Allianz Global Corporate & Specialty

TECHNICAL NOTE
TORSIONAL VIBRATION OF TURBOSETS

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Shaft cracks due to torsional vibration

In a new power plant, all four gas turbosets developed shaft cracks within 4 months of operation. The turbosets had shown an excessive trend of lateral vibrations and were stopped. Detailed inspection revealed cracks at the turbine shaft in the area of the coupling flange towards the generator on all units. If the units had not been stopped in time, further crack propagation could have caused an immediate rupture of the shaft which most probably would have led to catastrophic damage.
According to the investigation of the turbine manufacturer and main contractor, the fatigue crack was caused by torsional vibration of the shaft train. It was excited by so-called Sub-Synchronous Resonance (SSR), which has resulted from the interaction of electric net oscillation and the natural torsional frequency of the shaft train.
Another incident due to SSR occurred at a supercritical coal power unit. It resulted in a shaft crack at the steam turboset and was observed only four weeks after first commissioning.

Torsional vibrations are usually not monitored and not indicated by standard vibration equipment which measures the lateral vibrations of the shaft and bearing pedestals. Only after a significant crack propagation the resulting reduced shaft stiffness can affect the lateral vibrations and could be observed by a continuous vibration trend. In such cases, it is important to stop the turboset before the shaft breaks impulsively.

Background
SSR is a transmission system based problem (cf. [1]). In some areas power companies are faced with the need to transmit large amounts of power over very long distances. The long transmission lines normally have very high inductive reactance, which limits the amount of power that can be transmitted. If series compensating capacitors are installed in the line to lower the effective reactance, a series RLC circuit (resistance, inductance and capacitance) is developed, that introduces an electrical resonance frequency for the electrical current flowing in the transmission line. The frequency of the resonant oscillating current in the transmission line is typically below the frequency of the grid. This gives the name Sub-Synchronous Resonance, which is the main topic of this Technical Warning. Electrical disturbances, which occur above the grid frequency are described in the AGCS Trend Paper "Power System Harmonics" [2].

How SSR interacts with the generator

Currents that enter the generator armature windings from the transmission line electromagnetically couple with the turbine-generator rotor system and the transmission system. The magnetic field, resulting from the sub-synchronous currents flowing in the transmission line and in the generator armature winding, interacts with the main magnetic field produced by the generator rotor. As a result torque pulsations are produced on the generator rotor at the slip (difference) frequency of these two interacting and rotating magnetic fields. These torque pulsations will cause a resonance, if the slip frequency (so called "complement" of the line resonant frequency) coincides with one of the torsional natural frequencies of the turbine-generator shaft train.

Condition for torsional resonance is:

$$f_{n\_Torsion} = f_{Grid} - f_{SSR}$$

$f_{n\_Torsion}$	One of the torsional natural frequencies of the shaft train system
f_{Grid}	Grid frequency (50 Hz or 60 Hz ± possible grid frequency variation)
f_{SSR}	Sub-synchronous, electrical resonance frequency of transmission line system with series capacitor compensation

Risk assessment of SSR

The assessment of SSR is especially important to reduce the potential risk during commissioning phase and first year of operation. As long as there are no changes in the connected grid, the risk for SSR should not increase. However, the torsional vibration exposure by SSR may vary intermittently depending on the number of modules of series capacitor compensation put into service at a given time, the system transmission configuration, and the electrical and turbine loads (cf. [1], [3]).

Sub-Synchronous Torsional Interaction (SSTI)

A similar torsional resonance phenomenon as SSR can occur with generators connected to High Voltage DC (**HVDC**) Systems. These systems can also interact with torsional vibration of the shaft trains. It is usually referred to as **Sub-Synchronous Torsional Interaction** (SSTI, cf. [4], [5]). SSTI and SSR can potentially also occur on hydro power generators but has not been experienced yet. Especially classic HVDC technology equipped with thyristors can have a huge impact on SSTI.

Risk assessment of SSTI

A SSTI screening is a good practice to identify a strong coupling between a HVDC line and the turbine-generator rotor system. The need for such screening can be evaluated by the **Unit Interaction Factor** (*UIF*, cf. [4]):

$$UIF_i = \frac{MVA_{HVDC}}{MVA_i}\left(1 - \frac{SC_i}{SC_{tot}}\right)^2$$

UIF_i	Unit interaction factor of the ith unit
MVA_{HVDC}	Apparent Power rating of the HVDC system
MVA_i	MVA rating of the ith machine
SC_i	Short circuit capacity at the commutating bus, excluding the ith unit
SC_{tot}	Short circuit capacity at the commutating bus, including the ith unit

It involves the relative size of the HVDC system at the connection point compared to the rated power of the power plant unit. In addition, it is influenced by the electrical distance between the HVDC system and the power plant unit. Implementing a damping controller (**PSS – Power System Stabilizer**) could reduce the impact.

For HVDC Converter equipped with thyristors without PSS, strong coupling is given with $UIF > 0.1$. This means, that no SSTI screening is required for power plants which are coupled to a HVDC grid with $UIF \leq 0.1$. A safety factor of 10 should be considered on self-controlled HVDC Converters. Hence, below the threshold applicable for $UIF_{self\text{-}controlled\text{-}converters} \leq 0.01$, no SSTI Screening is required (cf. [7]). There is not yet any *UIF* threshold value published for the new HVDC technology with Voltage Source Controller (VSC).

Further potential sources for crit. torsional vibrations

- The above mentioned Power System Stabilizer, which is intended to damp torsional vibration by actively regulating the exciter current of the generator, might even increase torsional vibration, if the control loop is not working correctly. Such a malfunction of PSS has caused a shaft crack at a gas turboset. As typical for torsional vibrations, the problem was only observed after a long-term increase of lateral vibrations resulting from a growing shaft crack.
- The Low Pressure (LP) stages of large steam turbines have longer lengths of L-0 and L-1 blades. These blade rows create coupled blade-disk-torsional modes. Depending on mass and stiffness distribution of the components these coupled torsional modes can fall into the excitation range of the twice-line-frequency (two times grid frequency, 100 Hz or 120 Hz). In the past there have been new turbine projects as well as retrofit projects, where the proper calculation of the coupled blade-disk-torsional modes has been missed and dangerous fractures of last stage blades have occurred. The requirements to mitigate such design issues is subject of ISO 22266-1 (cf. [6], [7]).
- Furthermore, load unbalance and transient excitation from large power consumers such as arc furnaces in vicinity of the power station can induce high dynamic loads to generator turbosets, which could also produce fatigue cracks to the shaft.

Action

A basis for calculation and assessment of torsional vibration is provided by ISO 22266-1 [6], which describes the different sources of torsional vibrations and should be taken into account for turbo sets above 50 MW. SSR is also mentioned in this standard as a potential source. Due to the fact that this source of critical resonance depends on the grid properties and on the turbine torsional modes, it is actually in question, who is responsible for proving, that it cannot occur.

Recommendation

1. Assessing SSR exposure

A comprehensive study about Sub-Synchronous Resonance (SSR) should be conducted for new power plants with turbosets larger than 50 MW. The information required by the analysis should be provided by the plant owner and grid authority. The study should be made and evaluated by the turbo generator supplier or a specialized engineering company as per ISO 22266-1. The study provision should be mandatory for construction projects and also for the first operating years.

2. Assessing SSTI exposure

In the case, that turbo generators are connected to HVDC Systems, the Unit Interaction Factor should be evaluated. Depending on the UIF value a SSTI screening is required, as described above.

3. Managing SSR and SSTI exposure

When there is evidence of SSR or SSTI mitigation devices should be installed such as a Torsional Stress Relay (cf. [3], [8]).

Installation of the torsional stress relay should insure an immediate tripping of the turbine, if torsional resonance is detected, otherwise fatigue loads will be accumulated. A tuning of the torsional natural frequency on an existing shaft train seems to be very difficult (change of mass or stiffness). A modification or tuning of external grid properties is probably also not manageable.

4. Tracking of changes

Changes in the transmission system, especially the implementation of additional serial capacity or HVDC lines with Converter, require a new evaluation of SSR respectively SSTI.

References

[1] EPRI — Steam Turbine-Generator Torsional Vibration — Interaction with the Electrical Network

[2] AGCS TrendPaper 04 D 2017 ES 003 by Ron Irani, Version 2.0 Jul. 4, 2017

[3] Energiforsk Report 2017:355 - Sub Synchronous Oscillations, Grid interference on nuclear power plant operations

[4] Wilhelm Winter - Tennet, "Notwendigkeit der Untersuchung der Auswirkungen von HGÜ Systemen auf den Betrieb von Kraftwerken" in HDT Essen/Germany Fachtagung Turbogeneratoren 2015

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[5] VGB Powertech, White Paper „Betrachtung möglicher Auswirkungen des Betriebes von HGÜ-Systemen im Netz auf die Wellenstränge von Turbosätzen in Kraftwerken", Draft January 2019

[6] ISO 22666 Mechanical vibration — Torsional vibration of rotating machinery — Part 1: Land-based steam and gas turbine generator sets in excess of 50 MW

[7] GE Report GER-4724 (05/2013) –Torsional Dynamics – Large 2-pole and 4-pole steam turbine powertrains

[8] http://www.geenergyconsulting.com/practice-area/global-power-projects/torsional-stress-relay and http://www.geenergyconsulting.com/practice-area/global-power-projects/sub-synchronous-torsional-interaction-analysis-and-risk-mitigation

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