous resonance, turbine-generator.

1. Introduction

With the development of the global power system, the electronic equipment such as Thyristor Controlled Series Capacitor (TCSC) is widely used for high-voltage transmission. Meanwhile, the large-scale renewable energy connected to the grid, and the steam parameters of the unit are continuously improved, all these factors have greatly increased the risk of Sub-synchronous resonance (SSR) between turbine-generator and grid system [1, 2], and the fatigue fracture can be caused by torsional vibration of the turbine-generator interaction with the electrical network. And the shaft may be irreparable damaged in severe cases [3-6].

A torsional vibration and generator shaft cracks for a Power Plant are described in this paper. Based on the evaluation of turbine-generator operational data, and the study of the mechanism, it is concluded that the excessive torsional vibration and cracks on the generator rotor of the unit were caused by SSR from the grid, which had the natural frequency different from usual. Unfortunately, the generator rotor shaft of Unit 1 is judged as irreparable damages.

1.1. Turbine-Generator

The turbine has a HIP (High Intermediate Pressure) rotor and two LP (Low Pressure) rotors, which are supported by six journal bearings. The No.1 and No.2 bearings are in HIP rotor section, and from No.3 to No.6 bearings are in the LP rotor section as shown in figure 1. The turbine described herein is a 3 casing, tandem compound, double flow exhaust, condensing steam turbine consisting of single flow high-pressure turbines. The high-pressure turbine and the intermediate-turbine are in one casing, whose higher-pressure sides are facing each other. The double flow low-pressure turbine is in another
casing. The last blades are 36 inches. The turbine driver is directly coupled through a coupling to the generator.

Figure 1. Turbine-generator shaft of Unit 1.

The rated electrical power output of generator is 629,000kW at a power factor of 0.85 lagging. The generator is mechanically driven by its associated steam turbine, electrically excited by the static thyristor rectifier excitation system and internally cooled by hydrogen gas.

1.2. Phenomena of Vibration and Crack

The Unit-1 was started up at 7:20 on 24th Nov.2015 and synchronized to grid at 8:34, and the vibration of No.7 bearing increased to 78ump-p at 9:30 with the 25MW load. From 9:30 to 11:00, the vibration of No.7 bearing keeping decreased until to 40ump-p with the load of 70MW~120MW. The vibration of No.8 bearing increased from 15:00, and reached 90ump-p at 17:00 with the load of 400MW. Meanwhile, the pressure of hydrogen gas decreased rapidly. The vibration of No.8 bearing fluctuated from 60ump-p to 150ump-p after 18:00.

The interval of H2 gas pressure drop lengthened with the vibration decreased of No.8 bearing, and shorted with the vibration increased of No.8 bearing.

Figure 2. Operation record of Unit-1 from 24th to 25th.

Figure 2 shows the operation data of Unit-1 from 24th to 25th Nov. 2015. The behavior of the vibration was unstable, and especially the vibration of No.8 bearing exceeded 100μm p-p.

Unit-1 was operated on 23rd Dec. 2015 to confirm the phenomena with monitoring by engineers. The large vibration of No.8 bearing was reproduced and H2 gas leakage from generator at No.7 bearing was observed, the portion and size of the shaft cracks shown as in figure 3 and table 1. Therefore, the inspection of generator was carried out. As a result of the inspection, several heavy cracks were observed on the generator No.7 journal of Unit-1. Examples of cracks are shown in figure 4.
Figure 3. Portion of shaft crack on Unit-1 generator.

Table 1. Size of shaft crack on Unit-1 generator.

| Mark | A  | B  | C  | D  | E  | F  | G  | H  |
|------|----|----|----|----|----|----|----|----|
| Length (mm) | 76 | 255 | 400 | 155 | W C | W C | W C | W C |
| Max. depth (mm) | 27.5 | 48.7 | 84.7 | 8.8 | 2.9 | 2.8 | 7.5 | 7.1 |

W C: Whole circumference.

Figure 4. Typical crack on the rotor of generator.
2. Fault Analysis and Diagnosis

2.1. Fatigue Fracture

The incident described above includes following abnormal phenomena.

1. Large shaft vibration
2. \( \text{H}_2 \) gas leakage
3. Shaft cracks

But the most remarkable phenomenon is shaft cracks, because it is a very rare and critical phenomenon. Torsional induced fatigue cracks in a uniform shaft develop on the surface and in directions that depend upon the relative margins between the maximum shear stress and the material shear strength, and the principal tensile stress and the tensile strength of the material [7]. If the tensile margin is less than the shear margin, cracking would usually occur at 45 degrees to the rotor axis as shown in figure 3(a). Conversely, if the tensile margin is greater than the shear margin, cracking would usually occur parallel and perpendicular to the rotor axis as shown in figure 3(b).

Most often in practice, fatigue cracks originate on rotor surfaces and at stress concentrations which distort the nominal stress field so other crack initiation and propagation directions are possible and cracks may switch from one direction to another as they propagate. Cracking has also been observed to occur in several of these directions in regions close to stress concentrations as shown in figure 3(c). That is the typical appearance of fatigue fracture by torsional vibration.

Fatigue fracture is caused by cyclic stress which exceeds fatigue limit stress. The material, design and electrical torque issues were considered as the possible cause. The electrical torque issues are categorized as follows.

Case A. Cyclic electrical power change in normal operation.

The following operations make generator electrical power change in the normal operation.

1. Start up and shut down operation
2. Load change
3. Over current
4. Response of step torque change
5. Cyclic change of frequency
6. Negative phase sequence

It can be seen that the dynamic stress line and the static stress line can both be drawn on the modified Goodman Diagram [7]. The evaluation results of fatigue strength by Goodman diagram under each operating condition described are shows in figure 5. The stress levels for above operations are enough less than fatigue limit.
The design for the rotor of Unit 1 has enough fatigue strength under each operating condition. Therefore the Case A is not considered as a root cause of this issue.

**Case B.** Cyclic transient electrical torque at electrical failure

Three-phase and line to line short circuits at generator terminal and the worst case of out of phase synchronizing were considered as severe electrical failures. The fatigue life consumption are very small, and the largest value for single electrical failure is only 0.21%. So it was confirmed that the generator shaft has enough strength for severe electrical failures. Case B is not considered as a root cause of this issue.

**Case C.** Resonance of torsional vibration by system frequencies (50Hz or 100Hz)

The result of the torsional frequency response is shown in figure 6, all of the torsional modes are well separated from 50Hz and 100Hz, the torsional frequency response value around 50Hz and 100Hz is much smaller than the torsional frequency response value of Mode.1, Mode.2 and Mode3. So Case C is not considered as a root cause of this issue.

![Figure 6. Torsional frequency response analysis.](image)

**Case D.** Turbine-generator torsional vibration interaction with electrical network.

In this case, torsional vibration of turbine-generator power train is excited by natural frequency from electrical network or resonates mutually with electrical network [8]. In general, the following three issues are considered as the cause of excessive torsional vibration for turbine-generator rotors.

(a) Sub-synchronous resonance (SSR) with series capacitor compensated transmission lines in the grid system

(b) Interaction with High-voltage DC (HVDC) transmission system

(c) Interaction with load fluctuations and wide-range low-frequency noises generated from Electric Arc Furnace connected in the grid system

It is noted that HVDC transmission system is not applied, and the wide-range low-frequency noises are not found in the connected grid system. So it is judged that the cause of excessive torsional vibration that caused cracks on the generator rotor was arisen from SSR.

**2.2. Mechanism of SSR**

SSR is defined to be a resonance between a torsional natural frequency of a turbine-generator shaft train and a natural frequency of connected electrical system, in the region below nominal frequency (below 50 Hz). It can be modeled as figure 7 and the following equations.
Electrical natural frequency $f_e$ in above system can be shown as:

$$f_e = \frac{\omega_e}{2\pi} = \frac{1}{2\pi\sqrt{L_C}} = f_0 \sqrt{\frac{x_C}{x_L}}$$ (1)

Mechanical natural frequency $f_m$ in above system can be shown as:

$$f_m = \frac{\omega_m}{2\pi} = \frac{1}{2\pi\sqrt{k}}$$ (2)

In case $f_e + f_m$ becomes close to $f_0$ (50Hz), torsional vibration oscillation is sustained or grows up [9, 10]. It can be said as a negative-damping condition. In normal condition that no resonance is arisen, the damping for a torsional oscillation is positive. In this condition, a torsional vibration caused by some shocks during operation is attenuated by the damping and disappears with the passage of time.

2.3. Evaluation of Turbine-Generator Operational Trend Data

By thoroughly investigating the operational trend data of Unit-1 and 2, a remarkable point was found in the data of the date 2015/11/24. A special phenomenon, that the vibration of No.7 bearing of both Unit-1 and -2 were increased simultaneously, was arisen as shown in figure 8. It should be noted that the date, 2015/11/24 is the date on which the problem of Unit-1 was initially reported. The vibration level started to increase abnormally in the evening of that date.

After synchronizing of Unit-1, abnormal increase of vibration was found on Unit-2, while the output of Unit-2 was stable. Such a phenomenon that the vibration level of both of two units moved simultaneously was never found on any date except this date 2015/11/24. The cause of simultaneous move of vibration level of two generators should be an interaction through electrical system, because the installed locations of the two units are physically separated. This is remarkable evidence for the SSR [8].

It should also be noted that any abnormal increase of the vibration in Unit-1 was never found before 2015/11/24. Therefore, the cracks on the rotor shaft of Unit-1 should have been initiated and grown on 2015/11/24, and it caused the increase of vibration in the evening of that date.

2.4. Evaluation of Transmission Lines (Grid) Configuration Data

By observing the three dates’ data earlier, an abnormal vibration phenomenon at the second unit’s synchronizing operation was only occurred on 2015/11/24. Based on this fact, it can be said that the grid system on 11/24 had some configurational difference to the system on 11/02 or 12/23, and was in a condition that could cause special electrical interaction.

The transmission lines that have major relationship with the power station are 4 sets of 500kV lines which are series capacitor compensated. it should be noted that one of the two lines was out of service on 2015/11/24. Based on the above fact, it is obvious that the grid on 2015/11/24, had inductance and capacitance different to other dates, and it had different natural frequency which caused the SSR.
3. Process Mechanism

3.1. Mechanism
When Unit-1 was synchronized while Unit-2 was in operation, SSR occurred. The resonance frequency was about 27Hz that was the 2nd torsional natural frequency of turbine-generator power train. The torsional vibration with 27Hz grew on both Units. The large torsional vibration affected lateral vibration of both Units. So the vibration of No.7 bearing of both Units increased. The steam dumping value depends on load condition because steam volume affects steam dumping. The load of Unit-2 was about 550MW, and the load of Unit-1 was less than 25MW initially. So, Unit-2 rotor had higher dumping effect than Unit-1 rotor. As the result, the vibration level of Unit-2 was less than that of Unit-1.

The No.7 journal portion of Unit-1 had crack initiations on the root of fillets where stress was concentrated. As the result of crack propagation, the vibration of No.8 bearings of Unit-1 increased remarkably. The H2 leakage occurred through the cracked journal of No.7 bearing. So H2 gas pressure in the Unit-1 generator was frequently changed.

According to the mechanism above, almost all behavior of monitoring data and phenomena can be explained.

3.2. Measurement Data of Torsional Vibration
A signal from electromagnetic pickup for over-speed sensor was used for the speed signal for torsional vibration measurement. Measurement of torsional vibrations and power fluctuations on operating
Unit-2 was performed. It has reason to believe that torsional natural frequencies are the same of the two units cause of the same type. The shaft torsional vibration appears as time fluctuation of the turbine rotating speed. The figure 9 shows the FFT analysis result of the rotating speed fluctuation just after a sudden change in the generator power [11-13]. Three peaks can be seen at 13.74 Hz, 26.23 Hz and 30.30 Hz, which correspond to 1st, 2nd and 3rd torsional natural frequencies of the shaft train system in the sub-synchronous region, respectively.

Figure 9. The frequencies of speed changing.

Meanwhile, several numbers per day of impulse-shaped shocks were observed in the power fluctuation measurement. These shocks are thought to be come from switching of loads in the grid. The occurrence frequency and span of the shocks were random. These shocks caused torsional vibrations observed as fluctuations of rotating speed mainly of 2nd mode, but these torsional vibrations were attenuated with the passage of time. Any excessive torsional vibration or divergence of oscillation was not found throughout the measurement period. it mean that the system was stable at that time.

4. Conclusion
It is judgement that the cracks on the generator shaft were fatigue fractures caused by excessive torsional vibrations due to sub-synchronous resonance (SSR) phenomena between power grid system and torsional natural frequency of the shaft. The grid had a different frequency from usual when the Unit-1 was synchronized during the operation.

In order to prevent sub-synchronous resonance conditions from occurring again, it is needed that the study of operation of transmission lines (grid) should be performed, and the grid connected with power station should be operated in such a condition that its electrical natural frequency should be de-tuned from around 36 Hz, 23 Hz and 18 Hz, that is, subtractions of torsional mode (1~3) frequencies (around 14 Hz, 27 Hz and 32 Hz) from 50Hz.

It would be possible by determining the numbers of connected lines and/or by determining the compensation rate (capacity of series capacitors) in suitable manners. In addition based on necessity, it would also be effective as a back-up that any detection/protection device against SSR conditions installed at the substation or the power station.

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