OL3 turbine shaft torsional vibration measurements

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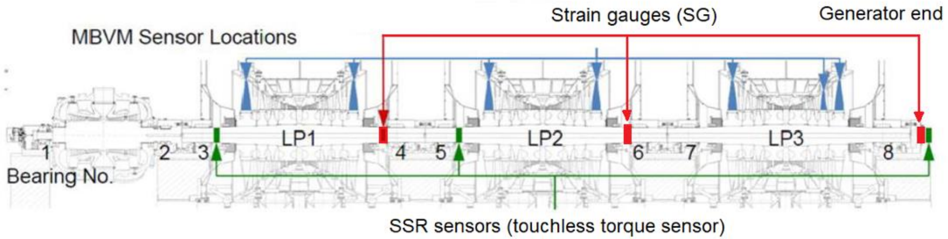
Background and VTT scope of work

- **Phase 1**
  - Evaluation of the shaft torque measurement system (SSR monitoring system) and blade vibration monitoring system on the OL3 turbine.

- **Phase 2**
  - VTT installed datalogging system to gather all the raw signals from torque measurement system (Strain gauges / SSR sensors).
  - Measurements lasted from January 2022 until March 2024 including the commissioning tests and first operational phase.
  - Analysis of major events during the measurement period.
  - Evaluation of SSR monitoring system performance

Sensor locations and VTT measurement system

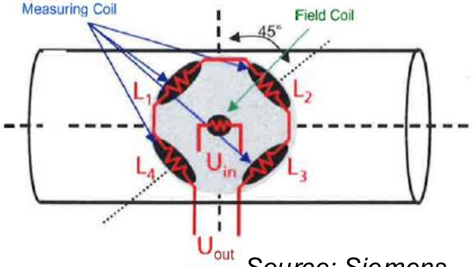
- In addition to permanent SSR sensors Siemens had installed strain gauges in three different locations at the turbine shaft.
- SSR sensor and strain gauge raw signals are logged at VTT measurement system
- Also, generator power and shaft rotational speed is logged.
- Measurement system consists of imc CRFX amplifiers and central unit.
- All signals are synchronized accurately and saved to PC for post processing.



Source: Siemens

OL3 SSR monitoring system - overview

- Sub-synchronous resonance
  - Torsional resonance events with frequency below the grid frequency and which can occur e.g. due to electric grid faults.
- System is based on Siemens touchless torque sensor (in this presentation called SSR sensor)
  - The touchless torque sensor uses the magnetostrictive effect to measure the torque
  - The magnetic permeability of the shaft material changes under stress and this can be measured with the sensors.
- Requires calibration with known stress state
  - Turbine known static torque at various power levels can be used
- Final monitoring system includes several sensors and appropriate filters to monitor the SSR events



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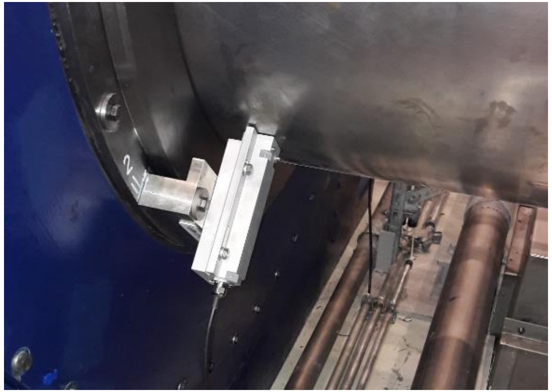
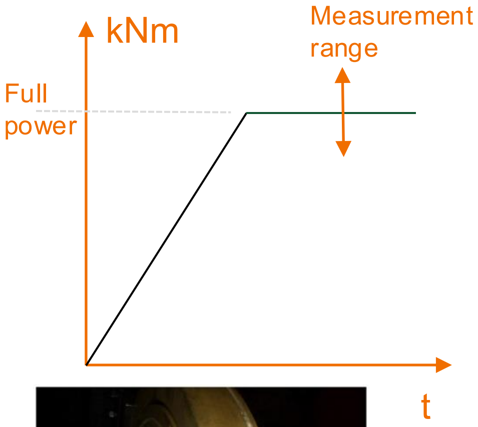

Source: Siemens

Semiconductor strain gauges and SSR sensors

- Strain gauges
  - Semiconductor type strain gauge
  - Can measure accurately dynamic range (+/- 30 microstrains, about +/- 491 kNm)
  - Cannot measure the whole torque range (about 10190 kNm at 1600 MW)
  - High temperature coefficient (Temperature Coefficient of gage factor 0.27 % / °C -> 16% at 80 °C)
  - Filtered to 5 – 2000 Hz
- SSR sensors (touchless torque sensor)
  - Can measure the whole torque range
  - Needs calibration (generator power, turbine thermodynamic condition)
- Acquisition frequency 2000 Hz



Source: Siemens

SSR sensor evaluation

- SSR sensors installed by Siemens were evaluated to understand better the accuracy of the system.
- Power level changes were used to evaluate the static component
- Bearing 8 offers a good place for comparison as strain gauge and SSR sensor are installed close to each other, also it is next to the generator.
- Vibration amplitudes for lowest three modes were compared to strain gauges and roughly a difference of 10 % was observed.
- It should be noted that semiconductor strain gauges have higher margin for uncertainties.

Table 13. Maximum amplitudes for each mode, calculated from averaged amplitude spectrum. The ratio between SG and SSR is calculated from average of strain gauge signals and SSR sensor signals. values in MPa.

	mode 1,	mode 2,	mode 3,
SG1	0.0242	0.0316	0.0485
SG2	0.0253	0.0331	0.0509
SSR1	0.0233	0.0293	0.0449
SSR2	0.0226	0.0288	0.0434
SG/SSR	1.078	1.114	1.126

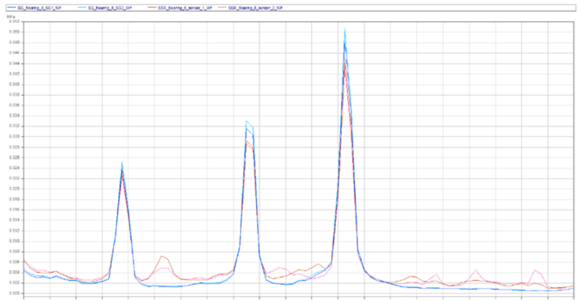


Figure 47. Comparison of SSR sensors and strain gauge signals at bearing 8. Results from averaged amplitude spectrum analysis. Blue lines are strain gauge signals and red lines are SSR.

Table 12. Difference of SSR1 / SSR2 in maximum amplitude for different torsional modes.

Bearing 3	Mode	difference [%]
	4	-0.63
Bearing 5		
	1	-2.57
	2	-2.12
Bearing 8		
	2	1.98
	3	3.36

Major events during the measurement campaign

- During the commissioning tests and first operational phase several different types of events were observed and analyzed
- In some turbine trip and load drop events rather high stress values were observed, but for very short period
- SSR event was observed during first FRT test
- Next slides show different events

			Bearing location		
			3	5	8
Date	Event	description	MPa	MPa	MPa
29.1.2022	Turbine trip		3.41	4.67	4.13
12.3.2022	Synchronization	Synchronization to grid	0.71	3.09	2.09
19.3.2022	Turbine trip 30%	Turbine trip from 30% power level	1.19	1.92	1.98
20.3.2022	PST test 30%	Power source transfer	2.75	**21.67**	**19.10**
21.3.2022	Synchronization	Synchronization to grid	0.72	2.79	2.18
29.8.2022	Synchronization	Synchronization to grid	0.77	3.45	2.45
29.8.2022	Turbine trip 50%	Turbine trip from 50% power level	5.51	**47.03**	**38.30**
1.9.2022	Houseload test	Load drop from 60% level to house-load level, 400 kV -> 110 kV	5.41	**41.79**	**34.15**
2.9.2022	Fast valving test	HP turbine valves are closed quickly for 2 s resulting in power drop of about 300 MW	1.38	1.48	1.48
28.12.2022	Synchronization	Synchronization to grid	0.74	3.37	2.25
29.12.2022	Turbine trip 100%	Turbine trip from 100% power level	2.05	2.18	2.19
30.12.2022	Synchronization	Synchronization to grid	0.79	3.77	2.37
30.12.2022	Load drop 100% -> 50%		1.30	1.15	1.52
2.1.2023	Houseload test	Load drop from 100% level to house-load level			
5.1.2023	Fault ride through (FRT)	Preparation for FRT test, SSR event triggered			
26.4.2023	Grid fault	At Hagby, Sweden. Forsmark 1&2 disconnected.	2.19	**11.16**	**13.51**
25.6.2023	Grid fault	At Hikiä	3.39	**22.90**	**9.87**
28.6.2023	Grid fault	3-phase short-circuit due to lightning at Huittinen			
29.11.2023	Fault ride through (FRT)	Preparation and test for FRT, second attempt			

Shown stress values for each case is the highest vibration amplitude (peak) at all three locations when the signals are band pass filtered to frequency range of **2** Hz to **23** Hz.

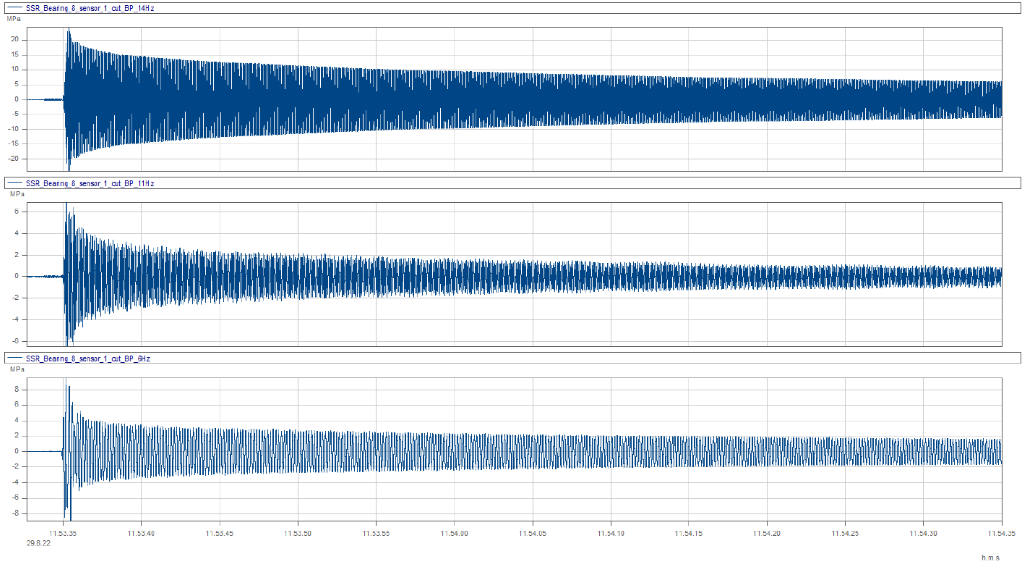
Major events

- 50% turbine trip on 29.8.2022

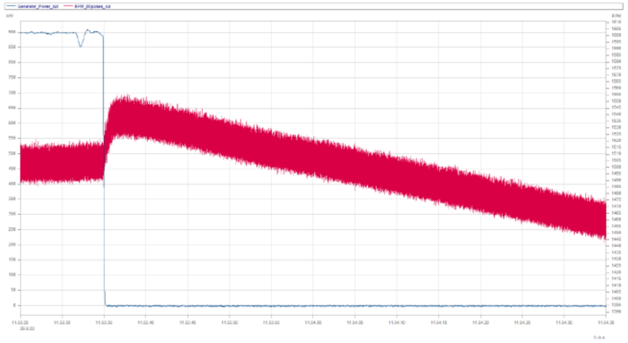
Bearing 8

Bearing 5

Bearing 3



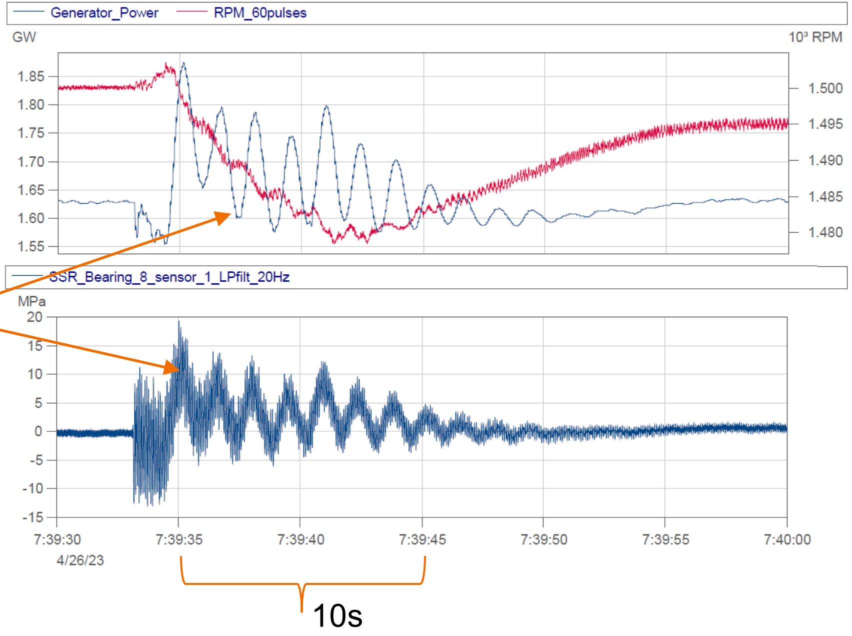
Location	Mode	Max amplitude [Mpa]
Bearing 8	(first mode)	9.5
Bearing 8	(second mode)	6.8
Bearing 8	(third mode)	24.1
Bearing 5	(first mode)	28.6
Bearing 5	(second mode)	16.8
Bearing 5	(third mode)	6.6
Bearing 3	(first mode)	2.2
Bearing 3	(second mode)	2
Bearing 3	(third mode)	0.9



Major events

- Hagby grid fault 26.4.2023
- Serious malfunction occurred in the Swedish transmission network [1]
- Operating voltage became very low in large parts of the transmission and distribution networks in the Stockholm region.
- Forsmark 1 and 2 were automatically disconnected from the grid.
- At OL3 Significant low-frequency (0.7 Hz) torsional forced vibration occurred below the frequency of the lowest torsional mode, which can be seen in the generator power signal as well as in SSR signals.

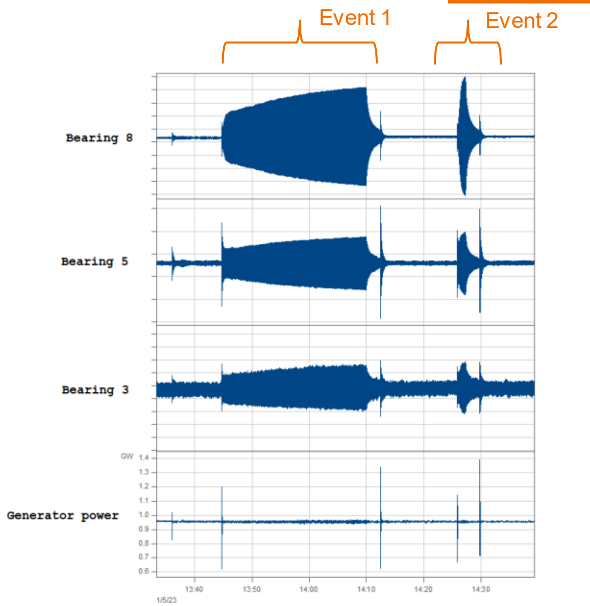
Location	**Mode**	**Max amplitude [MPa]**
Bearing 8	(first mode)	1.90
Bearing 8	(second mode)	2.07
Bearing 8	(third mode)	11.52
Bearing 8	Overall (0-20Hz)	16.3
Bearing 5	(first mode)	5.54
Bearing 5	(second mode)	5.38
Bearing 5	(third mode)	2.92
Bearing 5	Overall (0-20Hz)	11.7
Bearing 3	(first mode)	0.47
Bearing 3	(second mode)	0.58
Bearing 3	(third mode)	0.39
Bearing 3	Overall (0-20Hz)	2.3

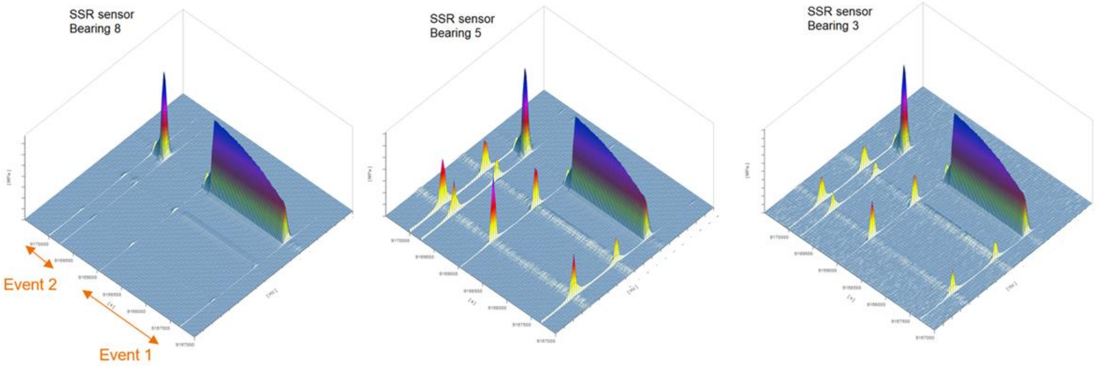


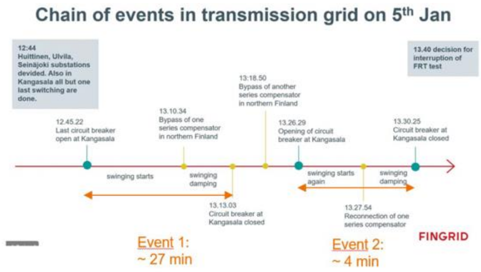
[1] Svenska kraftnät, “The disruption on April 26, 2023 - Description of the sequence of events of the disturbance, Version 1.0 Org. Nr 202 100-4284,” 2023.

FRT and SSR event

- During preparation work for Fault Ride-Trough (FRT) test on 5.1.2023 an SSR event occurred at OL3 turbine.
- Dynamics of the electrical grid were changed so that resonance could take place.
- Two separate events were seen where the torsional vibration amplitudes gradually rose indicating a resonance at the turbine shaft.
- Preparation work and test were cancelled due to the seen resonance events.
- Second FRT test was carried out later (29.11.2023) and went without resonance problems. However, the test caused OL3 to be disconnected from the grid.







Damping estimation

Without electric load, Turbine trip at 29.12.2022

- Damping estimates **without electric load**, after disconnection

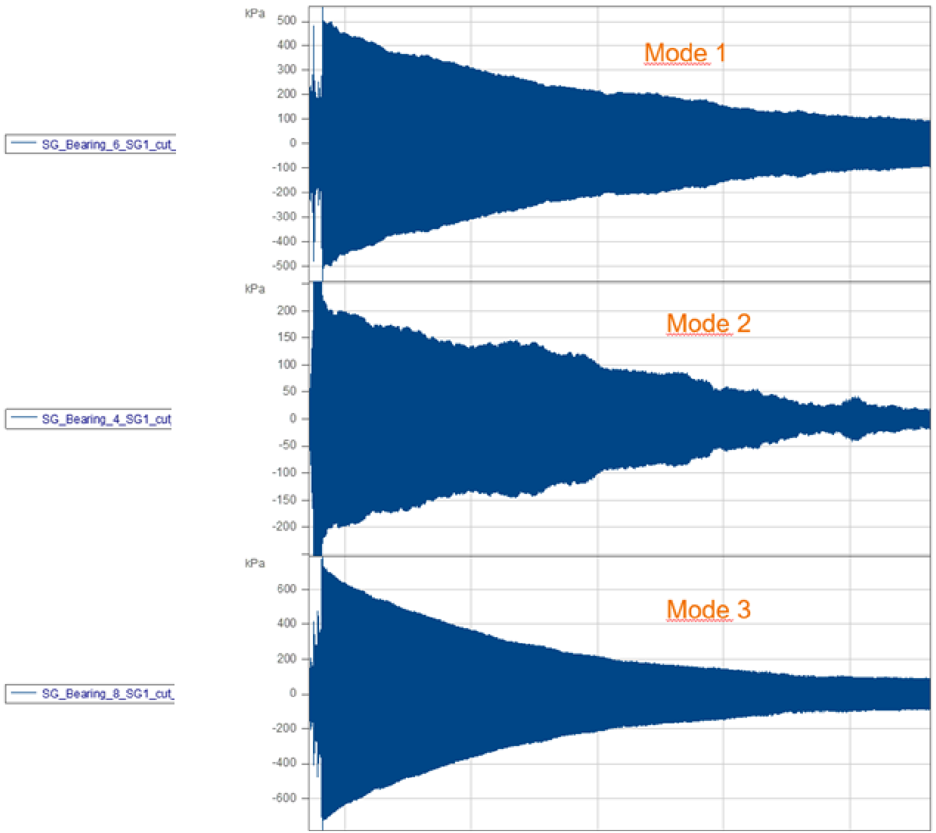
Logarithmic decrement:

$$\delta = \frac{1}{n} \ln \frac{x(t)}{x(t+nT)}$$

$$\zeta \approx \frac{\ln\left(\frac{x_0}{x_1}\right)}{2\pi}$$

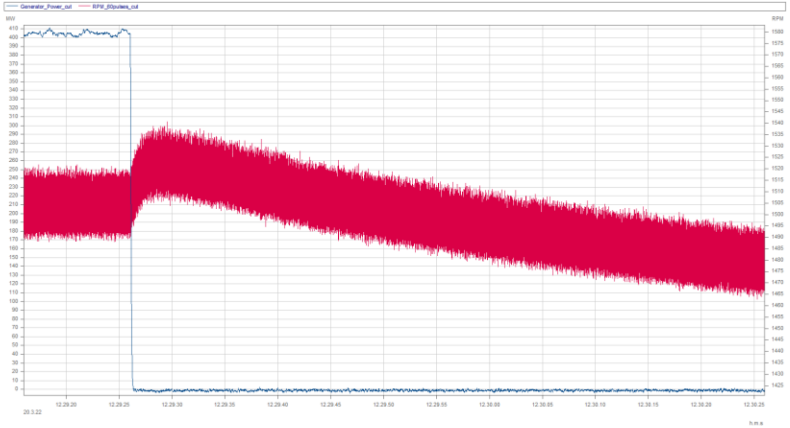
Mode	Modal damping ratio ζ (%)
1	0.008
2	0.005
3	0.006

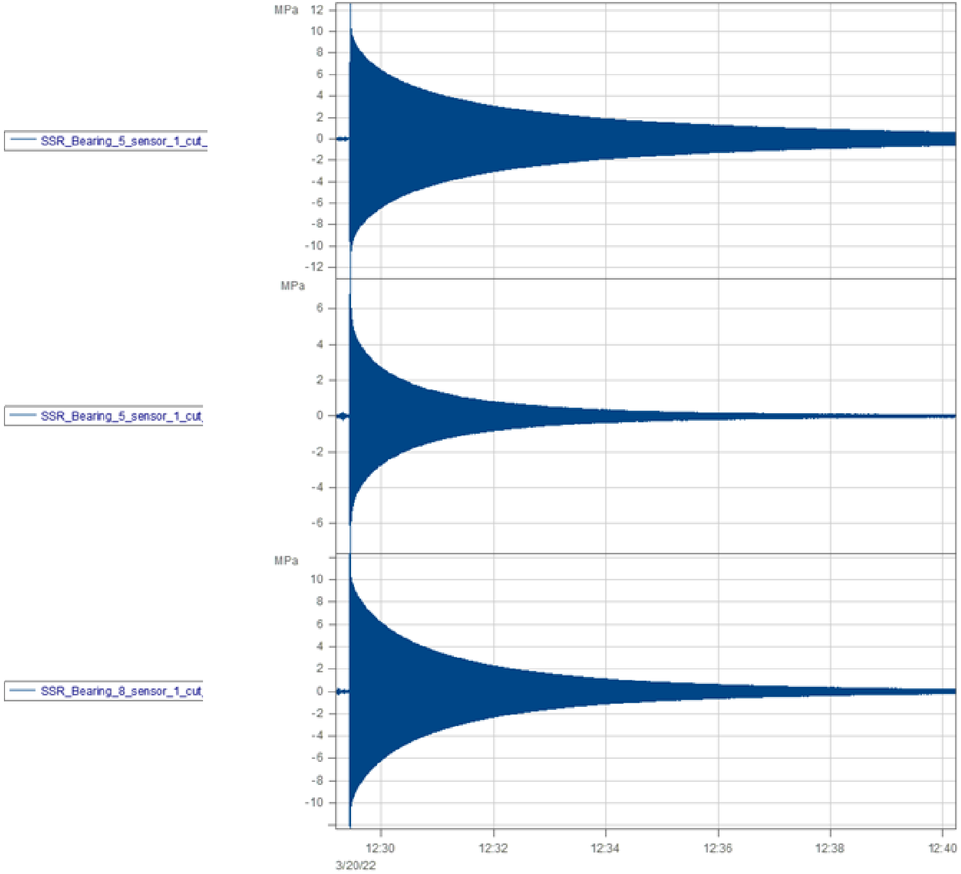
BP filtered modal responses (3Hz bandwith)



Damping dependency of stress amplitude
Power source transfer (PST) event 20.3.2022

- Damping estimates **without electric load**

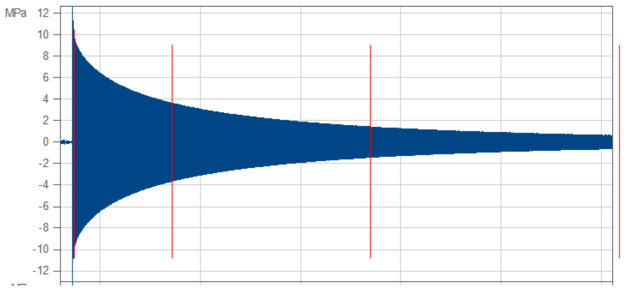




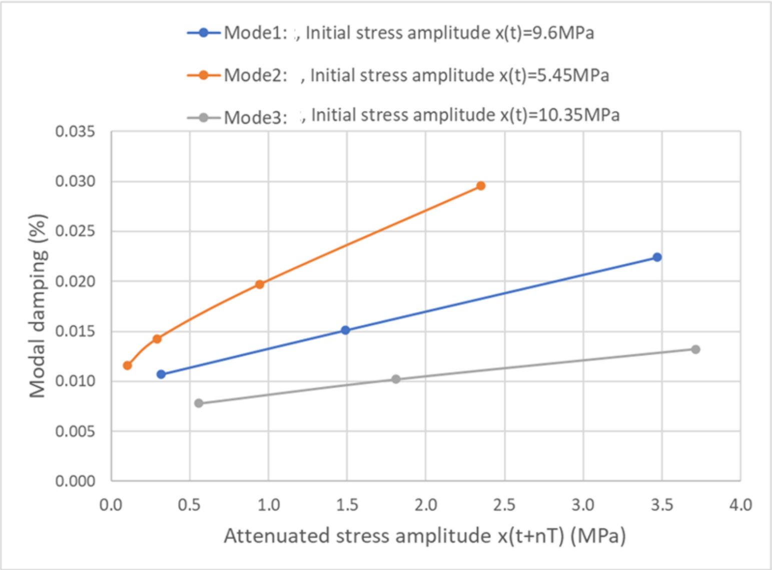
Damping dependency of stress amplitude
PST event 20.3.2022, without electric load

- Damping ratio is defined for segments of the damped oscillation, between stress amplitudes x(t) and x(t+nT)
- Damping increases with higher stress amplitudes

$$\delta = \frac{1}{n} \ln \frac{x(t)}{x(t+nT)} \qquad \zeta \approx \frac{\ln\left(\frac{x_0}{x_1}\right)}{2\pi}$$



Mode		Initial modal amplitude x(t) (Mpa)	Attenuated modal amplitude x(t+nT) (Mpa)	Modal damping (%)
1		9.62	3.47	0.022
		9.62	1.49	0.015
		9.62	**0.32**	**0.011**
2		5.45	2.35	0.030
		5.45	0.95	0.020
		5.45	0.29	0.014
		5.45	**0.10**	**0.012**
3		10.35	3.72	0.013
		10.35	1.81	0.010
		10.35	**0.56**	**0.008**



Discussion regarding mechanical damping

Damping increases with higher stress amplitudes

- In case of ideal viscous damping, the damping would not be amplitude dependent
- In this case, several different damping mechanisms are involved; therefore, basic viscous damping model do not describe accurately the damping behavior
- Accurate modelling of the amplitude dependency would require utilization of some non-viscous damping model

Potential sources of mechanical damping:

- Material damping effect
  - Characteristic of the material
- Structural damping effect
  - Contribution of e.g., the turbine blade attachment interface
- Aerodynamic damping (turbine)

Quantitative determination of contribution of different sources would require further investigations

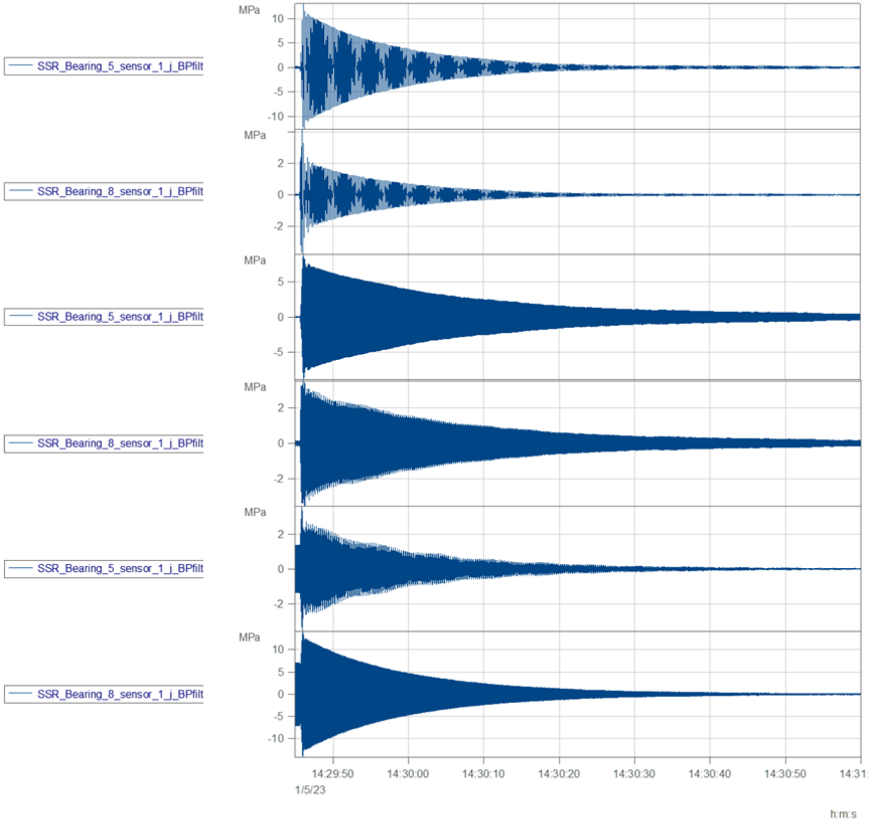
Damping estimation, with electric load

SSR event 2; 5.1.2023

- Damping estimates **with electric load**
- Dependency of electric load

- Naturally, contribution of electric grid depends on electrical properties (impedance) of the grid; topology, structure, connections etc
- Includes contribution of the **electric grid** and also **electromechanical forces of the generator**

	Modal damping ratio ζ (%)		
Mode	Houseload test 2.1.2023; With electric load, (~90 MW)	Fault ride through (FRT) test 5.1.2023; With electric load, (~950 MW)	3-phase short-circuit due to lightning 28.6.2023 With electric load, (~1550 MW)
1	0.20	0.22	0.38
2	0.05	0.07	0.14
3	0.06	0.08	0.22



Conclusions on damping

VTT

		Without electric load, after disconnection; low stress amplitude	Without electric load, after disconnection; high stress amplitude	Houseload test 2.1.2023; With electric load, (~90 MW)	Fault ride through (FRT) test 5.1.2023; With electric load, (~950 MW)	3-phase short-circuit due to lightning 28.6.2023; With electric load, (~1550 MW)
Mode		Modal damping ratio ζ (%)	Modal damping ratio ζ (%)	Modal damping ratio ζ (%)	Modal damping ratio ζ (%)	Modal damping ratio ζ (%)
1		0.008	0.01	0.20	0.22	0.38
2		0.005	0.01	0.05	0.07	0.14
3		0.006	0.008	0.06	0.08	0.22

- Contribution of mechanical turbine shaft itself for total damping of the system is small
- Mechanical damping of turbine shaft increases with higher stress amplitudes
- The electric grid (including also contribution of electromechanical forces of the generator) have significant contribution for the damping
- Damping increases when the electric load increases
  - Naturally, contribution of electric grid depends on grid properties (impedance); topology, structure, connections etc
  - It can also be assumed that the aerodynamic damping in the turbine increases when the load increases
  - Torsional modal displacement of third mode for the generator is very high compared to the turbine displacements ⇒ this would indicate that the generator and the electric grid have significant contribution to the damping of this mode at full load condition

beyond
the obvious

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