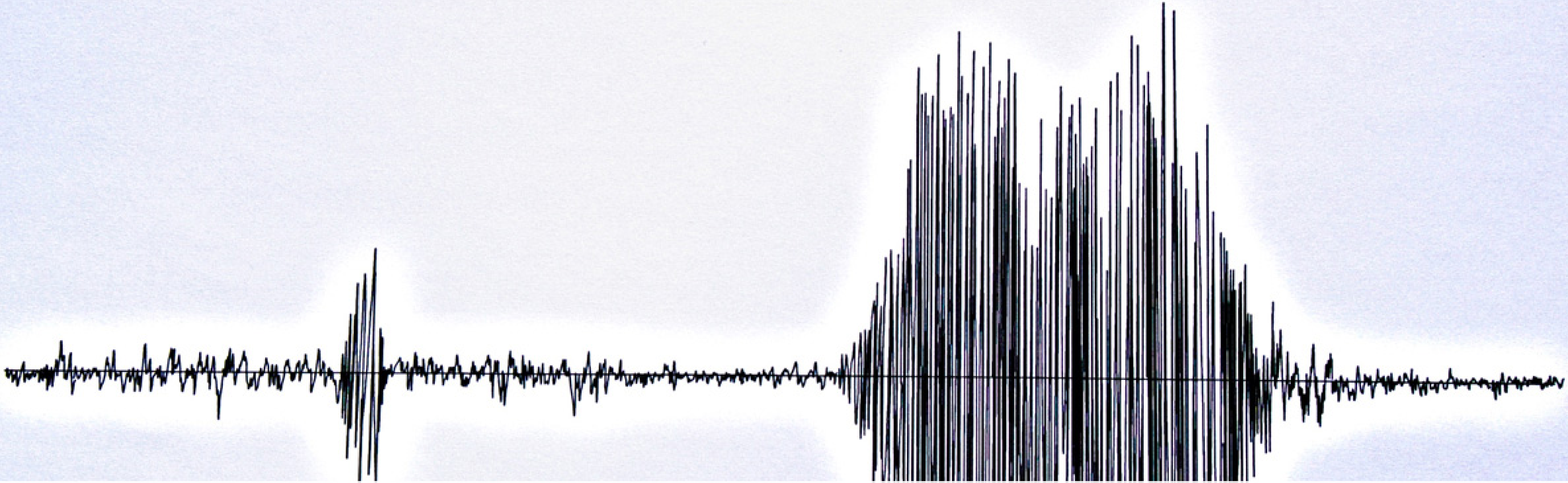


Torsional Vibrations in Shaft Trains

Vibrations in Nuclear Applications – Stockholm 08.11.2017

Wölfel

Torsional vibrations in shaft trains – Introduction

Focus of this presentation: Summary of the DRAFT-report “Torsional Vibrations in Shaft Trains of steam turbines”

- Motivation
- Background / Root Causes
- Practical Experiences
- Measurement & Monitoring
- Mitigation Measures
- flowchart for problem solution matrices (Introduction only)
- Conclusion
- Outlook

Torsional vibrations in shaft trains – Motivation

- Several years ago nuclear power plants (NPPs) have been mainly seen as a base-load source of electricity

- Large-scale deployment of intermittent smaller electricity sources (like wind power) took and takes place

- Now there is a significant share of intermittent and nuclear power source on the same electricity grid

- Utilities had to implement or improve the manoeuvrability (load-following) capabilities of their NPPs

- NPPs must now be able to operate in a load-following mode to balance fluctuations of total power generation

Torsional vibrations in shaft trains – Motivation

- The grid stability generated from big rotating inertias in NPPs is decreasing
- This leads to a negative impact on the grid stability caused by load fluctuations
- This again leads to problems like torsional interaction effects caused by subsynchronous resonances (SSR)

  Example: If the line resonant frequency is 20 Hz, resulting from the addition of series capacitors to reduce the reactance, potential SSR problems could arise if a turbine-generator on the system that generates 50 Hz current had a torsional mode at or close to thirty (50 - 20) Hz. This 30 Hz frequency is referred to as the “complement” of the line resonant frequency of 20 Hz in this case. Under these conditions the shaft response torques could build up to extremely high levels.

Torsional vibrations in shaft trains – Motivation

- For NPP operators it is necessary
  - to detect and to understand the problem/root cause
  - to define instructions in cases where threshold values are exceeded
  - to control the occurring torsional vibrations with means of mitigation measures.

- Motivated by this the report “torsional vibrations in the shaft trains of steam turbines” is now being set up

Torsional vibrations in shaft trains – Background / Rootcauses

The electrical stimuli that cause torsional vibrations in the turbine-generator originate from load cases, which are

- **not** considered in the baseline design of steam turbines (non-design load cases) due to the changing philosophy in energy production with small sources and therefor they need special attention.

- **already** considered in the baseline design (Baseline-Design Load Cases).

Torsional vibrations in shaft trains – Background / Rootcauses contd.

1. Non-Design Load Cases	
RC 1.1	Subsynchronous Resonance (SSR)
RC 1.2	Turbine-Generator Device Dependent Subsynchronous Oscillations (DDSO) with DC Power Converters
RC 1.3	Turbine-Generator Supersynchronous Torsional Interaction with DC Power Converters
RC 1.4	Large AC Arc Furnaces
RC 1.5	Intermittent (fluctuating) Oscillations arising from Steel Mill Operation
RC 1.6	Variable Frequency Electric Drives
2. Baseline-Design Load Cases	
RC 2.1	Transmission Line Short Circuits
RC 2.2	Planned or Emergency Line Switching Operations
RC 2.3	Unbalanced Phase Currents in the Grid
RC 2.4	Application of Power Electronics
RC 2.5	Equipment Connected to the Generator Terminals
RC 2.6	Synchronizing the Generator Out of Phase (SOP)
RC 2.7	Turbine-Generator Load Rejection
RC 2.8	Loss of Synchronism

Torsional vibrations in shaft trains – Practical Experiences

Practical experiences were made by the members of ENRGIFORSK and other operators

The practical experiences in this context are failures that potentially lead to an outage of the turbine. Generally there are at least 3 different kinds of failures:

- Fracture,
- gross structural damage and/or
- cracking of components

Each failure can be traced back to a certain root cause.

Torsional vibrations in shaft trains – Practical Experiences

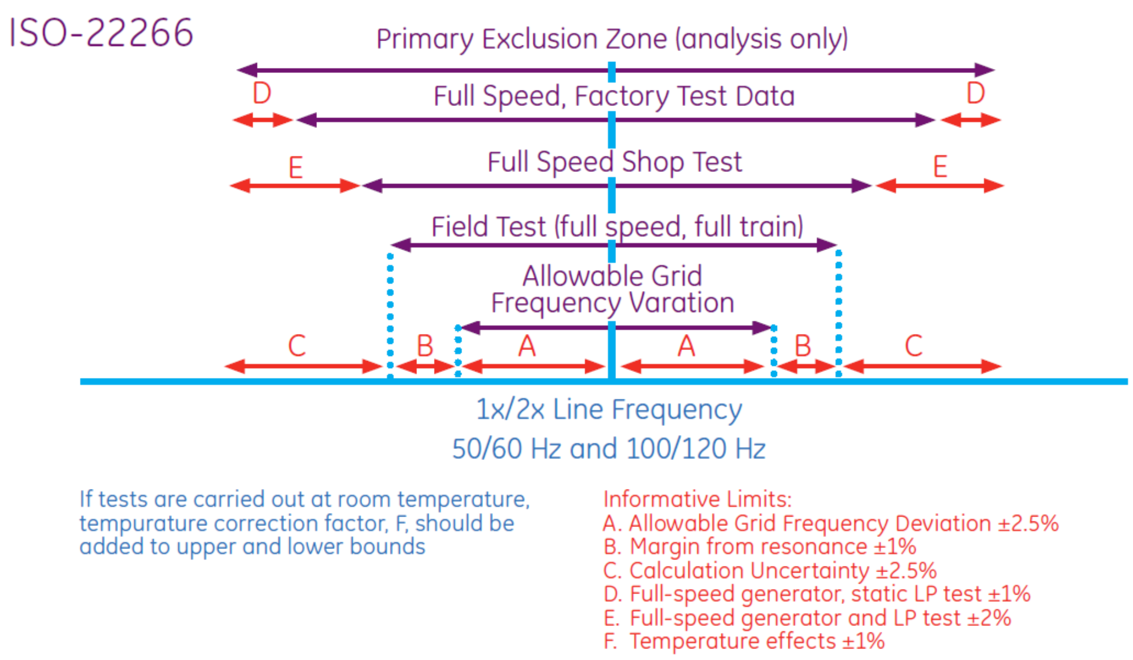
Examples of typical experienced failures traced back to certain root causes

Typical experienced failure	Tracable root cause
Blade cracking incidents of LP turbine blades from torsional resonance near 120 Hz	probably RC 2.3 and RC 2.7
Shaft failures on 2P and 4P units by SSR	RC 1.1
Shaft cracking incidents from 120 Hz torsional stimuli	probably RC 2.3
Retaining ring fracture due to DDSO involving DC equipment at a steel mill	RC 1.2
Retaining ring fracture due to supersynchronous torsional interaction from power frequency spikes at a steel mill	RC 1.3

Torsional vibrations in shaft trains – Measurement and Monitoring

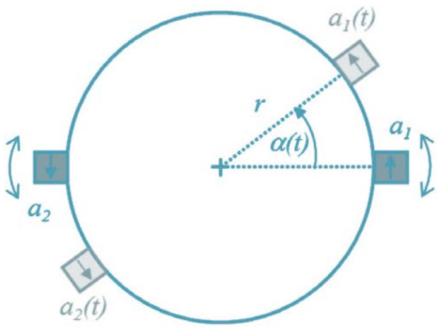
Torsional vibration monitoring during operation shall measure and observe torsional vibration and provide a warning that the turbine-generator is

- being subjected to unexpected torsional stimuli (incidents) or
- operating close to torsional mode resonances caused by a harmonic torque in accordance to recommended frequency variations, see ISO-22266 →



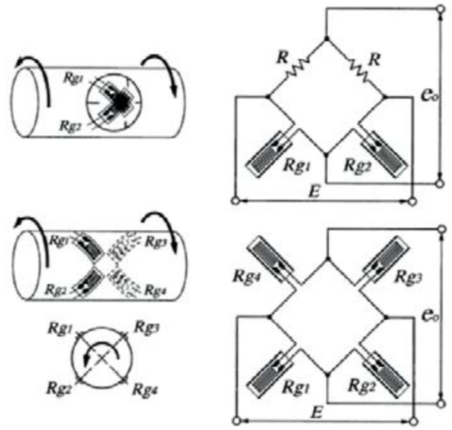
Torsional vibrations in shaft trains – Measurement and Monitoring

Direct Measurement Methods - Linear Accelerometer

Function / Mounting	+	-
Two linear accelerometers are fixed in parallel on the rotating shaft as shown below. The two accelerometers will measure the tangential acceleration. As they move in the opposite direction in the fixed system of the rotation axis, for any translational acceleration of the shaft the average of both accelerometers is taken	High dynamic range	Expensive telemetry or sensitive slip rings needed
	Low sensitivity to translational vibrations	Mass loading for relatively small shafts (e.g. shaft unbalance)
		Centrifugal forces may lead to dangerous loss of sensors
		No absolute angular position available

Torsional vibrations in shaft trains – Measurement and Monitoring

Direct Measurement Methods – Strain Gauges

Function / Mounting	+	-
Measuring torsional elongation or stress (shear stress) **Strain gauges glued on the shaft**	Direct measurement of torsional elongation or shear stress	Expensive telemetry or sensitive slip rings needed
	Low sensitivity to other deformation than torsional	Mass loading for relatively small shafts (e.g. shaft unbalance)
		Centrifugal forces may lead to dangerous loss of sensors
		Exact angular speed and position not known, no absolute position available

Torsional vibrations in shaft trains – Measurement and Monitoring

Direct Measurement Methods – Dual-Beam Laser Interferometer

Function / Mounting	+	-
Angular velocity is computed from velocity measured in direction of the laser beams on the two pointed areas through the Doppler shift.	Contactless	Expensive device
	Low sensitivity to translational vibrations	Exact angular speed and position not known, no absolute position available
	Low sensitivity to shape of the shaft	No usage in confined environment
	Easy instrumentation	Visual contact between shaft and sensor required.

Torsional vibrations in shaft trains – Measurement and Monitoring

Coder-Based Measurement Methods – Magnetic Pick-Up

Function / Mounting	+	-
Detection of changes in magnetic field or magnetic flux. **Sensor types: magneto-resistive, magneto-inductive or Hall effect**	Price: mass production for automotive and industrial application	Number of gear teeth limits number of pulses per revolution
	Simplicity of instrumentation: sensor fixed on non-rotating component	Accuracy of measurement depends very much on machining accuracy and teeth deformation
	Typically: metallic teeth used as coder	Sensor must be fixed very closely to the shaft (<0.5 cm)
	Low sensitivity to ambient dust	Generating of fictive torsional vibration possible by relative displacements between sensor and shaft

Torsional vibrations in shaft trains – Measurement and Monitoring

Coder-Based Measurement Methods – Optical Sensor

Function / Mounting	+	-
Generating of electrical signal depending on light intensity. **Coders with sufficient visible contrast mounted on the shaft or its end (e.g. zebra tapes or zebra discs)**	Simplicity of instrumentation: sensor fixed on non-rotating component	High sensitivity to ambient light
	Direct mounting on gears possible	Visual contact between shaft and sensor required.
	Coder easy to implement by using contrasted paint or zebra tapes	
	Measurement of very high pulse rate	

Torsional vibrations in shaft trains – Measurement and Monitoring

Coder-Based Measurement Methods – Incremental Encoder

Function / Mounting	+	-
Combination of coder and sensor in one device (often optical technology) **Three embedded coders**	High-pulse rate (typically 50 to 500)	Relatively complex instrumentation limits usage for in-vehicles or mobile measurement
	Duty-cycle related analysis	

Torsional vibrations in shaft trains – Measurement and Monitoring

Comparison of Commercial Systems

Company	Product Name	Measurement Method	Mounting Type	Measured Values	Annotation
Geislinger	Geislinger Monitoring	Coder based Hall-sensors	Sensors positioned close to wheels with grooves or angle encoders	Torque and vibratory angle	n ≤ 1500 rpm
GE	TSR Torsional Stress Relay	Direct strain gauges	Strain gauges attached to shaft collar-type or strap-type	Torque	
Torque and More	Advanced Active-3 Torque Sensors	Coder Based Hall-sensors	Non-contact Plug-and-Play Ferro-magnetic shaft material required	Torque	
Siemens	LMS Test.Lab Torsional Vibration Analysis	Coder Based N/A	Depends on selected sensors	Depends on selected sensors	
Suprocktech	TDMS (Turbine Dynamics Monitoring System)	Direct Strain gauges and accelerometers	Mounted on shaft	Torsional and also lateral dynamics	

Torsional vibrations in shaft trains – Mitigation Measures

The mitigation measures are split into

- mitigation procedures and
- available mitigation systems.

In the description of each mitigation measure the failure, for which the procedure is applicable is named including the reference to the specific root cause.

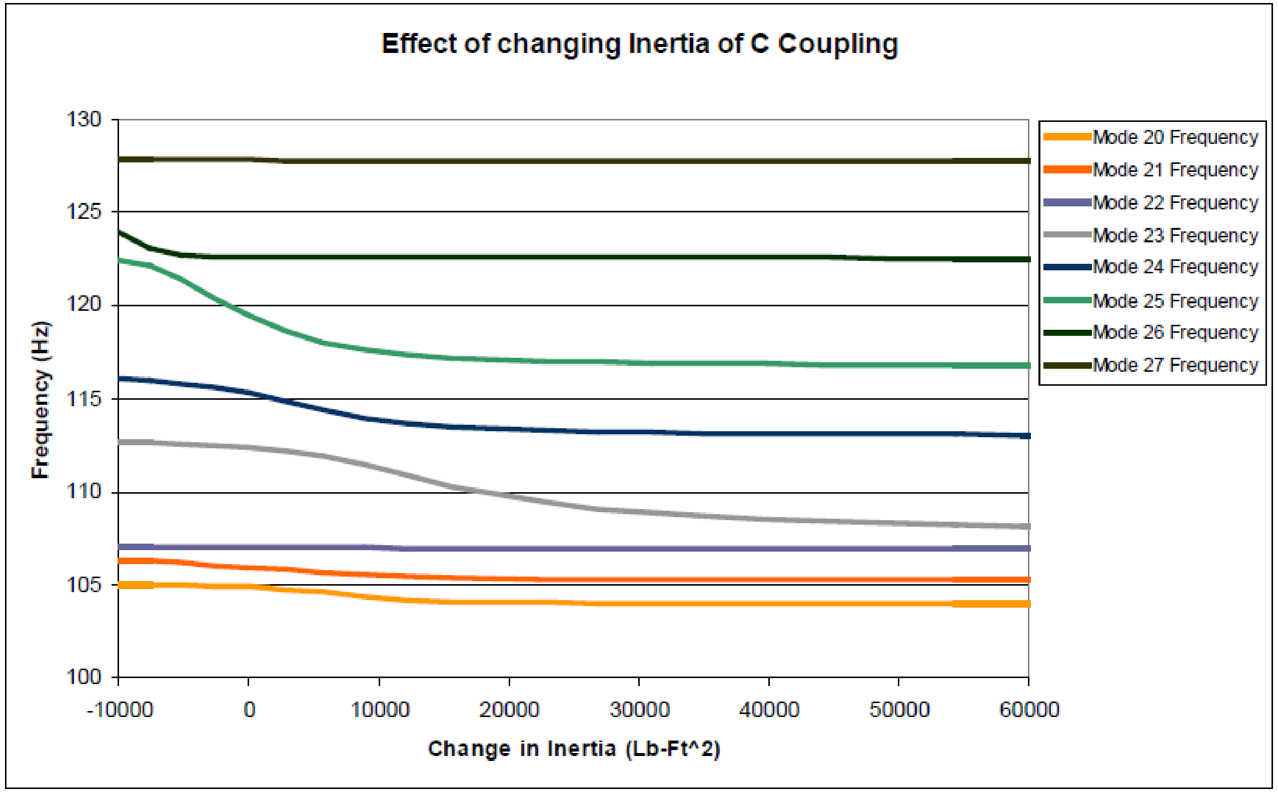
Torsional vibrations in shaft trains – Mitigation Measures

Mitigation procedures

#	Mitigation Procedure	Applicable to
1	Modifications to Shift a Torsional Frequency	For all root causes that excite torsional natural frequencies of the steam turbine e.g. by SSR
2	Delay in High Speed Reclosing HSR	“Transmission line short circuits”, see RC 2.1
3	Defined Step Change	“Planned or Emergency Line Switching Operations”, see RC 2.2
4	Selective Transpositions of transmission lines	“Unbalanced Phase Currents in the Grid”, see RC 2.3
5	Harmonic Filters	“Application of Power Electronics”, see RC 2.4
6	Unit Interaction Factor (UIF)	“Turbine-Generator Device Dependent Subsynchronous Oscillations (DDSO) with DC Power Converters”, see RC 1.3
7	Rapid Acceleration through Critical Speeds	“Variable Frequency Electric Drives”, see RC 1.6

Torsional vibrations in shaft trains – Mitigation Measures

Mitigation procedures – Example: Modifications to Shift a Torsional Frequency



Torsional vibrations in shaft trains – Mitigation Measures

Commercially available mitigation systems

#	mitigation system	Applicable to
1	Torsional Vibration Damper	All Root Causes
2	SSR filters in power transformer	"Subsynchronous Resonances (SSR)", see RC 1.1
3	Supplementary Excitation Damper Control (SEDC)	All Root Causes
4	Static VAR compensators (SVC)	"Transmission Line Short Circuits" and "Planned or Emergency Line Switching Operations", see RC 2.1 and RC 2.2
5	Superconducting magnetic storage units (SMES)	all Root Causes that cause transient excitations, e.g. RC 2.1, RC 2.2, RC 2.6 and RC 2.7

Torsional vibrations in shaft trains – Flowchart

Matrix: Detection & Investigation

Matrix: Mitigation

Measurement
--> Comparison with Threshold Values

-->

2. Threshold Values
a. Warning --> continue
b. Exceeded --> STOP

-->

3. Measured Data & System Parameter
--> Root Cause Determination

-->

4. Selection
a. Procedure
b. Mitigation System

-->

5. Implementation
--> Test
--> Launch

Torsional vibrations in shaft trains – Conclusion

There is sufficient knowledge and background available to solve potential problems related to torsional vibrations in shaft trains. The report “Torsional Vibrations in Shaft Trains of Steam Turbines” gives – amongst other points – an overview on

- different known root causes,
- a collection of practical experiences and incidents,
- means of measurement and identification and
- possible mitigations measures.

Appendix A shall contain a problem solution matrix associated to the process in the flowchart. It shall guide the operator through the process all the way from problem identification to the mitigating system.

Torsional vibrations in shaft trains – Outlook

Some items of this report need further attention and processing in the framework of a follow-up project:

- Development of root cause analysis derived from
  - measured data of torsional monitoring (and others)
  - actual system parameters and
  - machine specific threshold values.

- Check the applicability of torsional vibration dampers for Steam Turbines