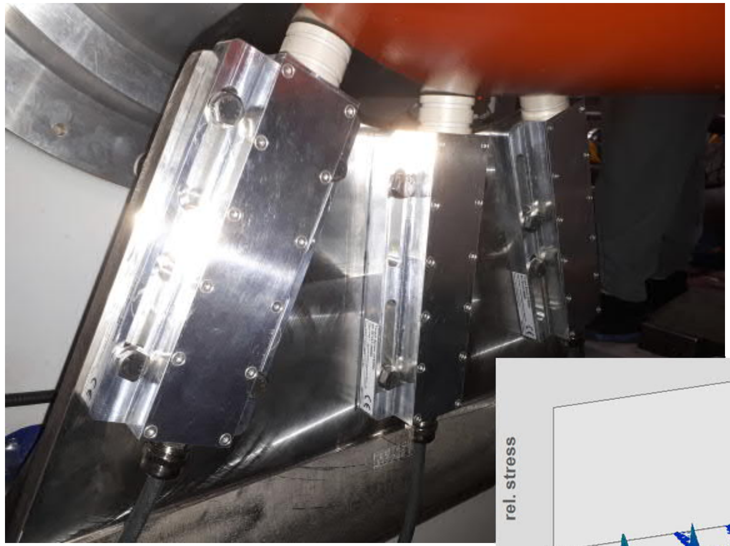
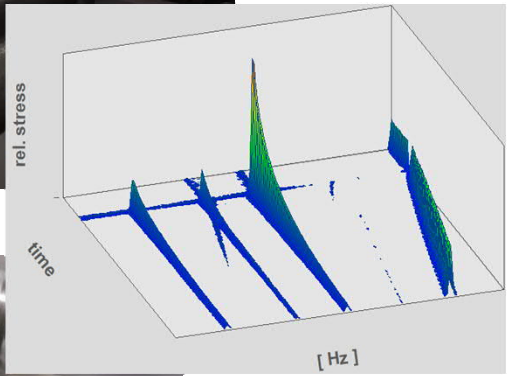
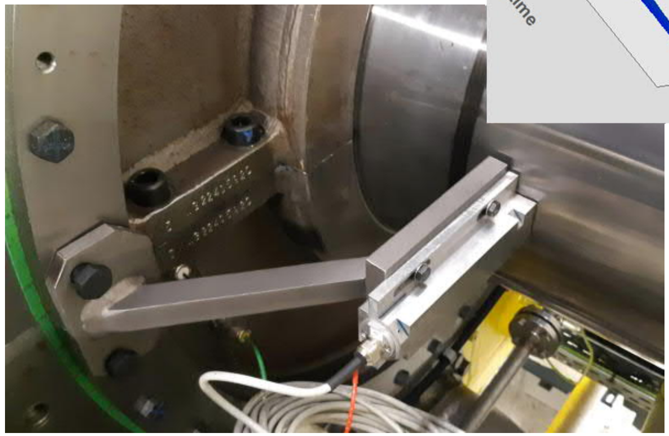
Direct touchless sensing of torsional vibration stresses in power plant shafts

Energiforsk Conference – Vibrations in nuclear applications, Stockholm, November 9th, 2023

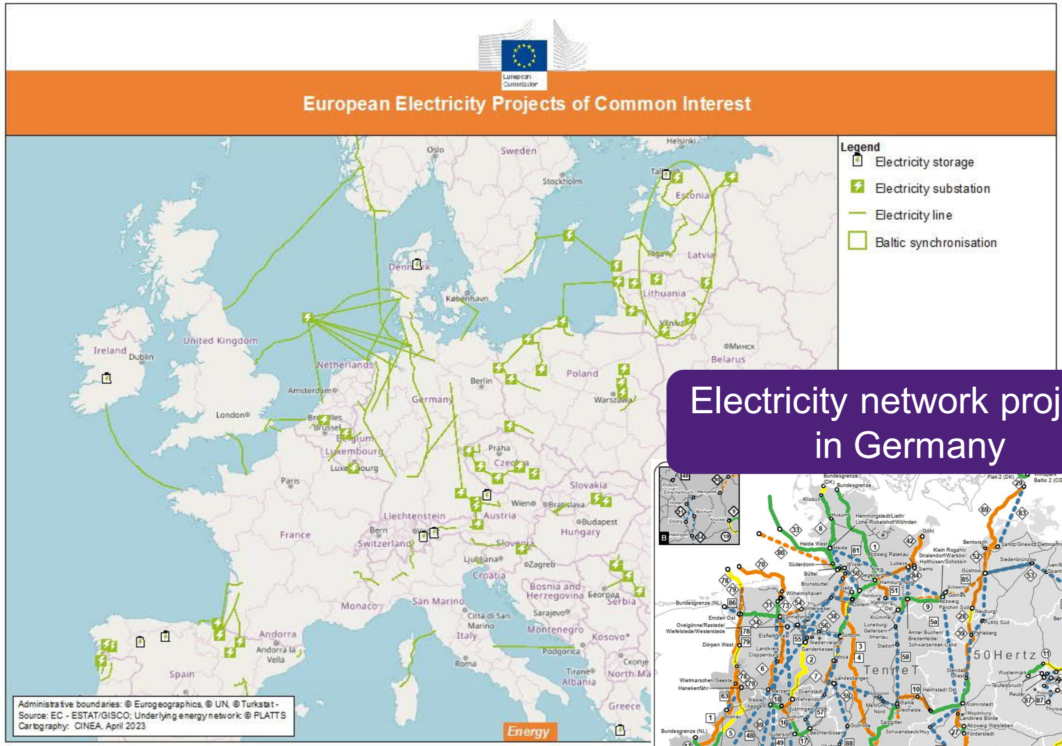
Content



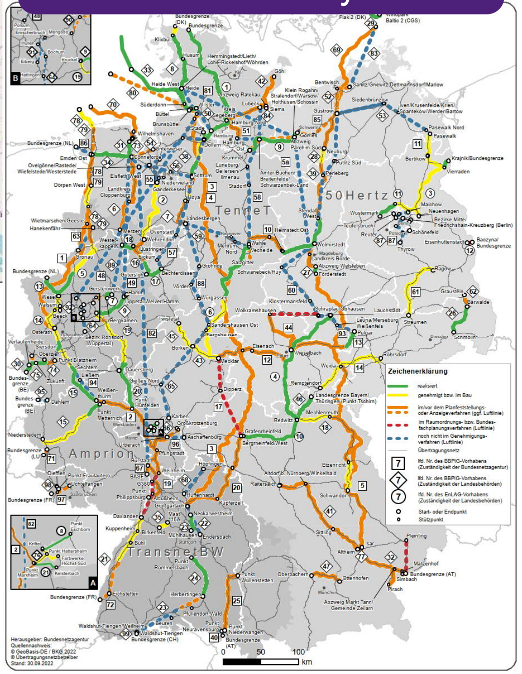




Background



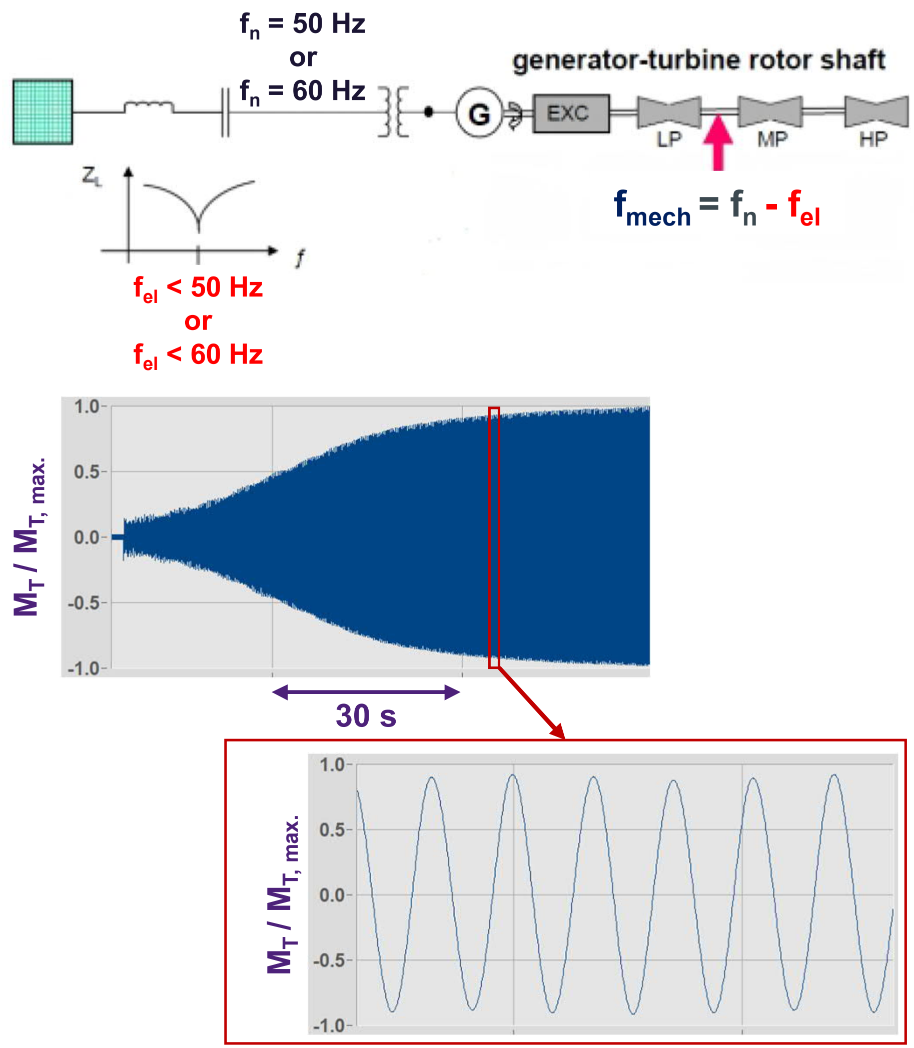
Electricity network projects in Germany



Actually, electricity networks are changing rapidly. The reasons are the following:

- Due to the transition of the electricity supply to higher amounts of renewable energy, more and more stabilizing rotational masses are decommissioned (Nuclear power plants, Steam power plants) => grid will have to be stabilized otherwise
- The classical AC power grid is more and more supplemented by high voltage DC links (HVDC)
- Renewable Energy sources (Wind/Solar) increase volatilities inside the power grid
  - ➢ **The risk of electricity network incidents, Sub-Synchronous Resonances (SSR) and Sub-Synchronous Torsional Interaction (SSTI) rises remarkably**

Sub-Synchronous Resonances (SSR)



Subsynchronous Resonance (SSR) is a turbo-generator interaction phenomena arising due to the coupling of the power grid and the turbo-generator resulting in unstable, i.e. non-attenuating, torsional vibration of unknown magnitude:

- In transmission lines and other electrical grid components inductivities and capacities exist, that can form LC oscillating circuits
- The eigenfrequencies f_{el} of such oscillating circuits may be very low, e.g. for longer transmission lines
- Oscillations in the electrical network of frequency f_{el} lead to a subsynchronous excitation torque of frequency $f_{mech} = f_n - f_{el}$

  f_n: Grid frequency

- If f_{mech} coincides with one of the resonance frequencies of the turbo-generator and its connected shaft train, a SSR event may occur

Introduction: Sensor measurement principle

Torque cause tensile and compressive stress in the shaft,
oriented in a 45-degree cross

↓

Villari-Effect
(inverse magneto strictive effect)

$$X_v = f(\sigma)$$

↓

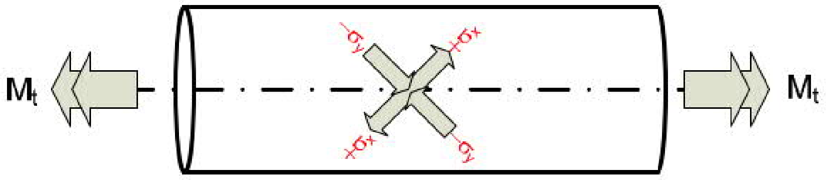
$$\mu = \mu_0(1 + X_v)$$

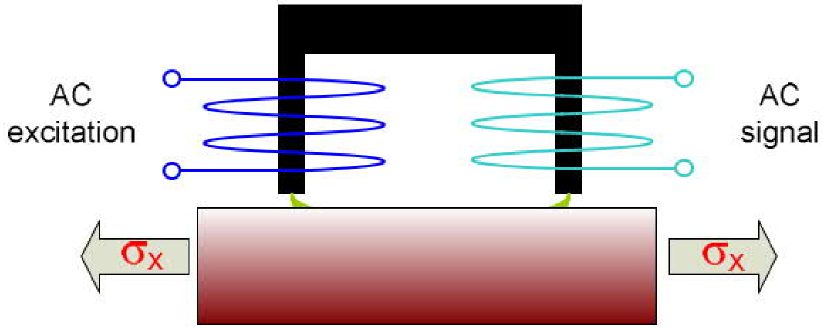
magnetic permeability of the shaft material is stress dependent.
This physical phenomenon can be exploited for the design of a non-contact torque sensor by the measurement of the magnetic flux

↓

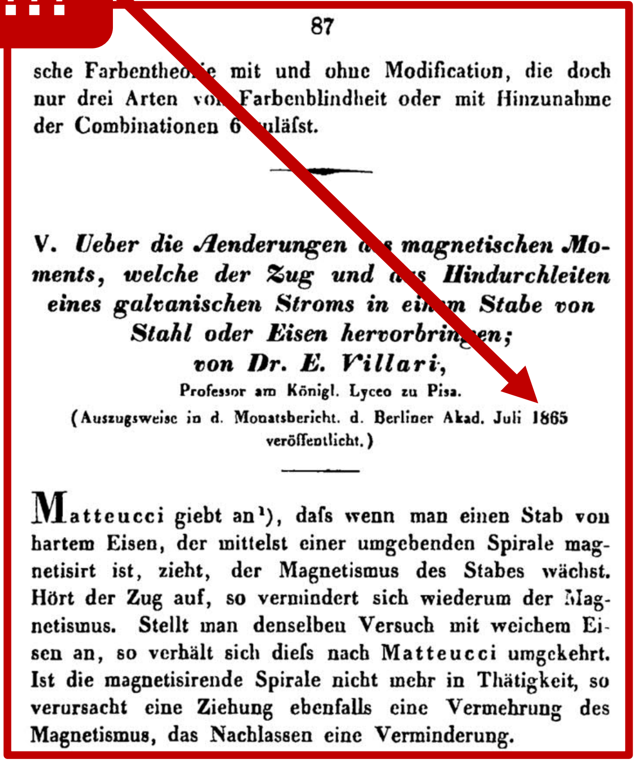
Magnetic induction B is proportional to magnetic field strength H

$$B = \mu * H$$





1865 !!!



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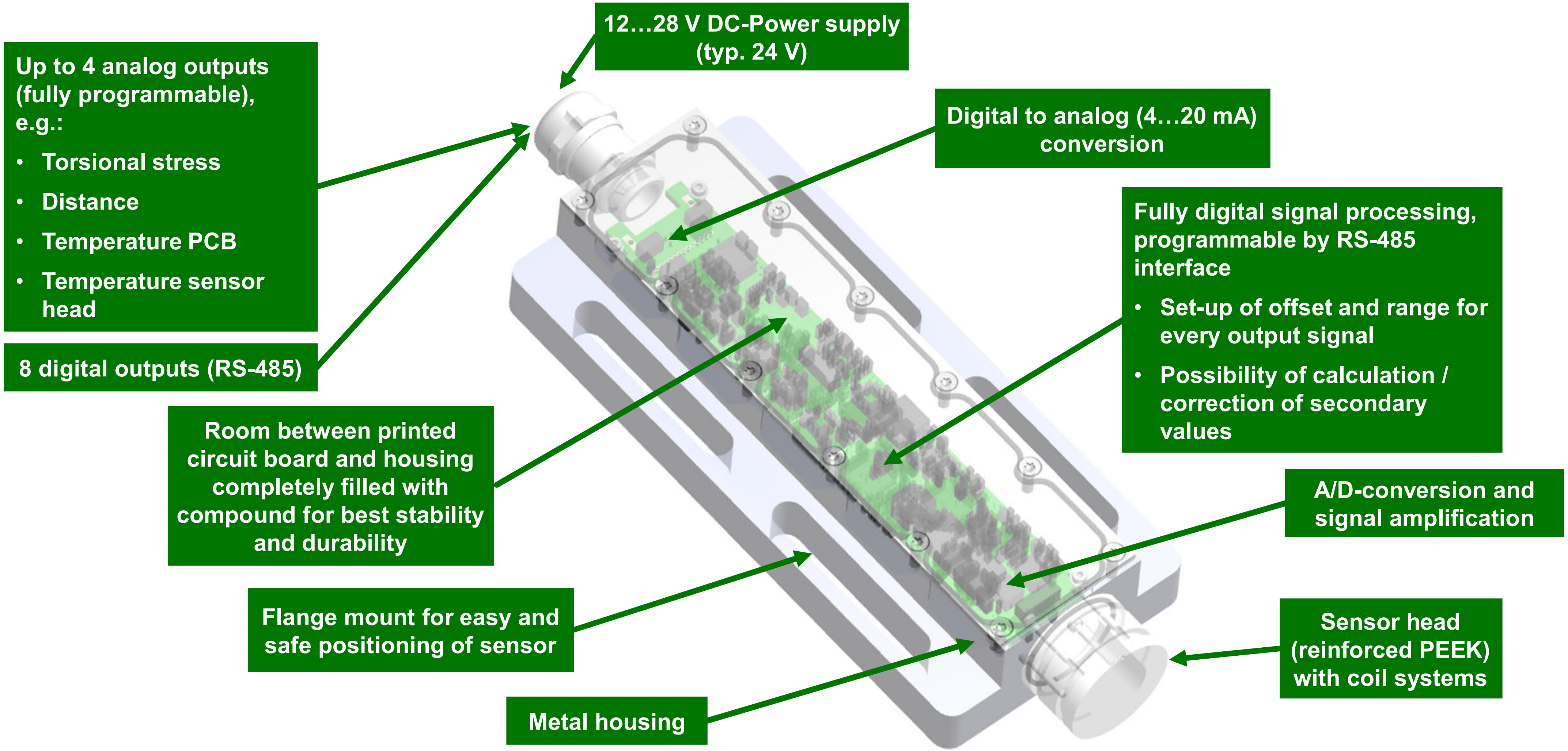
sche Farbentheorie mit und ohne Modification, die doch nur drei Arten von Farbenblindheit oder mit Hinzunahme der Combinationen 6 zuläfst.

V. *Ueber die Aenderungen des magnetischen Moments, welche der Zug und das Hindurchleiten eines galvanischen Stroms in einem Stabe von Stahl oder Eisen hervorbringen;* von Dr. E. Villari,
Professor am Königl. Lyceo zu Pisa.
(Auszugsweise in d. Monatsbericht. d. Berliner Akad. Juli 1865 veröffentlicht.)

Matteucci giebt an[1]), dafs wenn man einen Stab von hartem Eisen, der mittelst einer umgebenden Spirale magnetisirt ist, zieht, der Magnetismus des Stabes wächst. Hört der Zug auf, so vermindert sich wiederum der Magnetismus. Stellt man denselben Versuch mit weichem Eisen an, so verhält sich diefs nach Matteucci umgekehrt. Ist die magnetisirende Spirale nicht mehr in Thätigkeit, so verursacht eine Ziehung ebenfalls eine Vermehrung des Magnetismus, das Nachlassen eine Verminderung.

Sensor signal is also dependent on:
Material/microstructure, distance and temperature!

Digital Torsion Sensor DTS 2004



Adjustment of sensitivity for power plants in load operation

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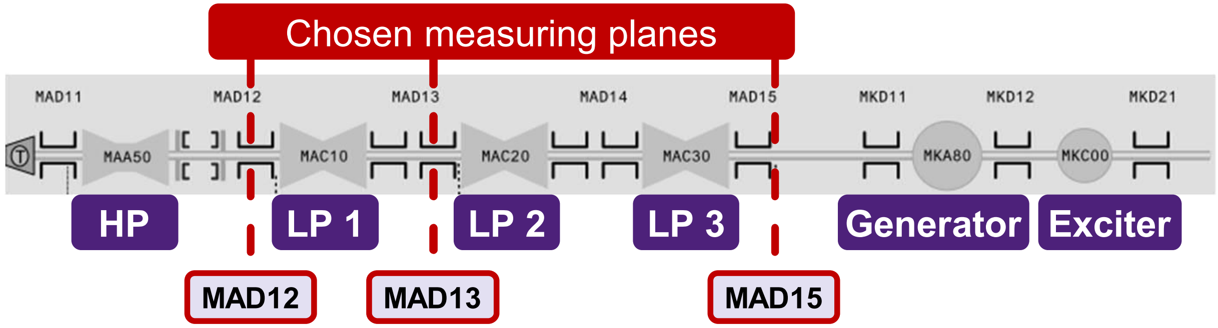
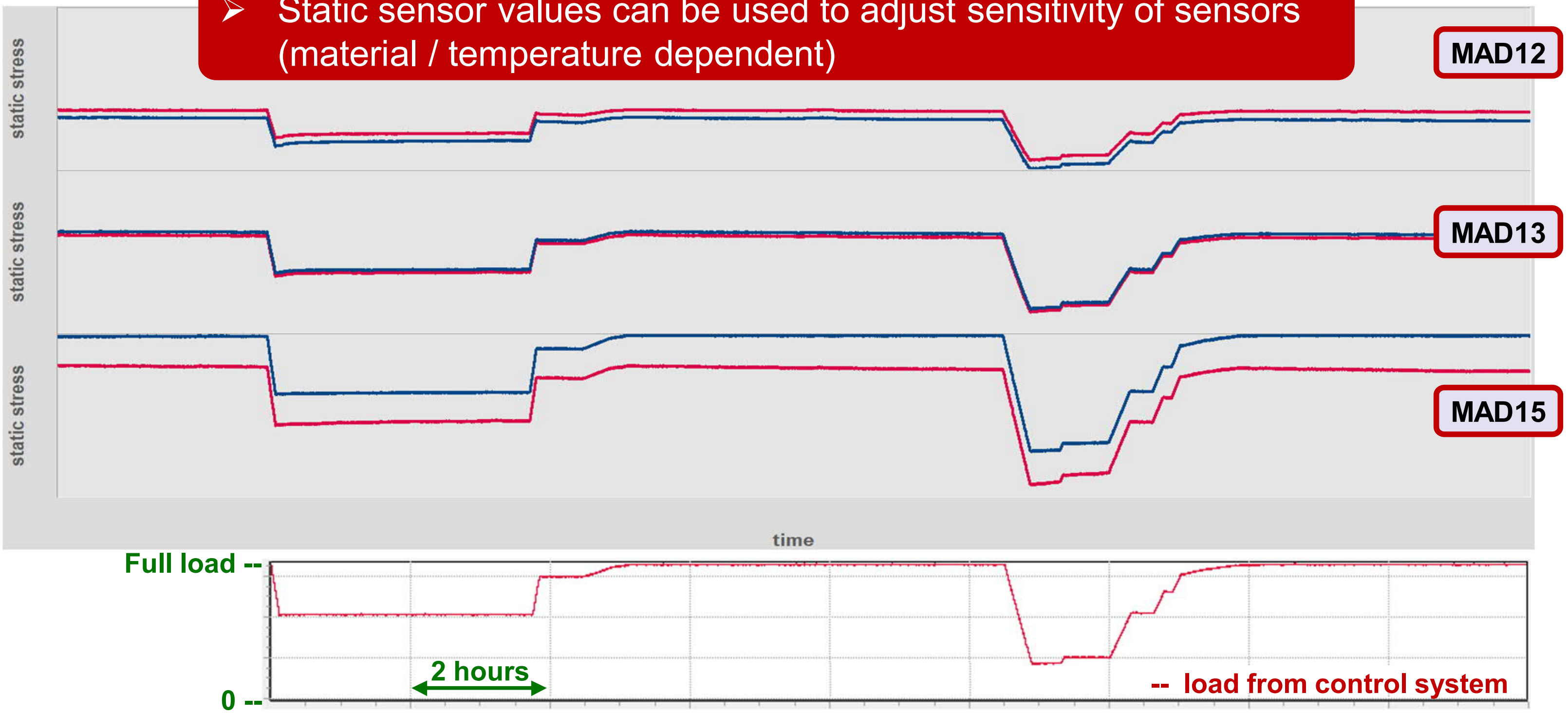


- Static sensor values can be used to adjust sensitivity of sensors (material / temperature dependent)



- **The sensitivity of the sensors depends, among other things, on the material**
- **Therefore, a one-time individual setting of the sensor sensitivities is necessary for each rotor**
- **This can be done in power plants by comparing the static portion of the sensor signal with the current mechanical power**

Comparison with conventional methods

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Methods based on angular differences or speeds, inductively (teeth/grooves on the shaft) or (laser-) optically determined	Strain gauges on the shaft and transmission of signals by telemetry	Touchless, magneto-strictive sensor
Advantage • Proven technique	**Advantages:** • Proven technique • Direct method	**Advantages:** • Direct method • Easy to retrofit • Suitable for continuous monitoring • Functionality proven
Disadvantages: • Indirect method • Teeth / strip tapes necessary • Dirt susceptible (optics)	**Disadvantages:** • Elaborate and expensive telemetry necessary • Mainly used in prototypes / on test fields	**Disadvantages:** • So far, less common in the power plant market • One-time determination of sensitivity necessary

Configuration of Torsional Vibration Monitoring System in a nuclear power plant

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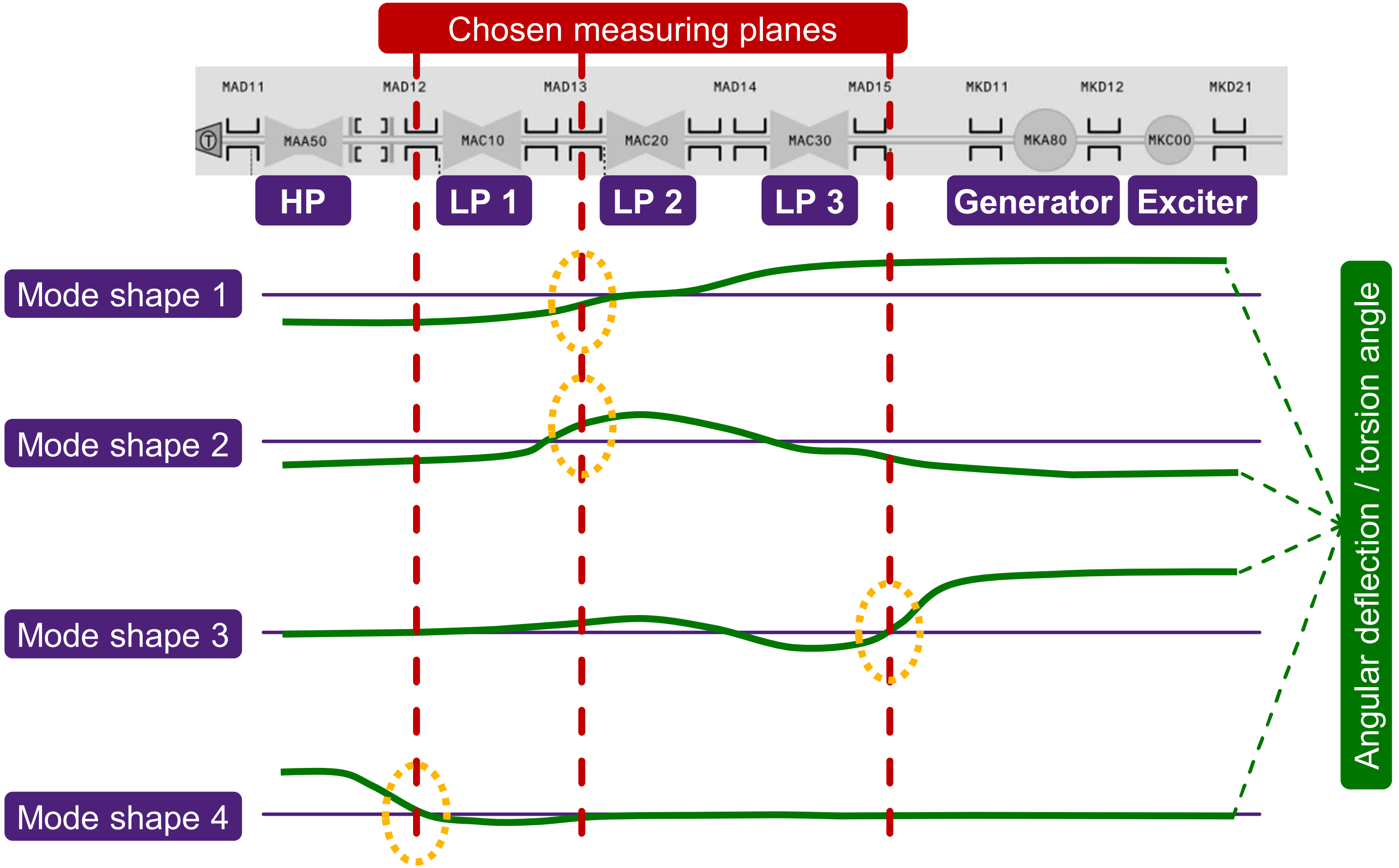
SST-9000 steam turbine



Measuring planes chosen by:

- Accessibility
- High gradients in angular deflection at certain modes
  - ➢ High torsional stresses
  - ➢ High measuring signal

Synchronization event (FFT waterfalls)

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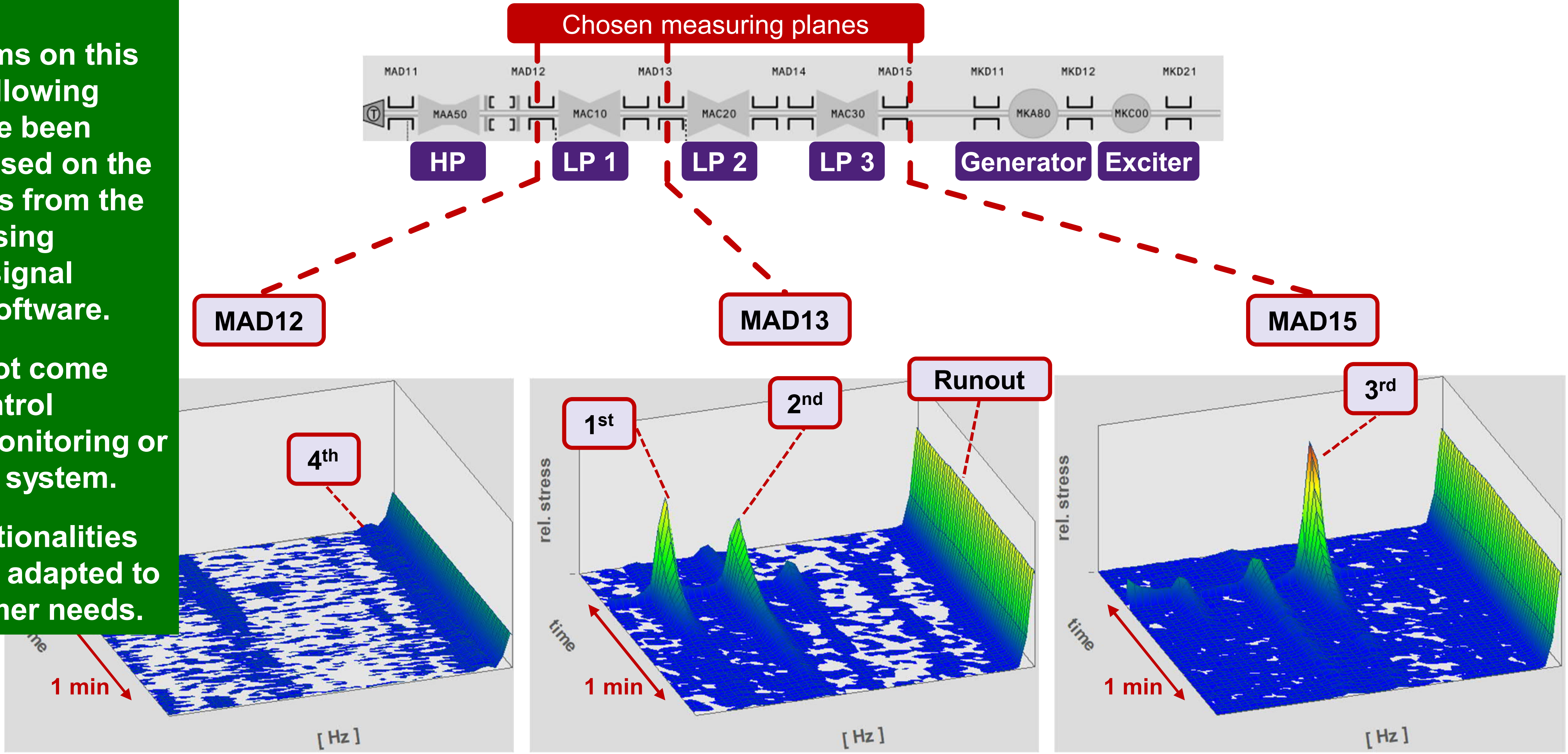
Remark:

All diagrams on this and the following slides have been created based on the raw signals from the sensors using standard signal analysis software.

They do not come from a control system, monitoring or protection system.

Their functionalities have to be adapted to the customer needs.



Complete load rejection from 30% load (FFT waterfalls)

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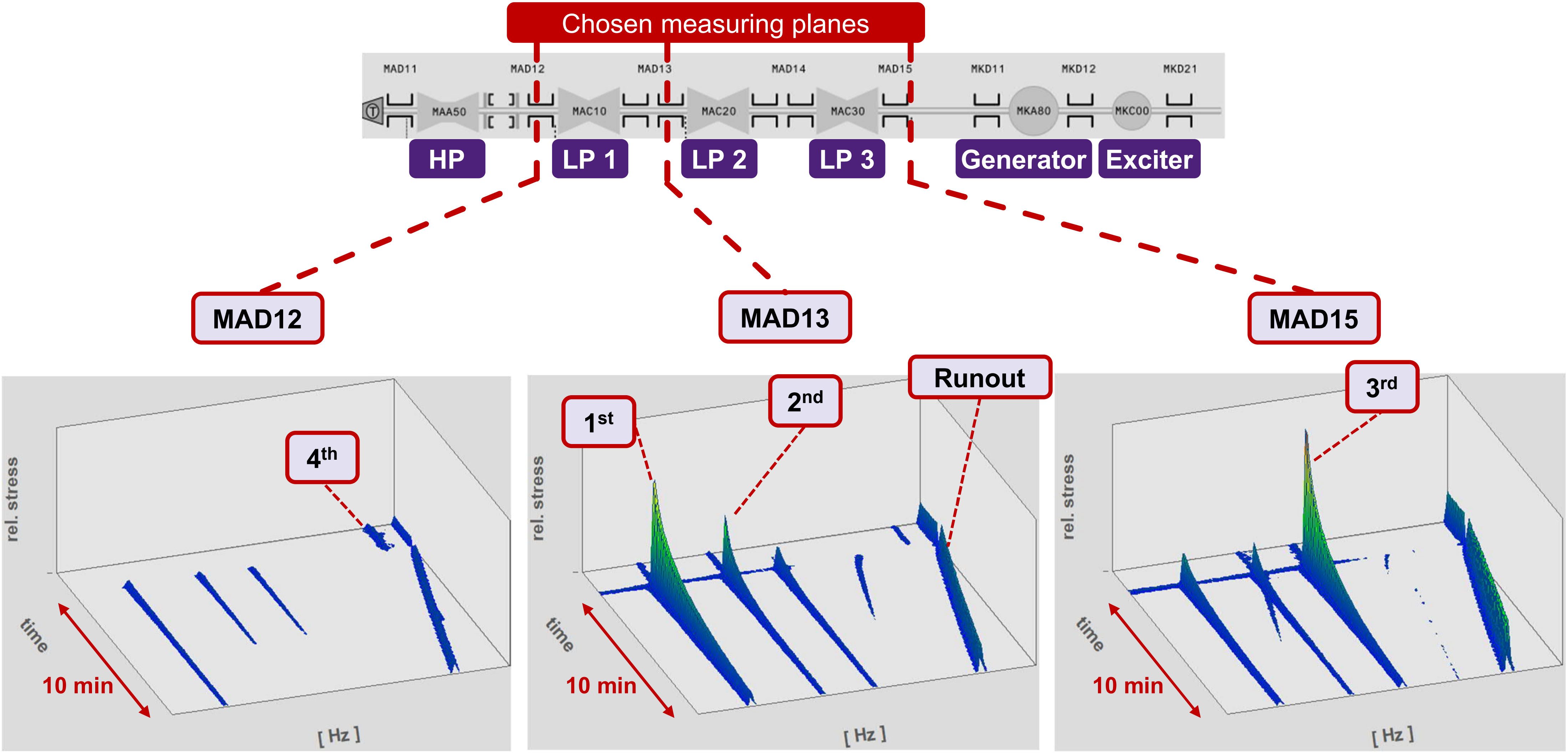
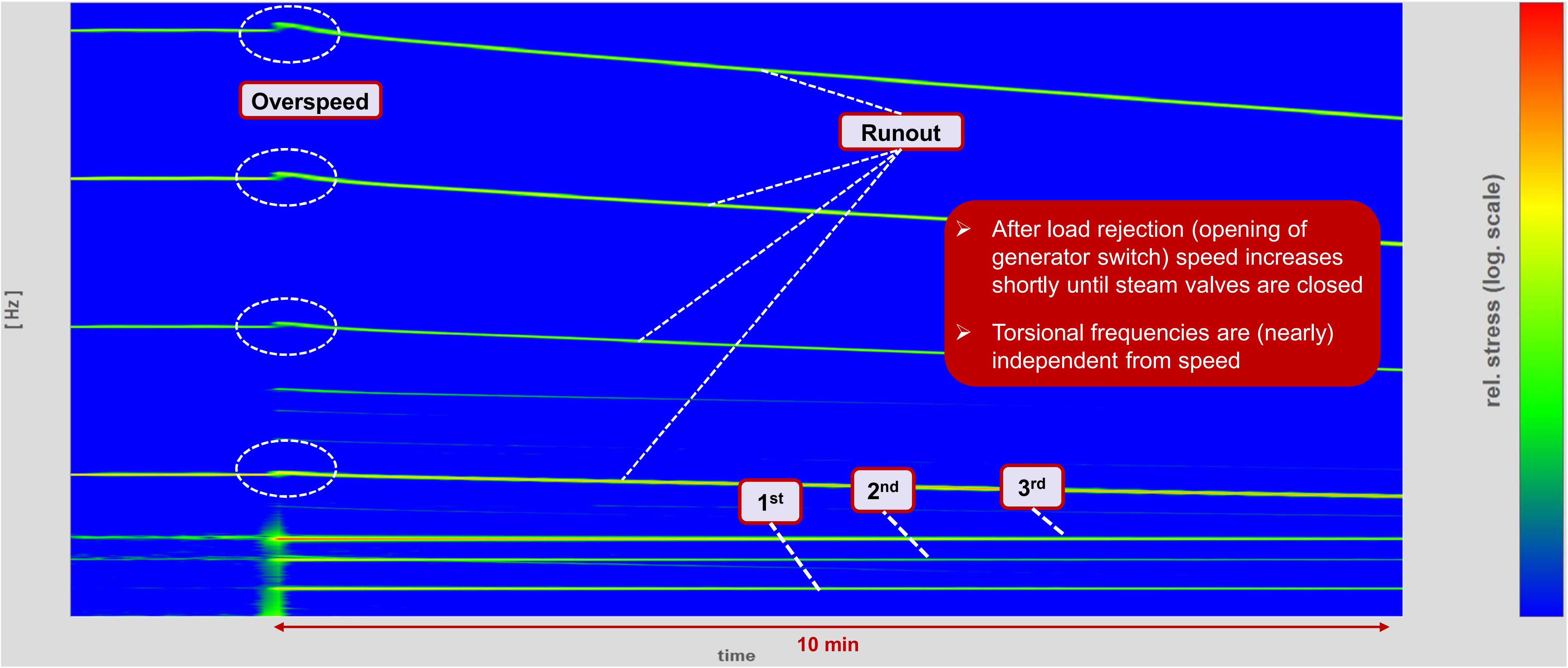


Ingo Balkowski , Energiforsk Conference, Stockholm, November 9th, 2023 11

Complete load rejection from 30% load (color plot)



- After load rejection (opening of generator switch) speed increases shortly until steam valves are closed
- Torsional frequencies are (nearly) independent from speed

Complete load rejection from 30% load (Mode amplitudes over time derived from FFT waterfall)

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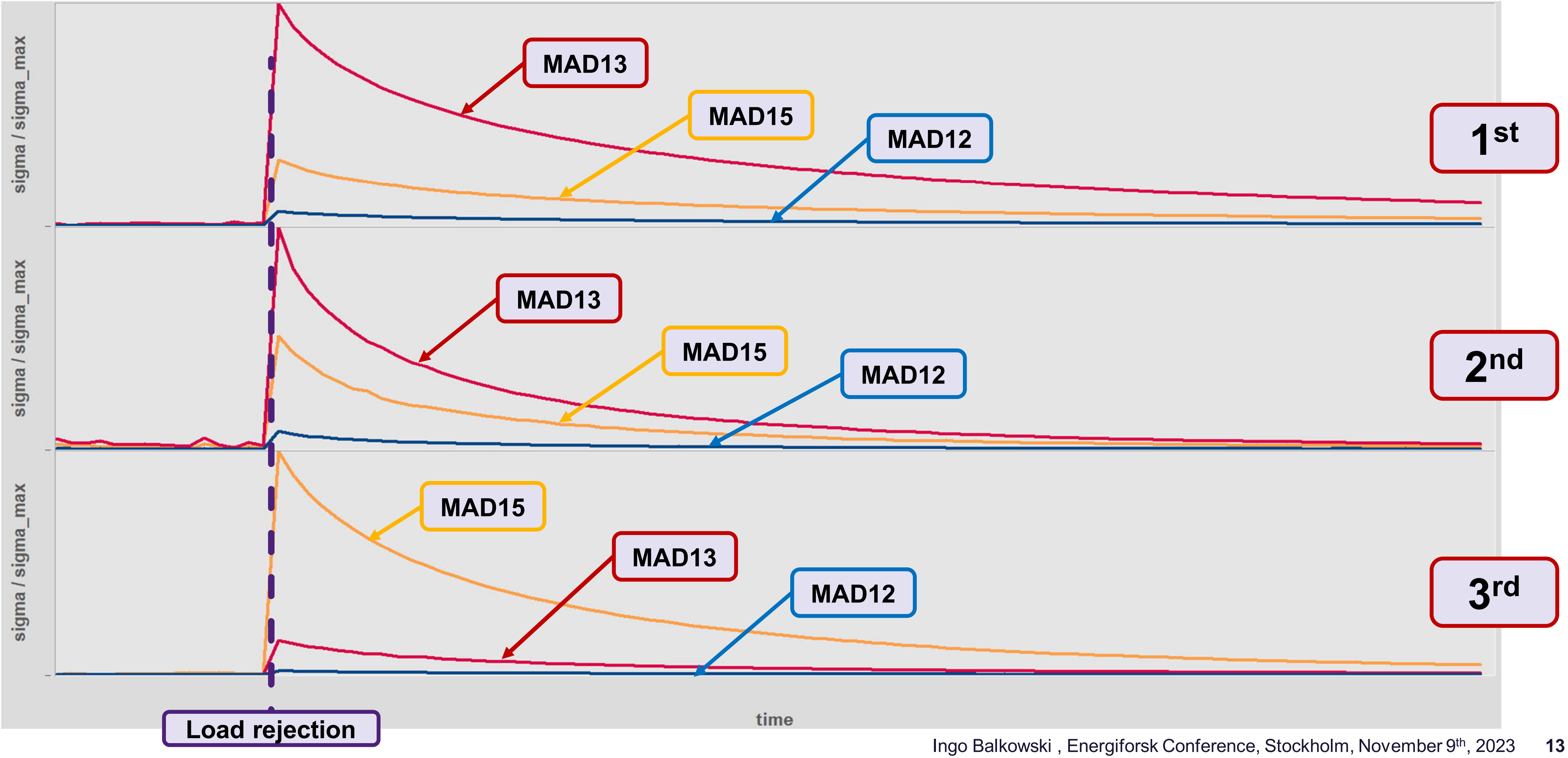
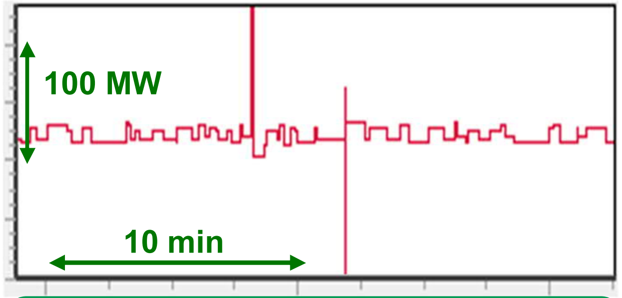
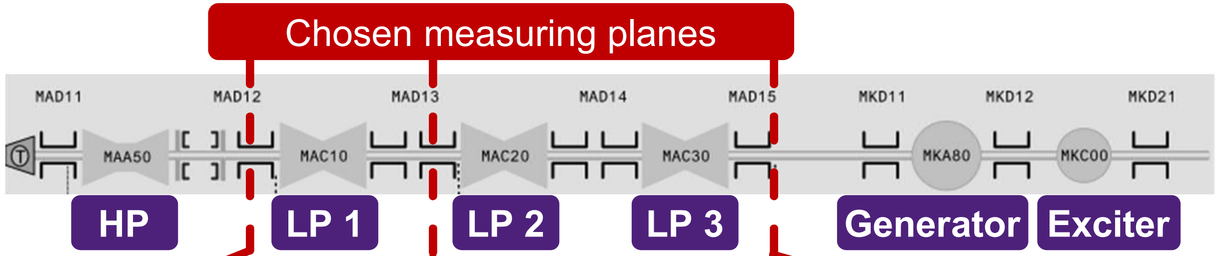
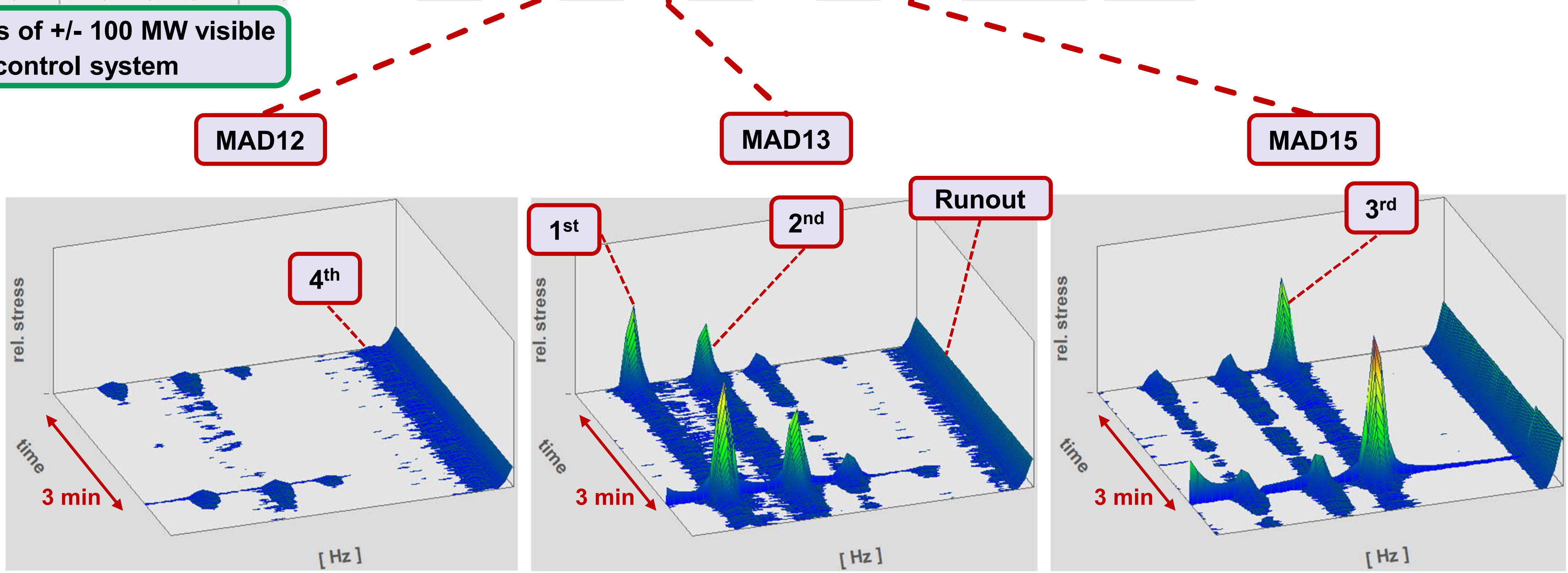


Grid event during full load operation (FFT waterfalls)



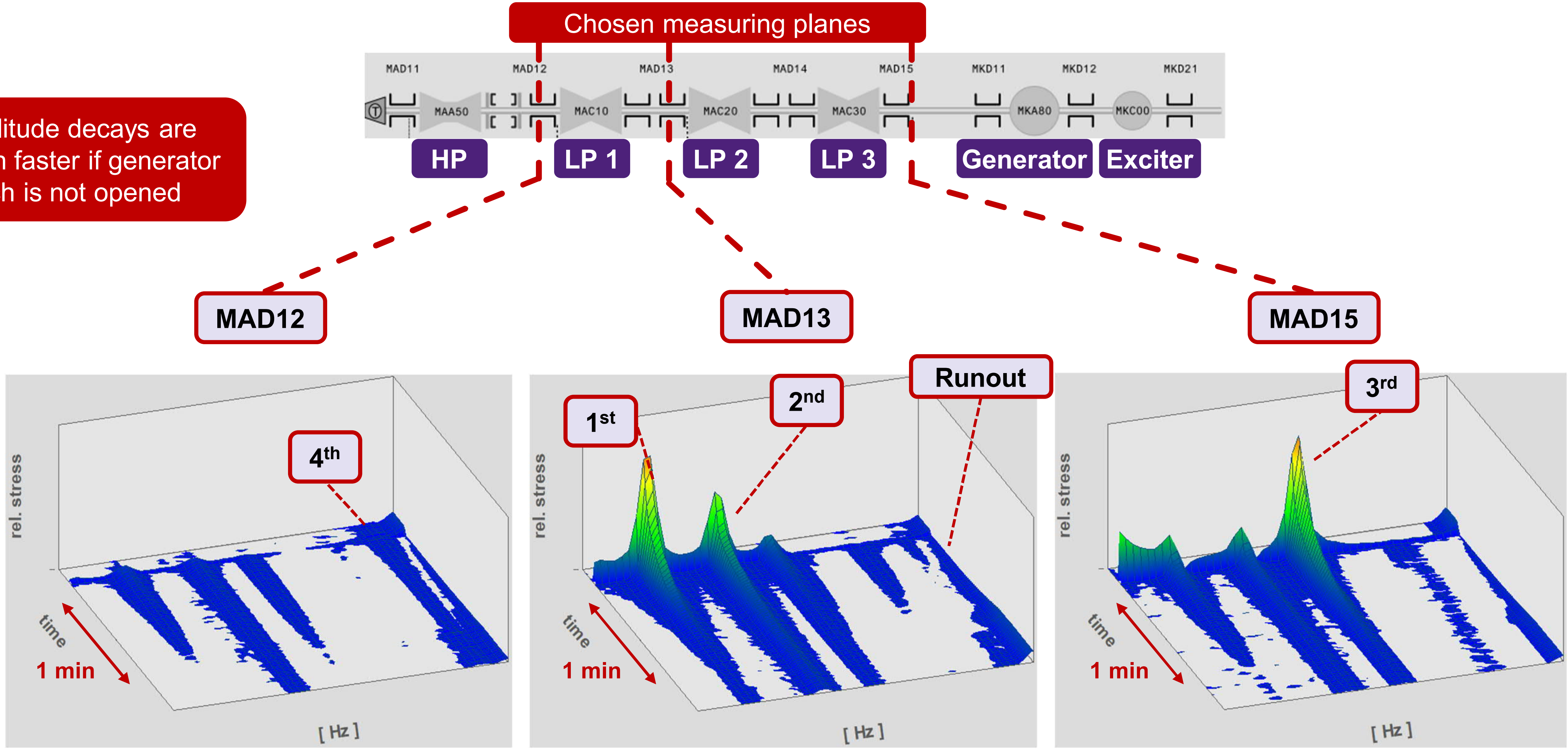
Load peaks of +/- 100 MW visible in control system



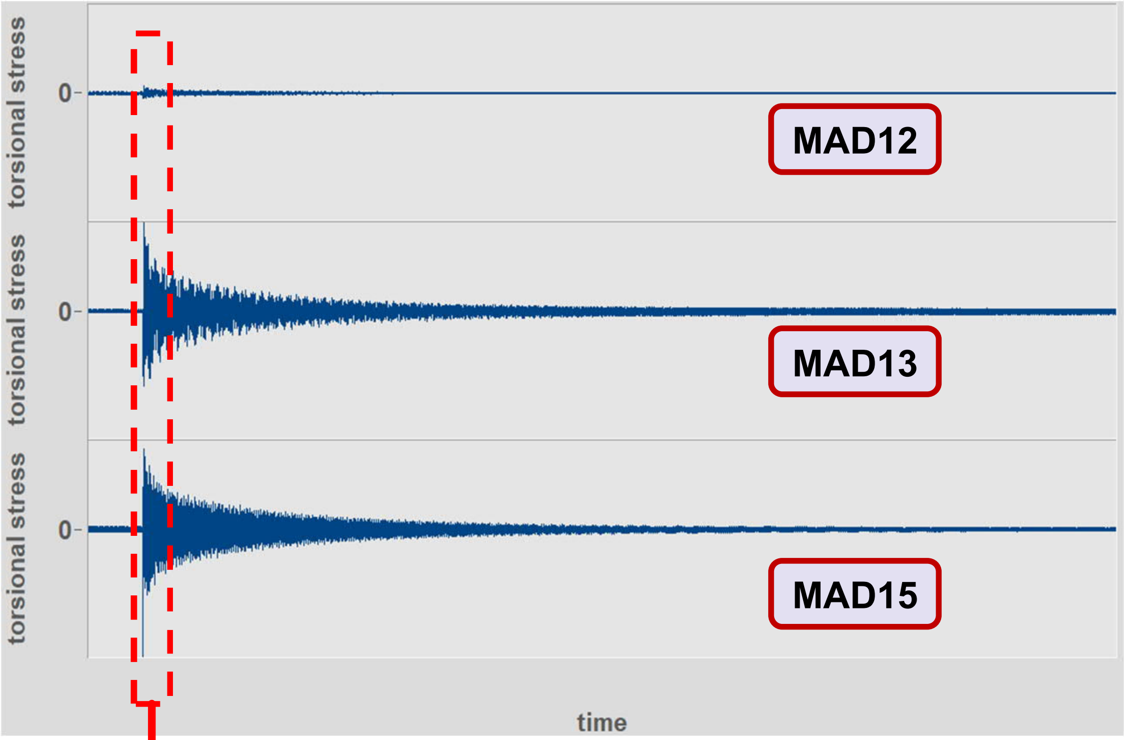


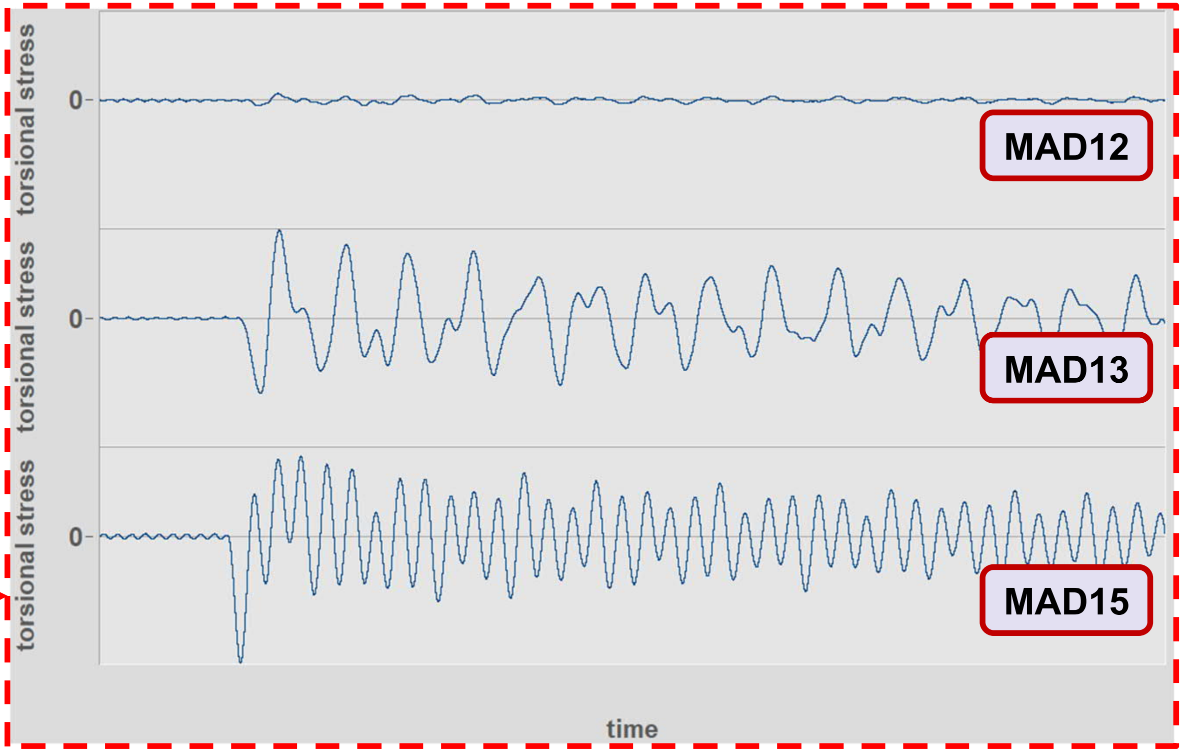
Load rejection from 100% load to house-load (FFT waterfalls)

- Amplitude decays are much faster if generator switch is not opened



Load rejection from 100% load to house-load (Bandpass-filtered time signals)





Detection of real SSR-events during the preparation phase of a planned FRT-test

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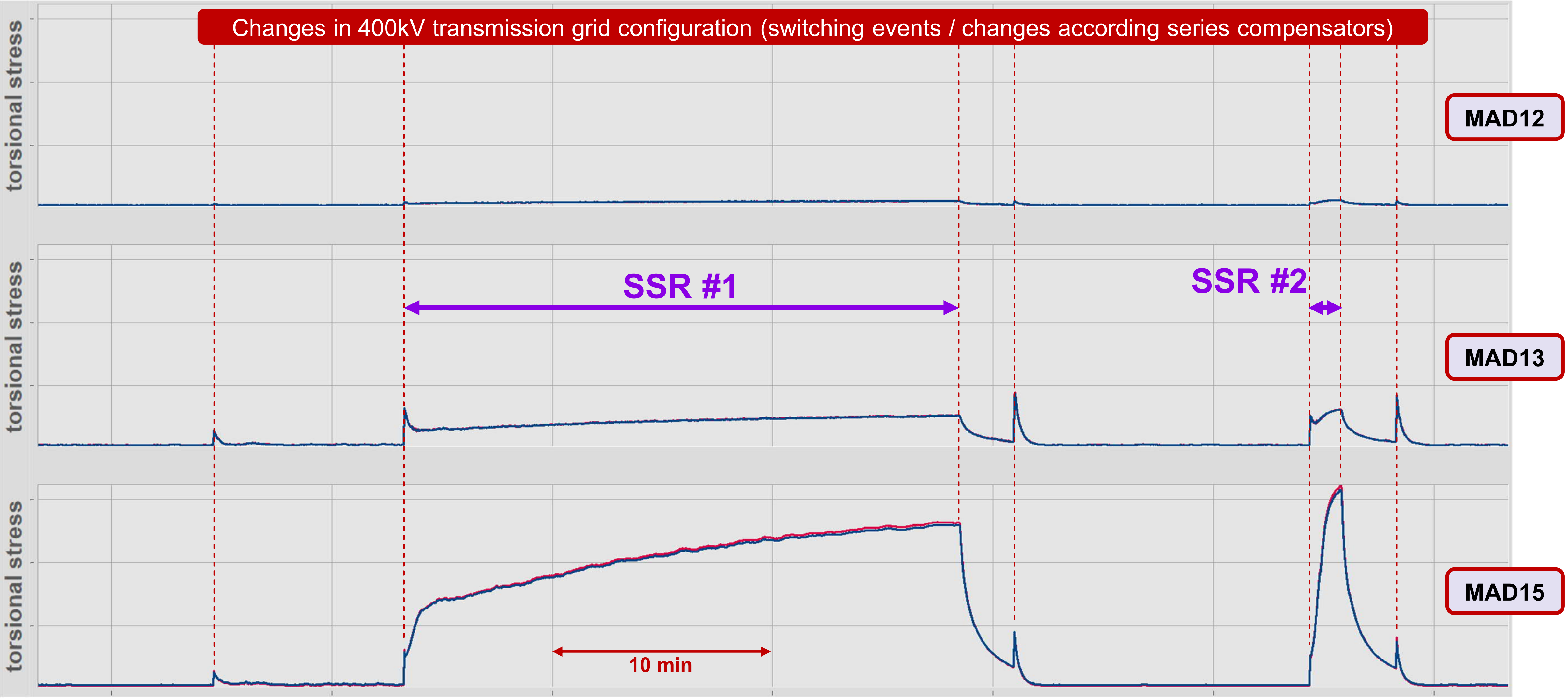
During the preparation phase of a planned FRT (Fault Ride Through) test real SSR events occurred:

- During the commissioning phase of the nuclear power plant a so-called Fault Ride Through (FRT) test was planned in order to prove that a short-time grid event in the 400kV transmission line near the power plant (e.g. a short circuit) does not lead to a trip of the power plant (according to the grid code)
- Just for the case that this test would be not successful and the power plant would trip, the impact on the transmission grid had to be limited.
- Thus, a smaller grid around the power plant with a limited number of consumers was planned to be built up by disconnecting this test grid from the overall grid at several substations.
- During building up this test grid by the transmission grid operators two real SSR events occurred and were recorded by the measurement systems.

  ➢ **See following slides**

Torsion-amplitudes vs. time during FRT preparations (band pass filter applied)



Torsion vs. time during FRT preparations (low pass filter applied)

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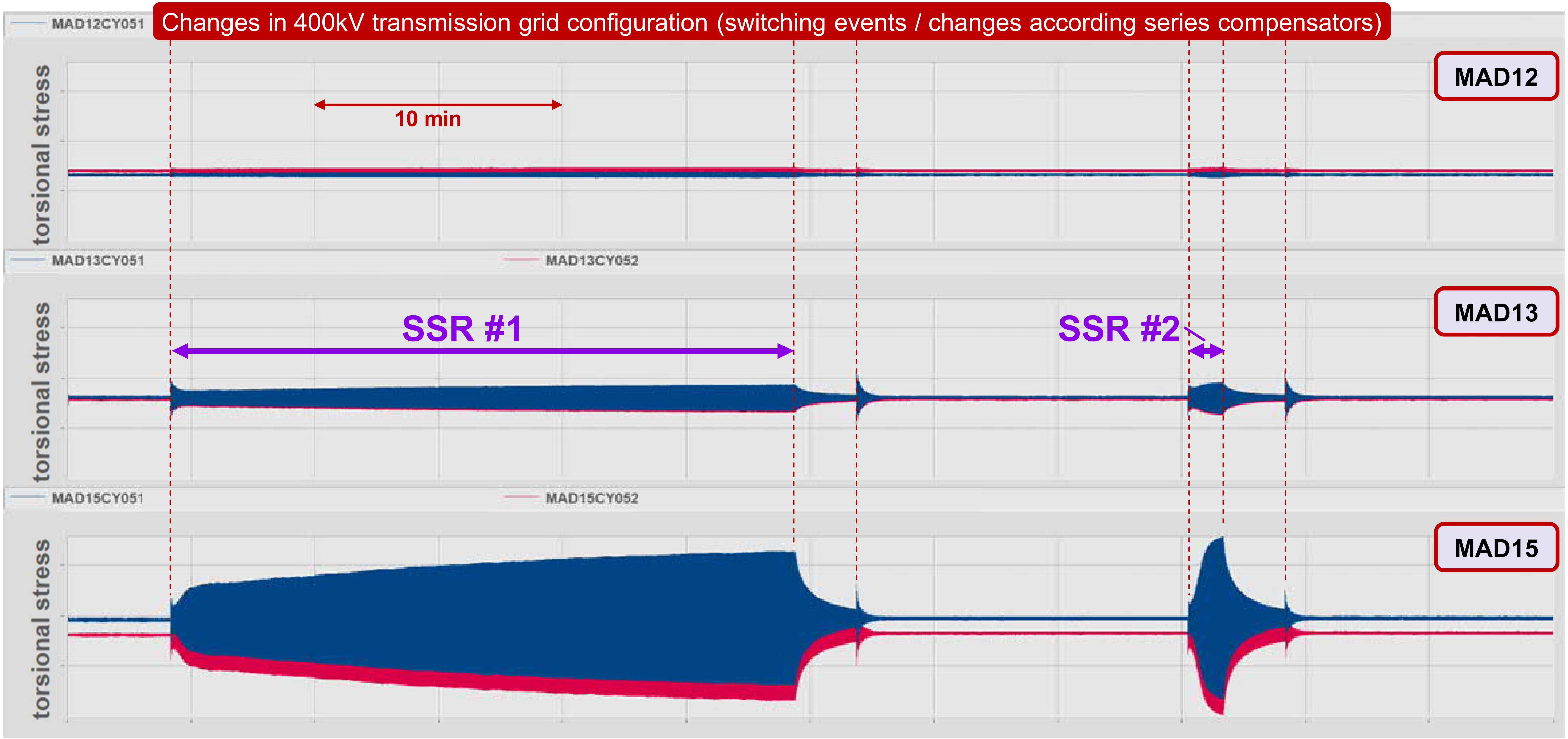
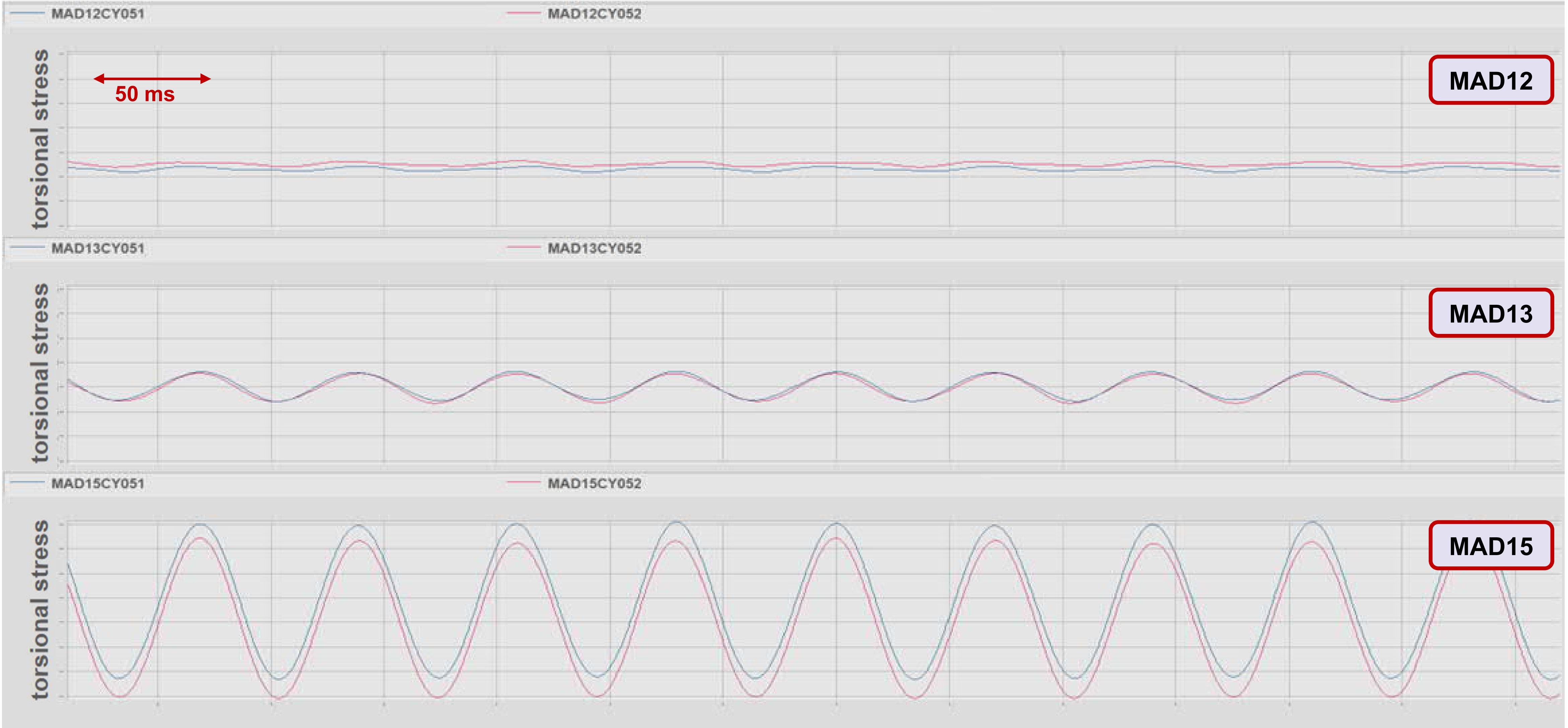
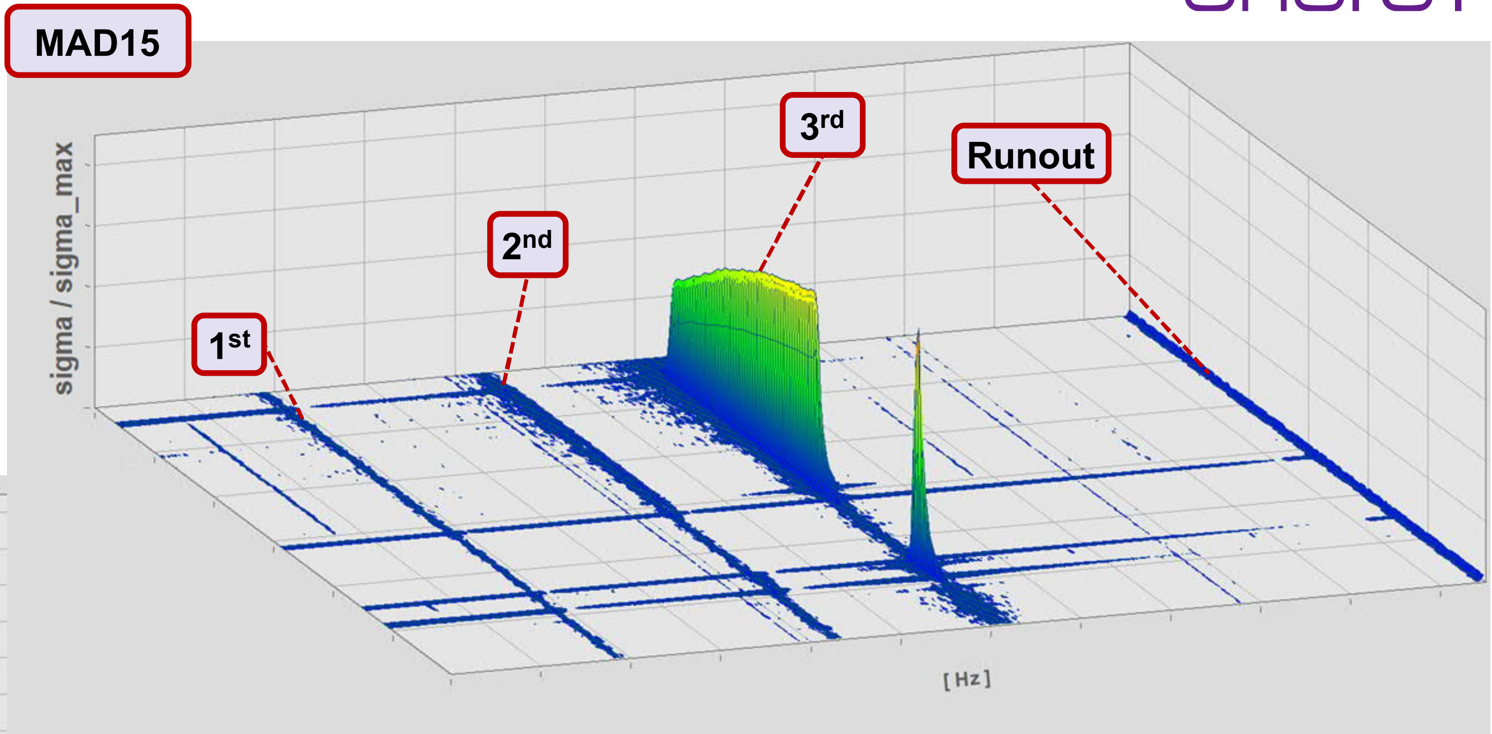
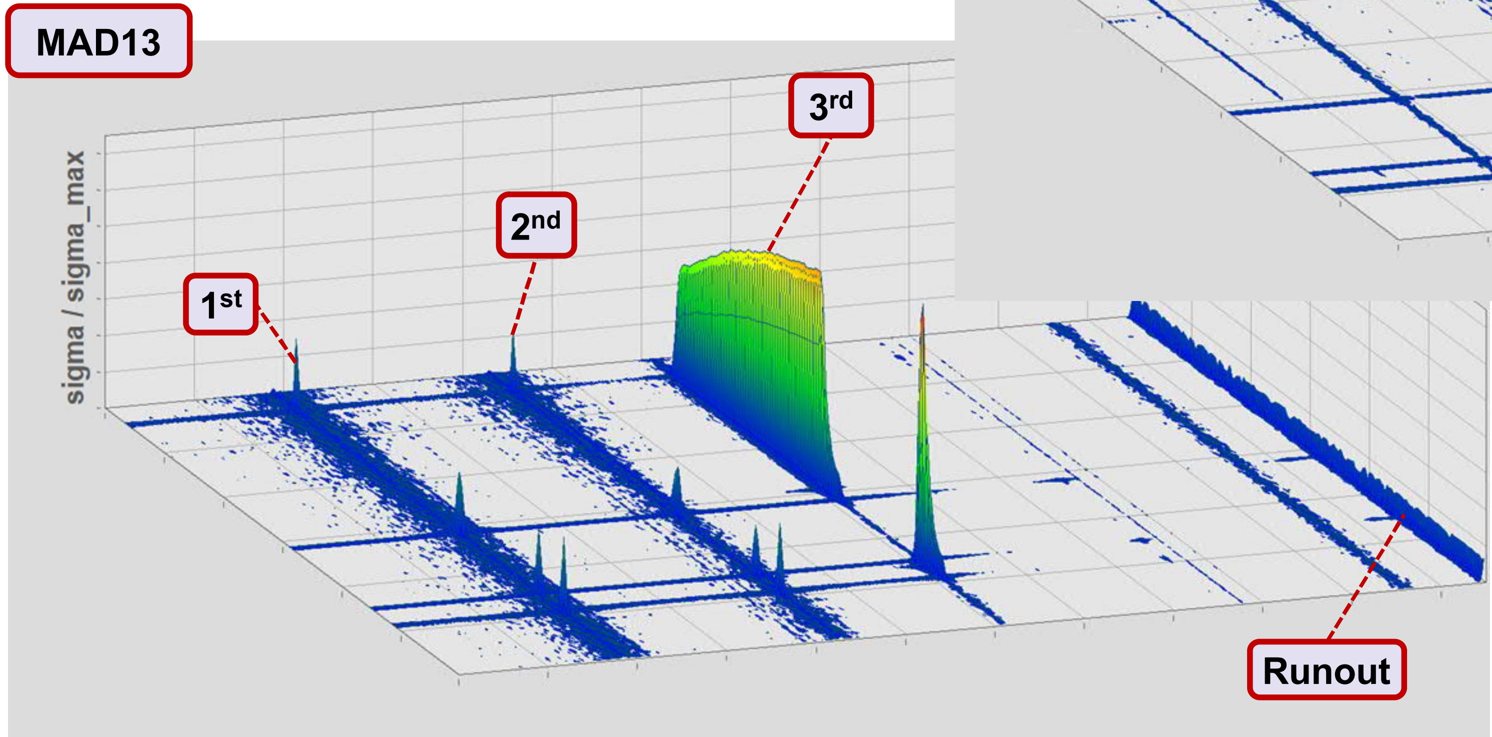


Torsion vs. time during FRT preparations (low pass filter applied), detail



Torsion-0-pk-waterfall diagrams during FRT preparations, MAD13 and MAD15



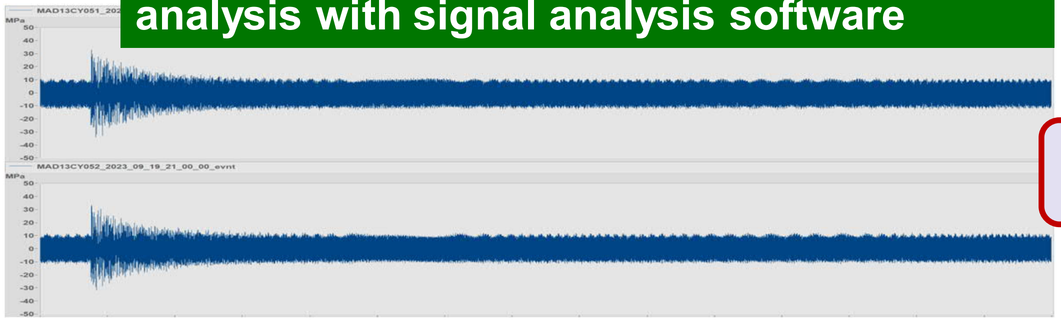


- During SSR torsion signals are dominated by only one Eigenfrequency (here: 3rd) that is excited from the grid
- 1st and 2nd torsional Eigenfrequency only remarkable at switching events (impulse excitation)

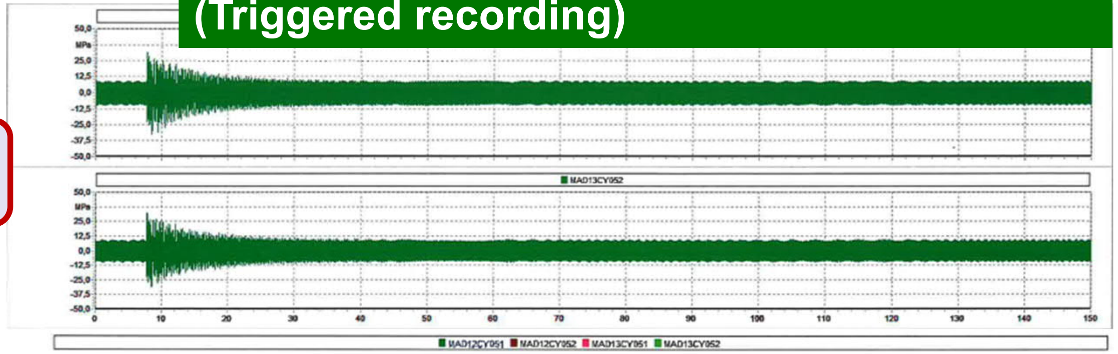
Comparison between offline raw sensor signal analysis and VIBROCAM / VIB3000 analysis, MAD13 (Example: Grid event, Sept. 2023)

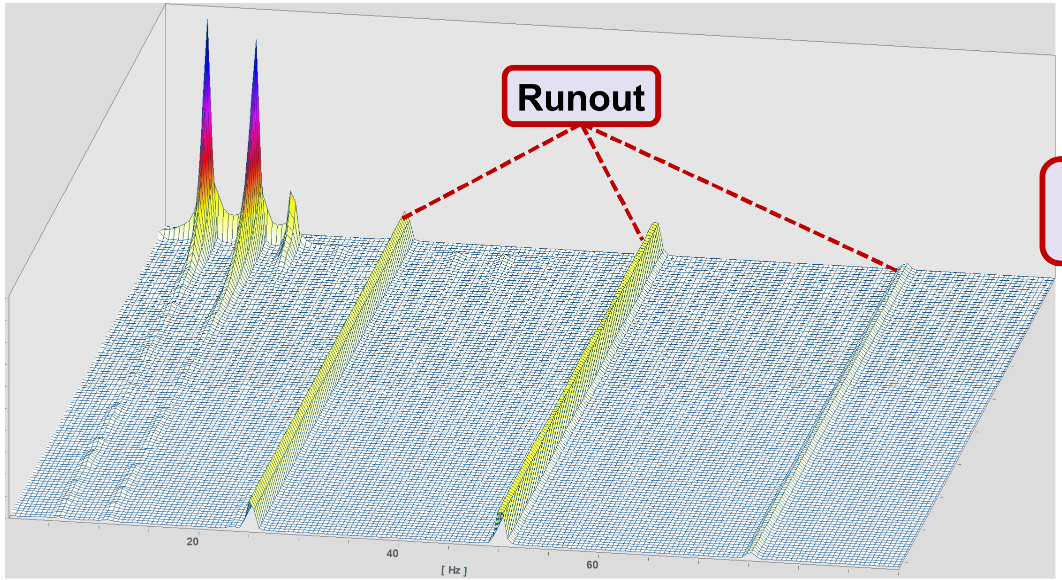
Sensor raw signals recording and offline analysis with signal analysis software

VIBROCAM / VIB3000 analysis of event (Triggered recording)

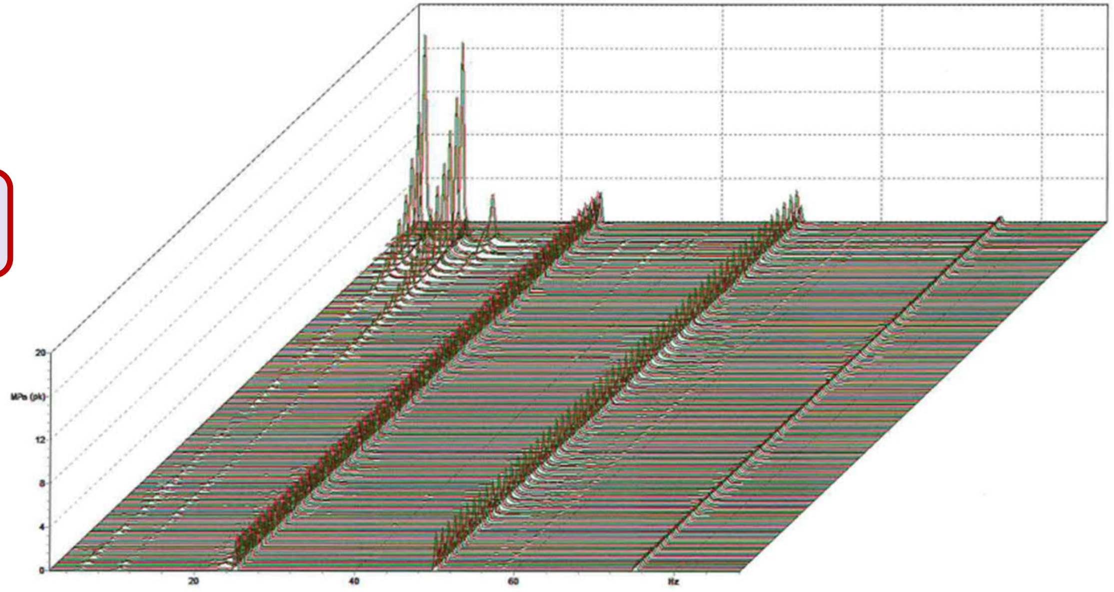


Signals vs. time

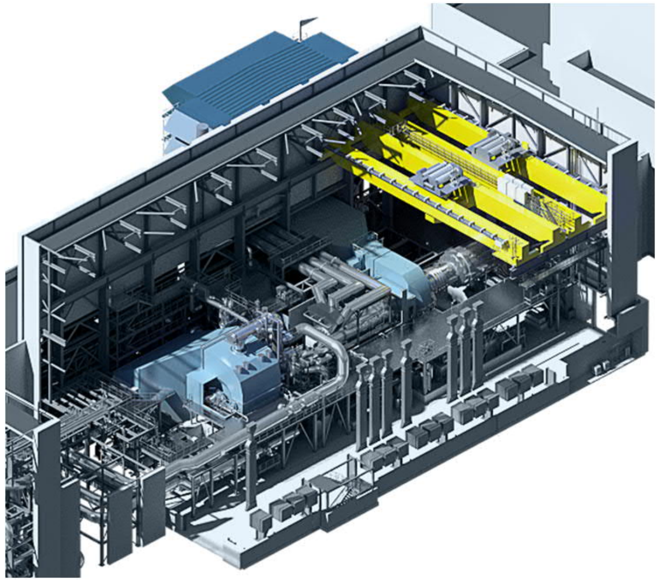


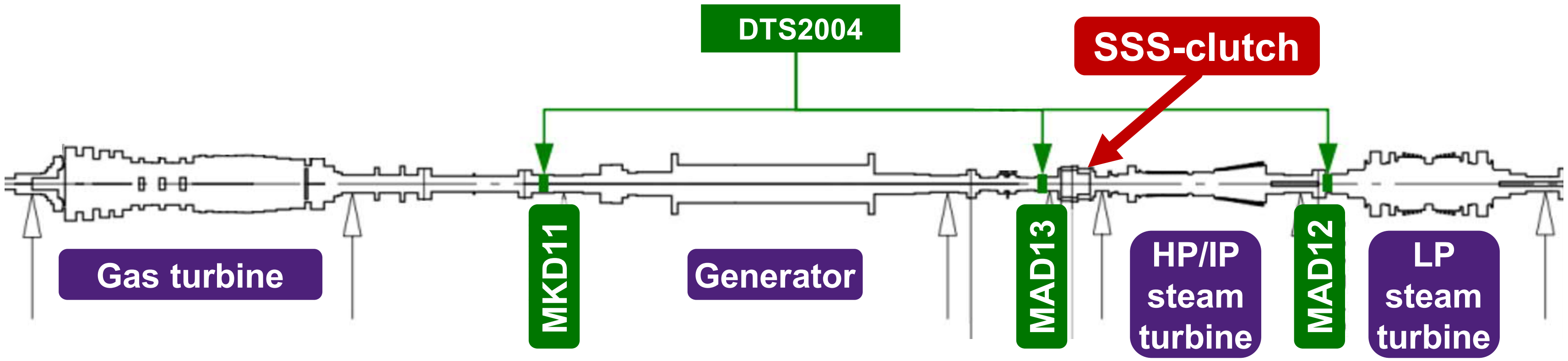


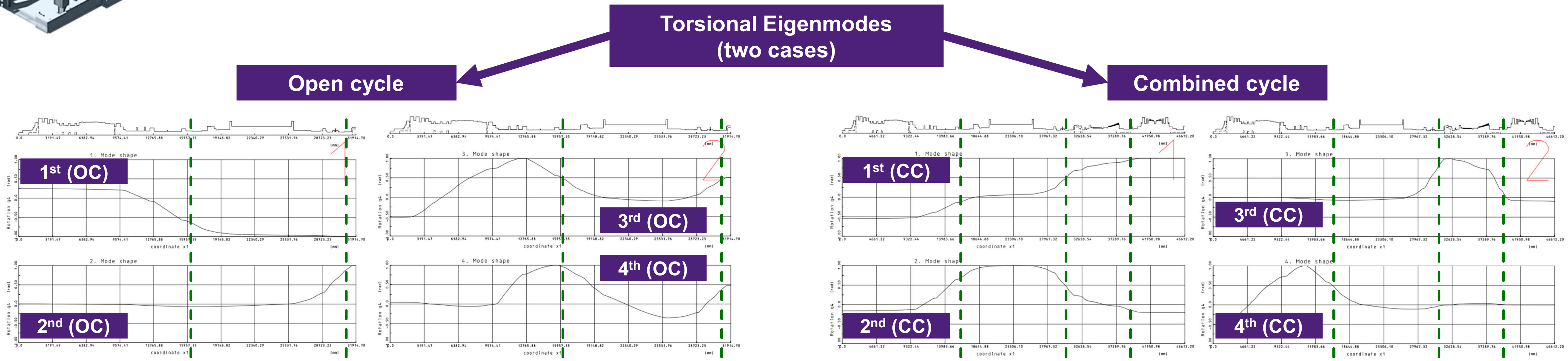
FFT waterfalls



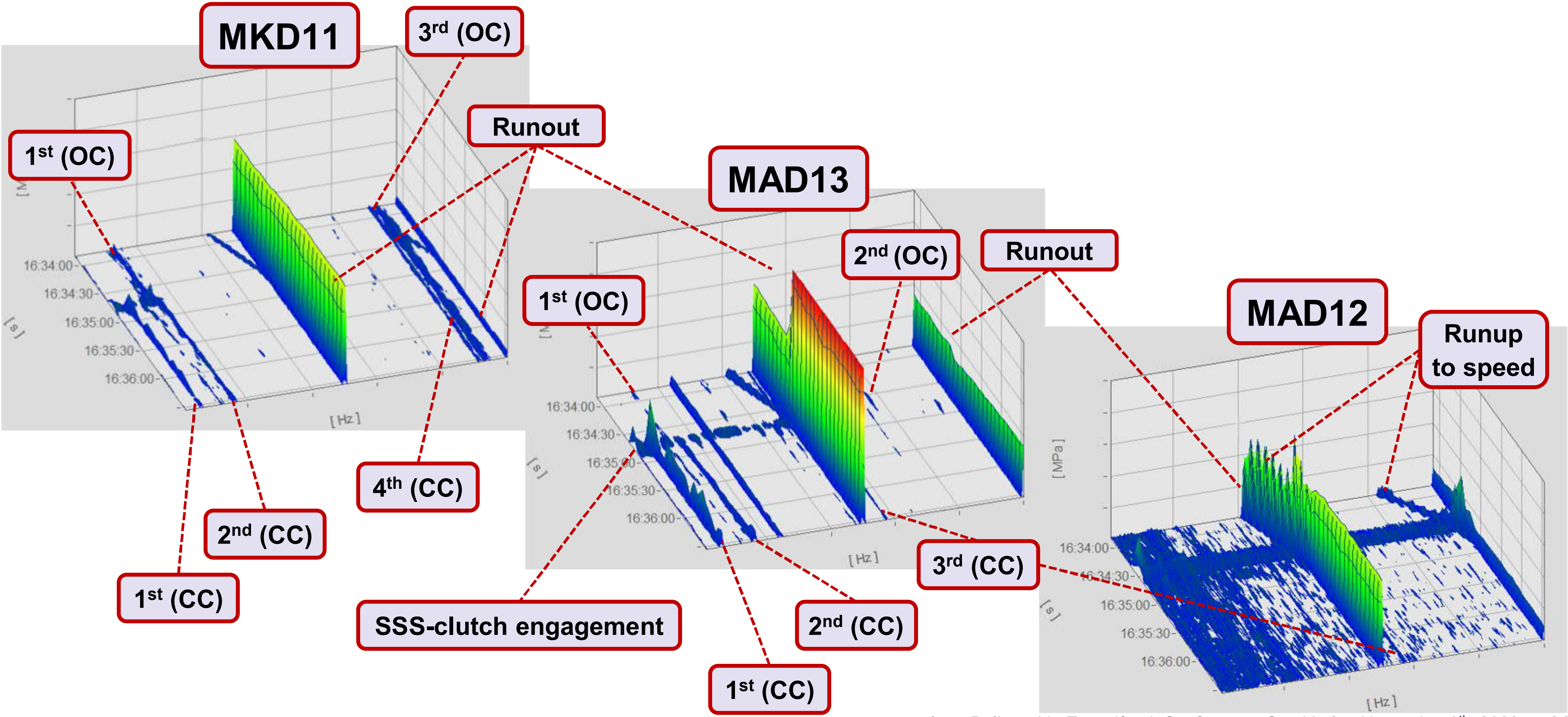
Configuration of Torsional Vibration Monitoring System in a Single Shaft Combined Cycle Power Plant (CCPP)



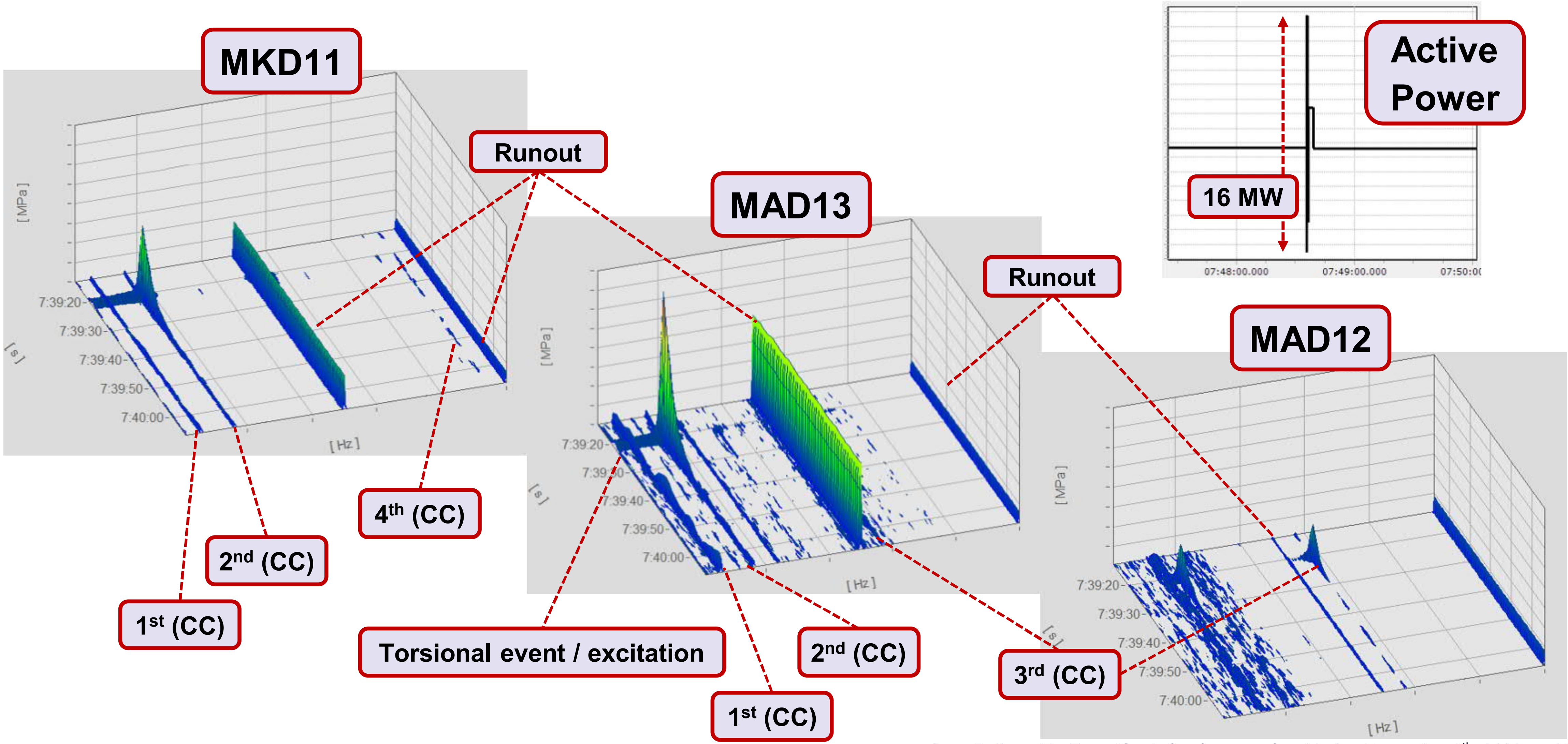




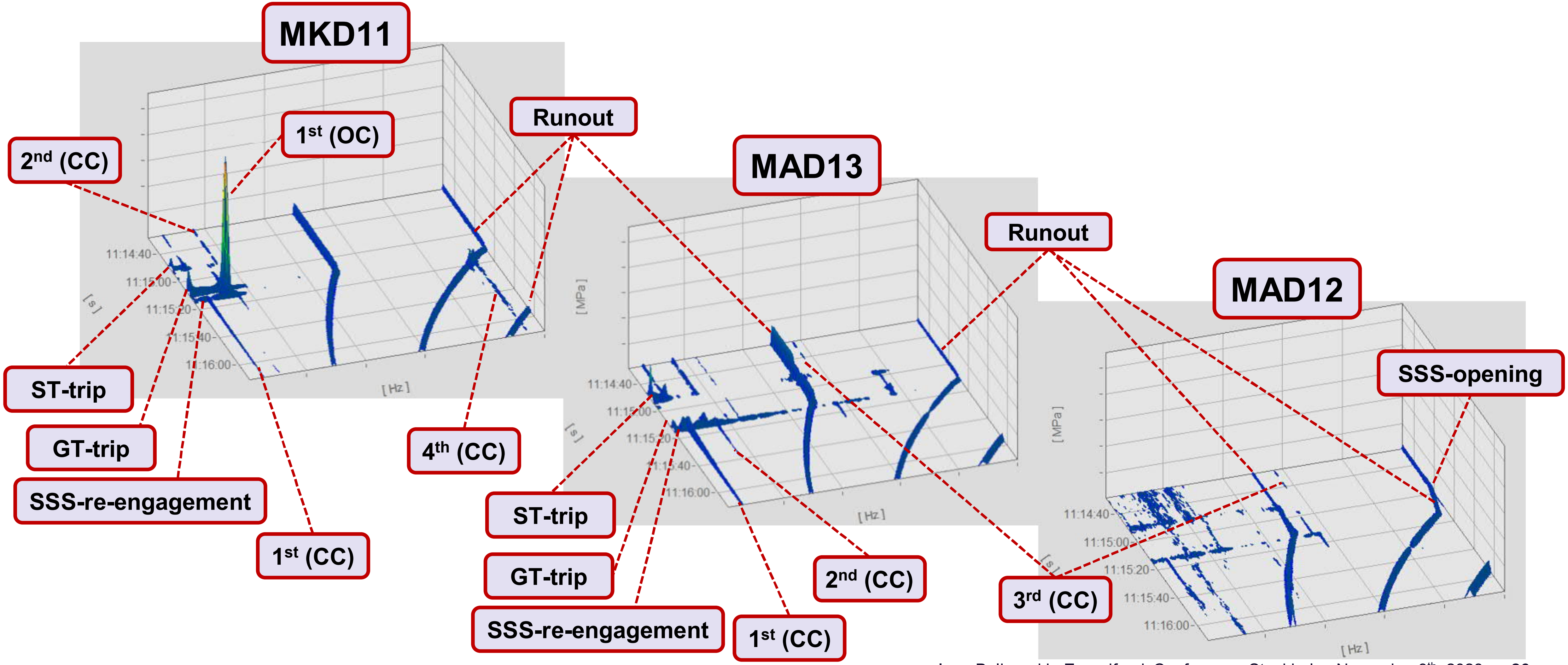
SSS-clutch engagement (FFT waterfall)



Baseload operation, 2nd mode (CC) -event (FFT waterfall)



Shutdown from full load (FFT waterfall)



Shutdown, MKD11 color plot

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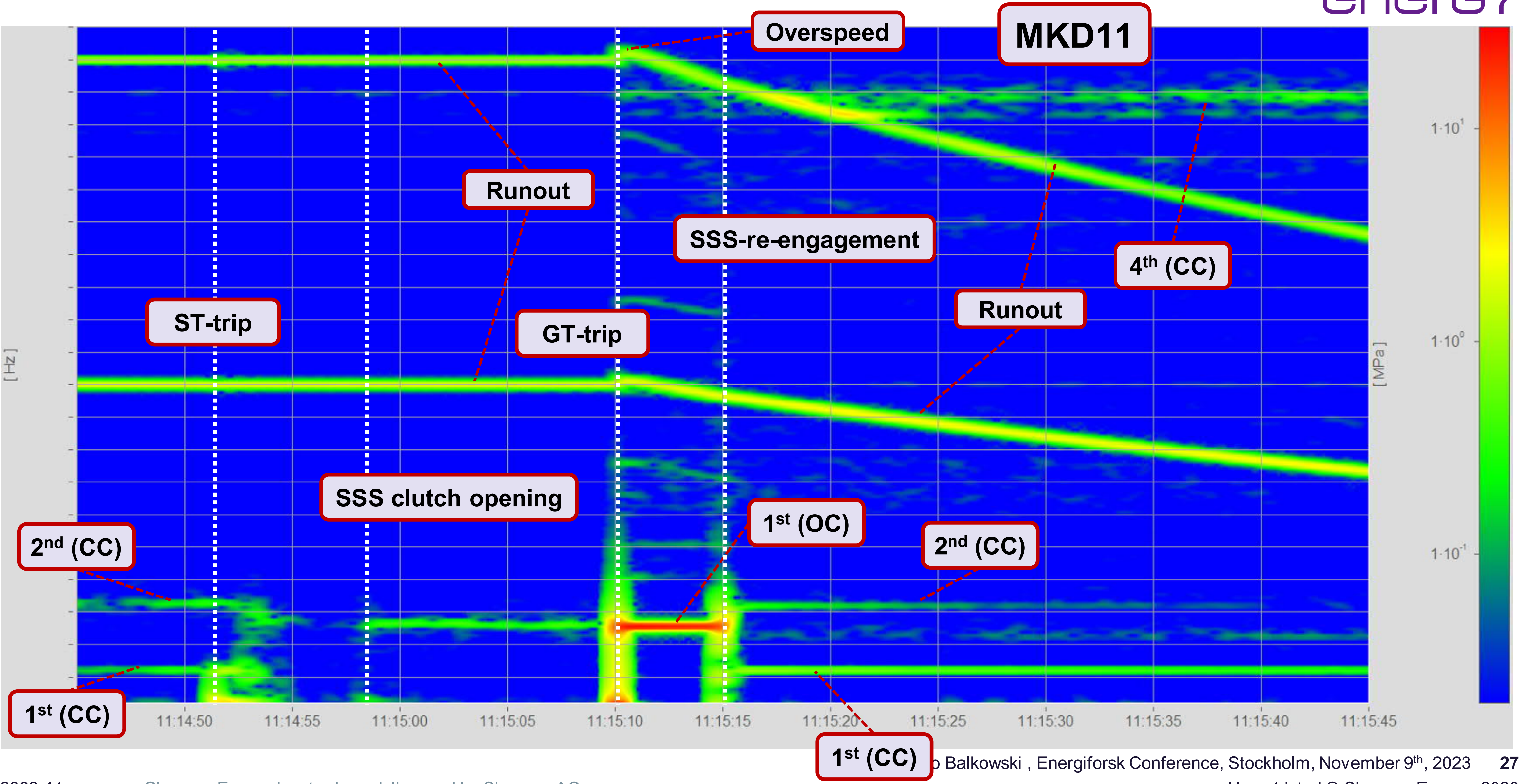

Configuration of Torsional Vibration Protection System at a Rotating Grid Stabilizer (RGS) with Flywheel

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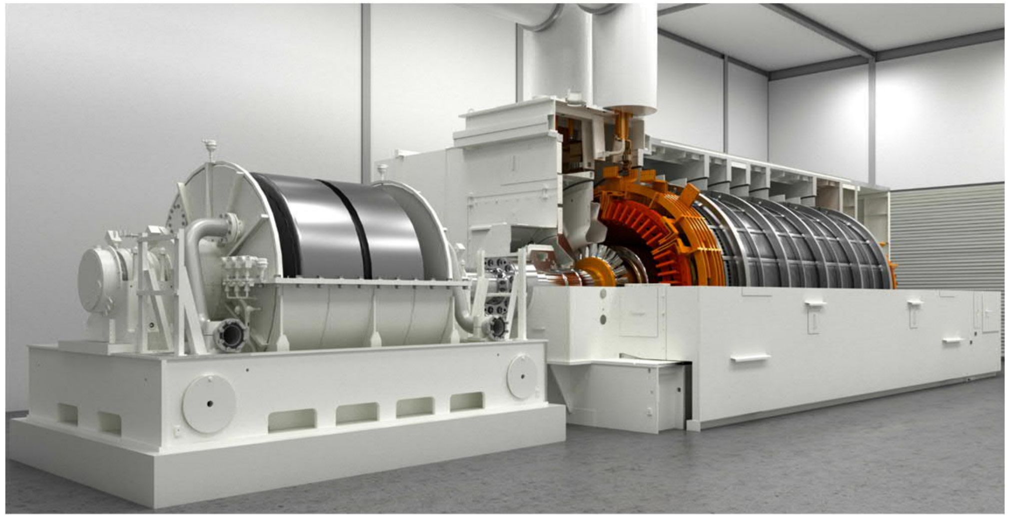
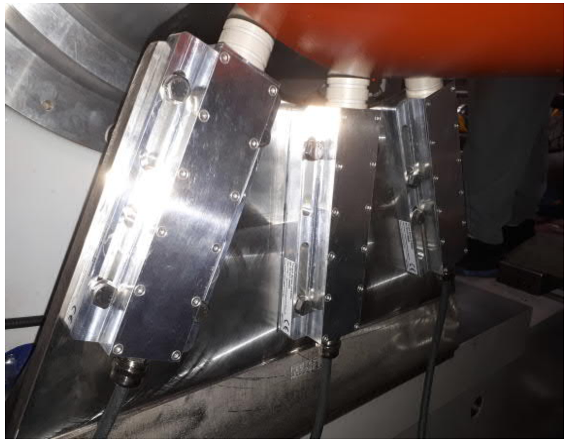
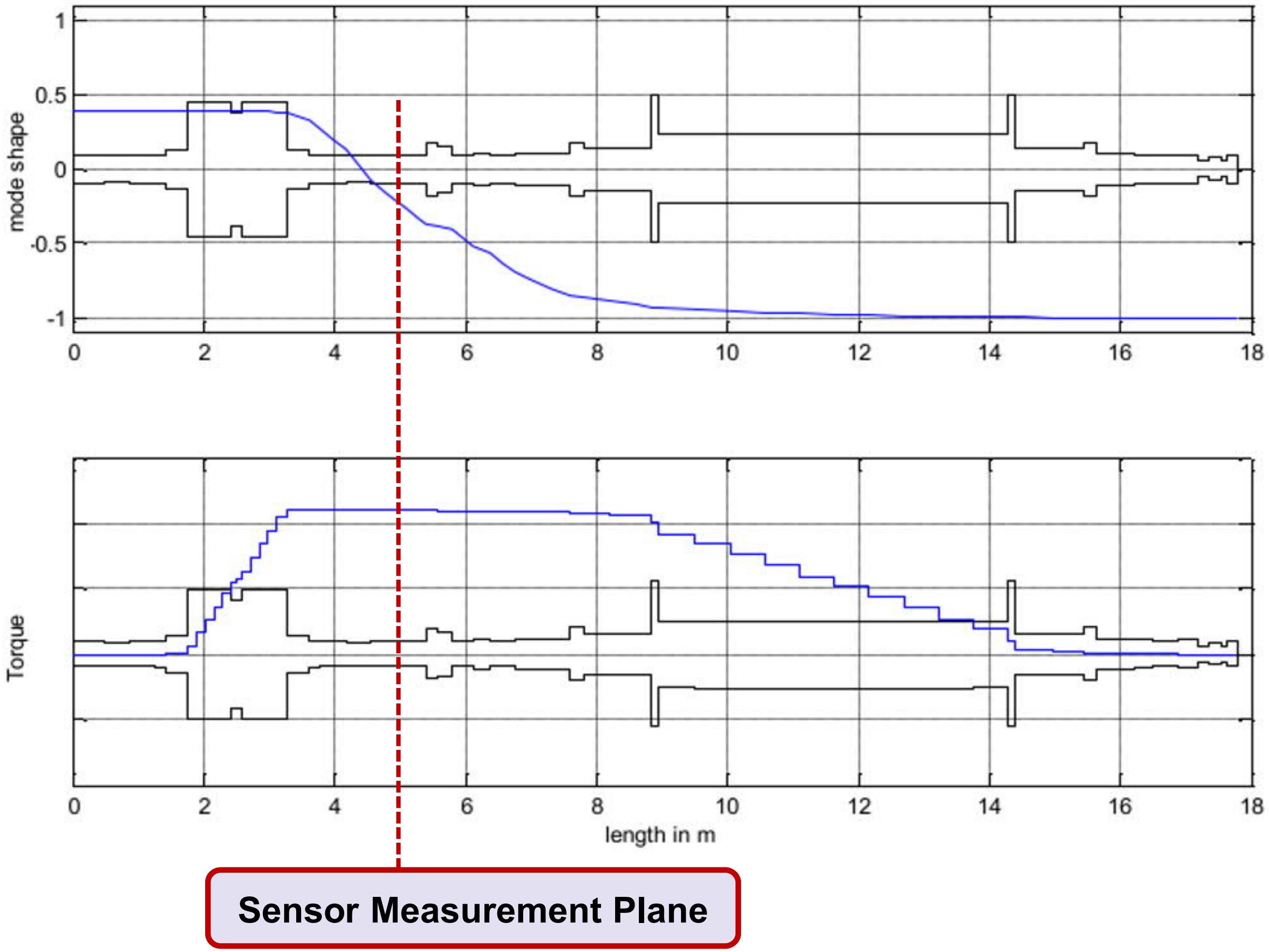


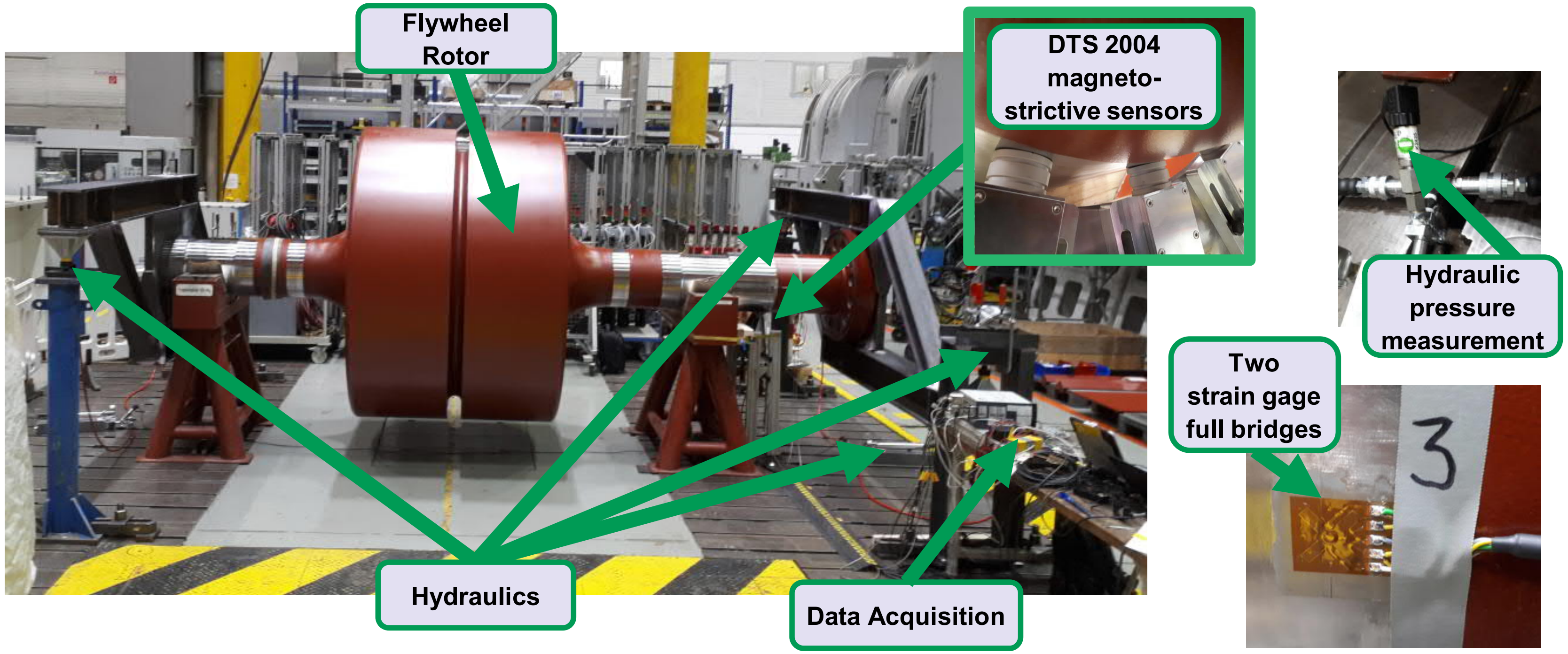


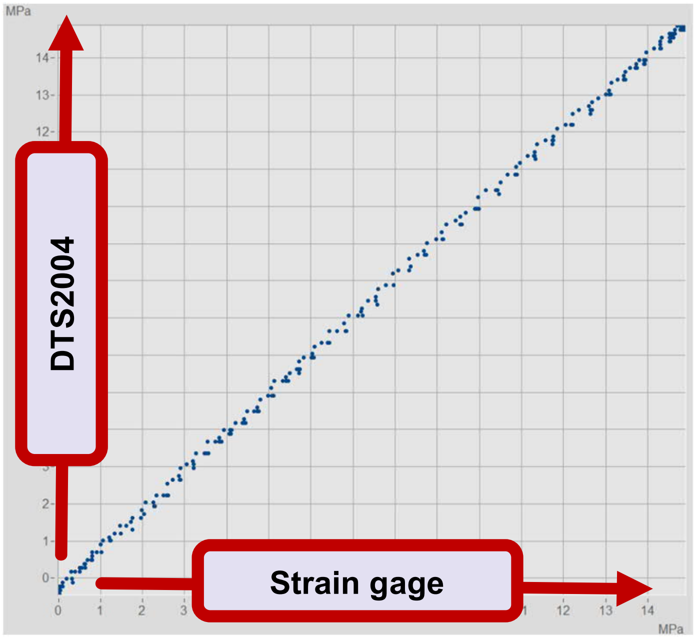
Facts:

- 3 Sensors (only for redundancy purposes)
- Only one main subsynchronic torsional vibration mode



Set up for sensor sensitivity adjustment for Flywheels (as no static torsion is available during later operation on site)





- In the case of rotating grid stabilization systems with flywheels and without any turbine, it is not possible to adjust the sensor sensitivities by comparing the static portion of the sensor signal with a static mechanical power (because there is none)
- In this case, sensitivity adjustment on the removed (or not yet installed) rotor is possible by applying a static moment by means of lever arms and hydraulics

Spectra over time (color plot) of DTS2004 raw signal, 1st Synchronization after startup (commissioning phase)

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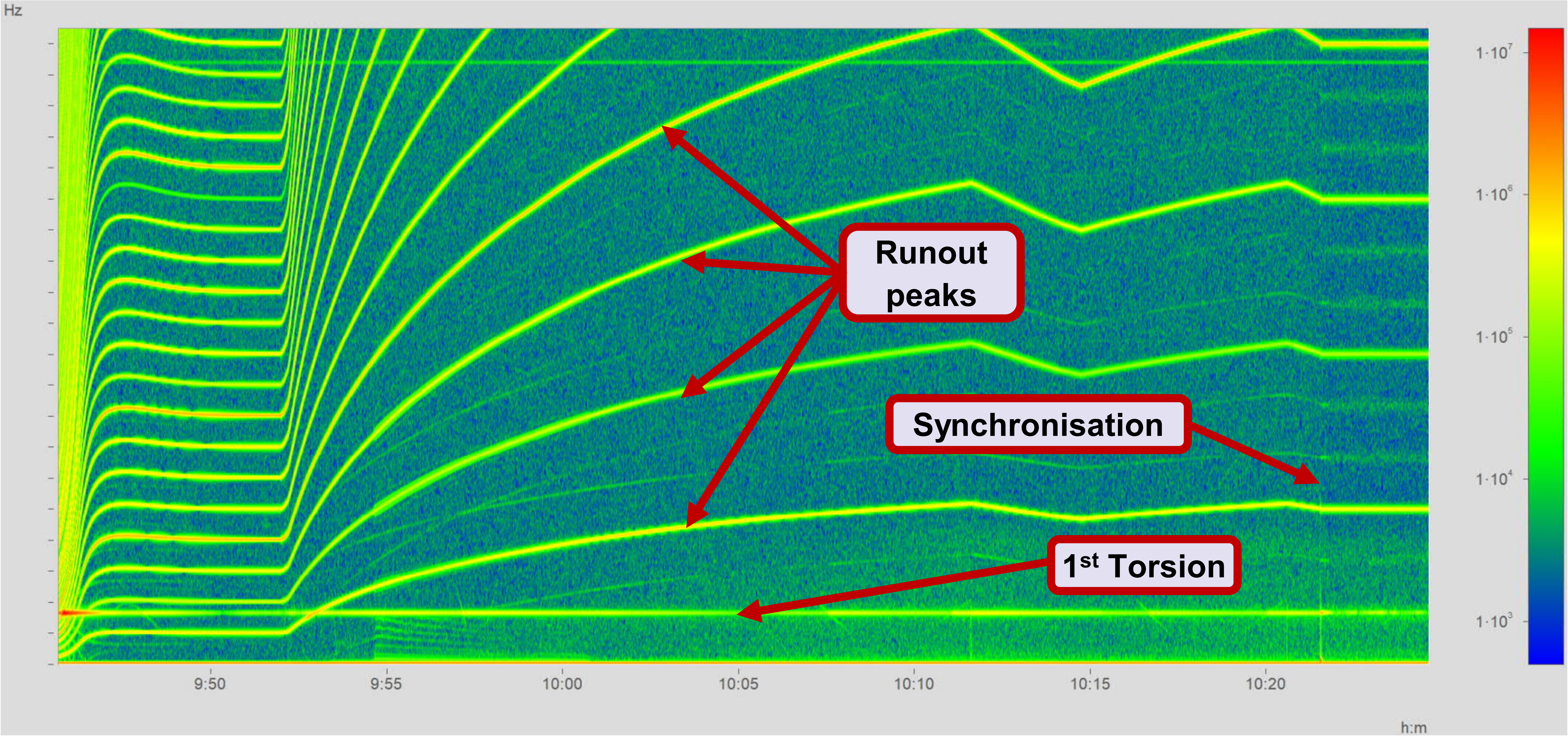

Signals of DTS2004 and speed over time during startup and synchronization in commissioning phase

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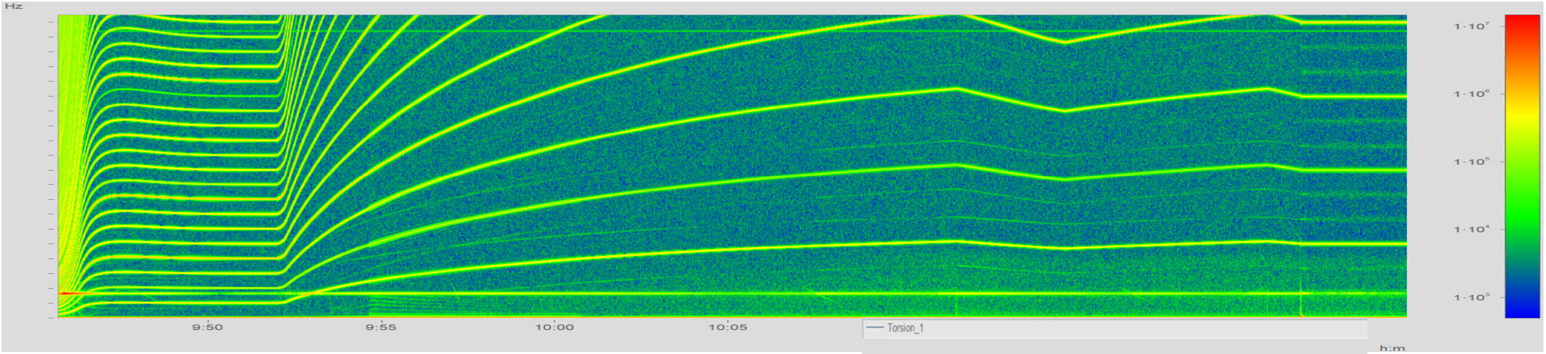
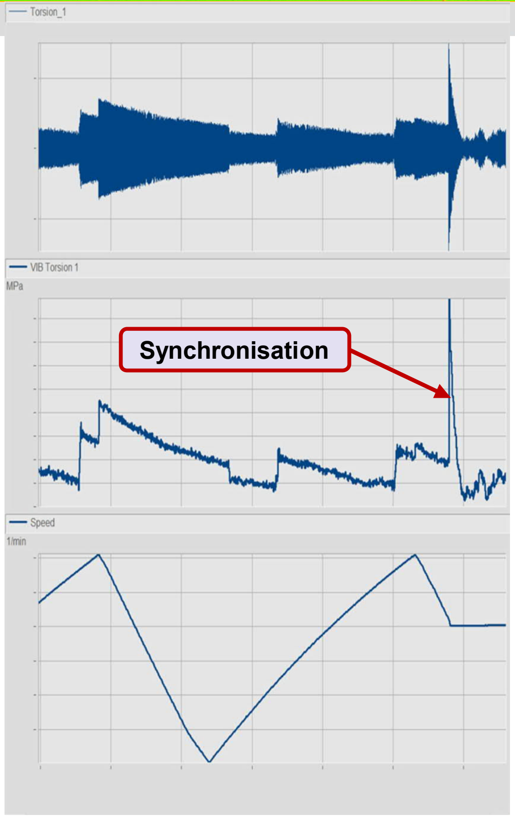




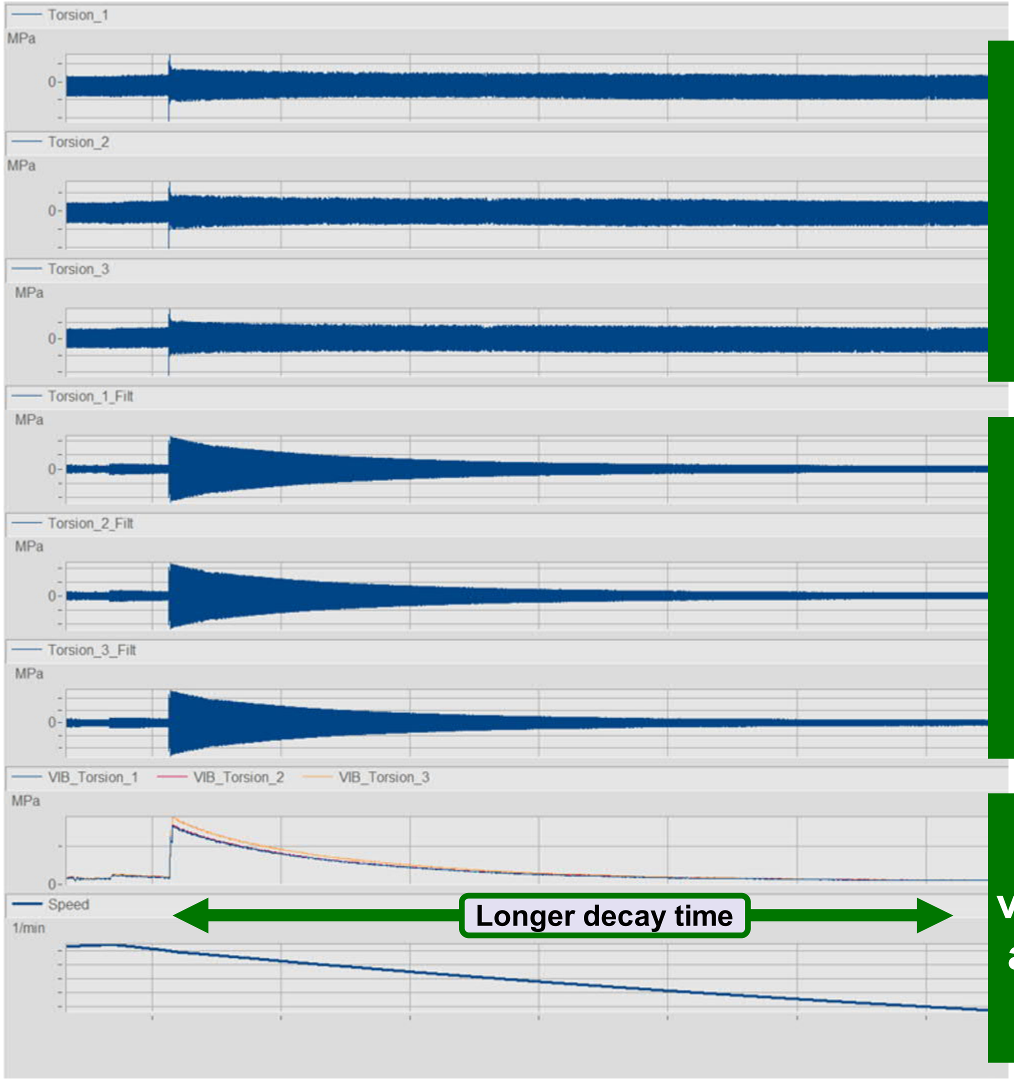
Bandpass-filtered raw signal

Torsional vibration trend signal in control and protection system (Vib3000)

Corresponding speed signal from control system

- Smaller excitation already during startup
- Damping after excitation due to synchronization comparably high due to electric forces in generator gap

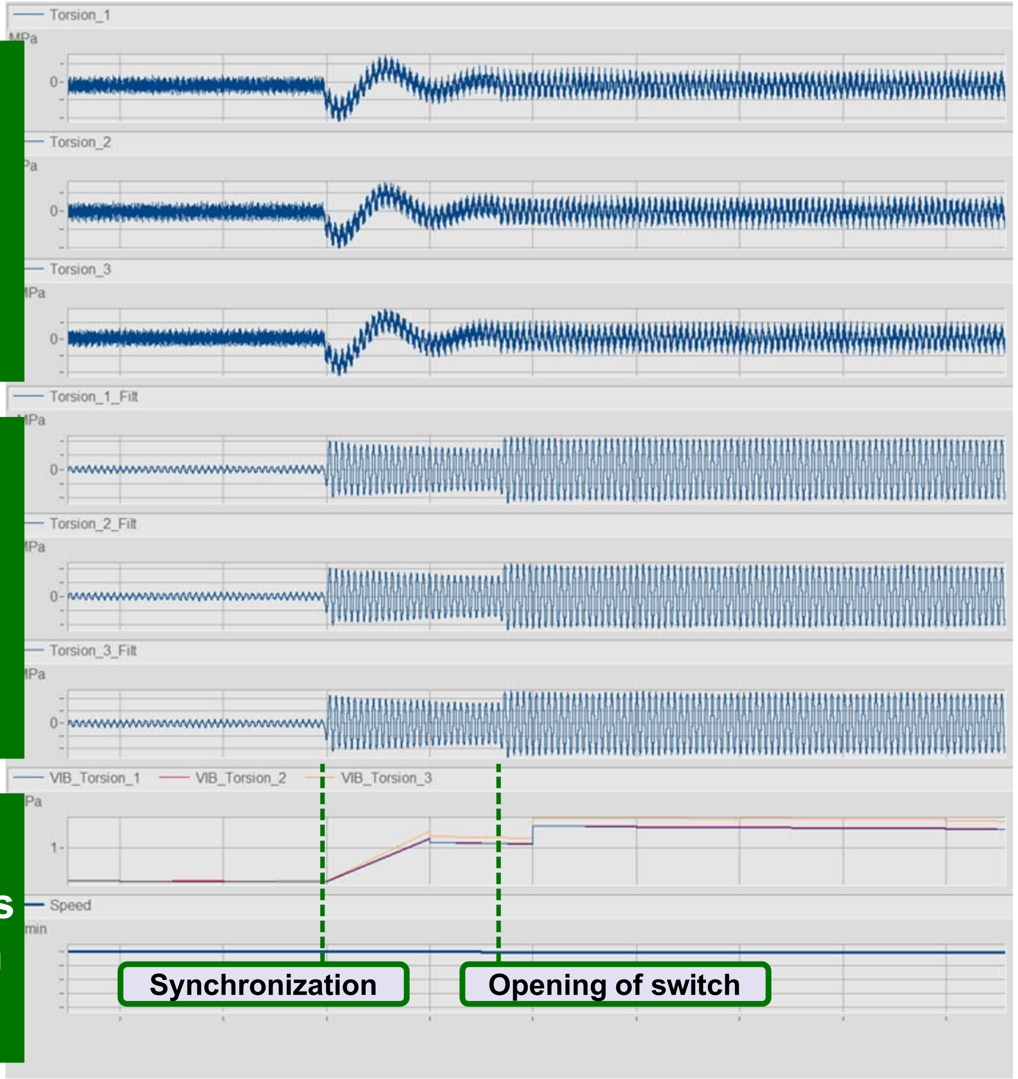
Synchronization and direct opening of generator switch (special test performed during commissioning phase)



Unfiltered raw signals

Bandpass-filtered raw signals

Torsional vibration signals and speed from control system



Conclusions

- The digital torsional vibration sensors DTS2004 are performing as expected (or better)
- Even very low torsional vibration stress amplitudes of < 0.1 MPa can be detected using appropriate signal analysis
- Upper limit of stress measurement range is far above material strength, but it is questionable if the measurement values would be reliable beyond the elastic limit of the material. Sensitivity can be adjusted to customer needs in sensor firmware.
- Runout of sensor has to be considered for precise measurements (inherent for eddy current measurement principle) => signal filtering is beneficial
- Long time stability is proven at several power plants (only one sensor failed during the last years due to extensive external overheating)
- Sensor technology can be used with several types of Siemens Energy monitoring and protection data acquisition hardware solutions (e.g., Vib3000, GenAdvisor, etc.)

Contact

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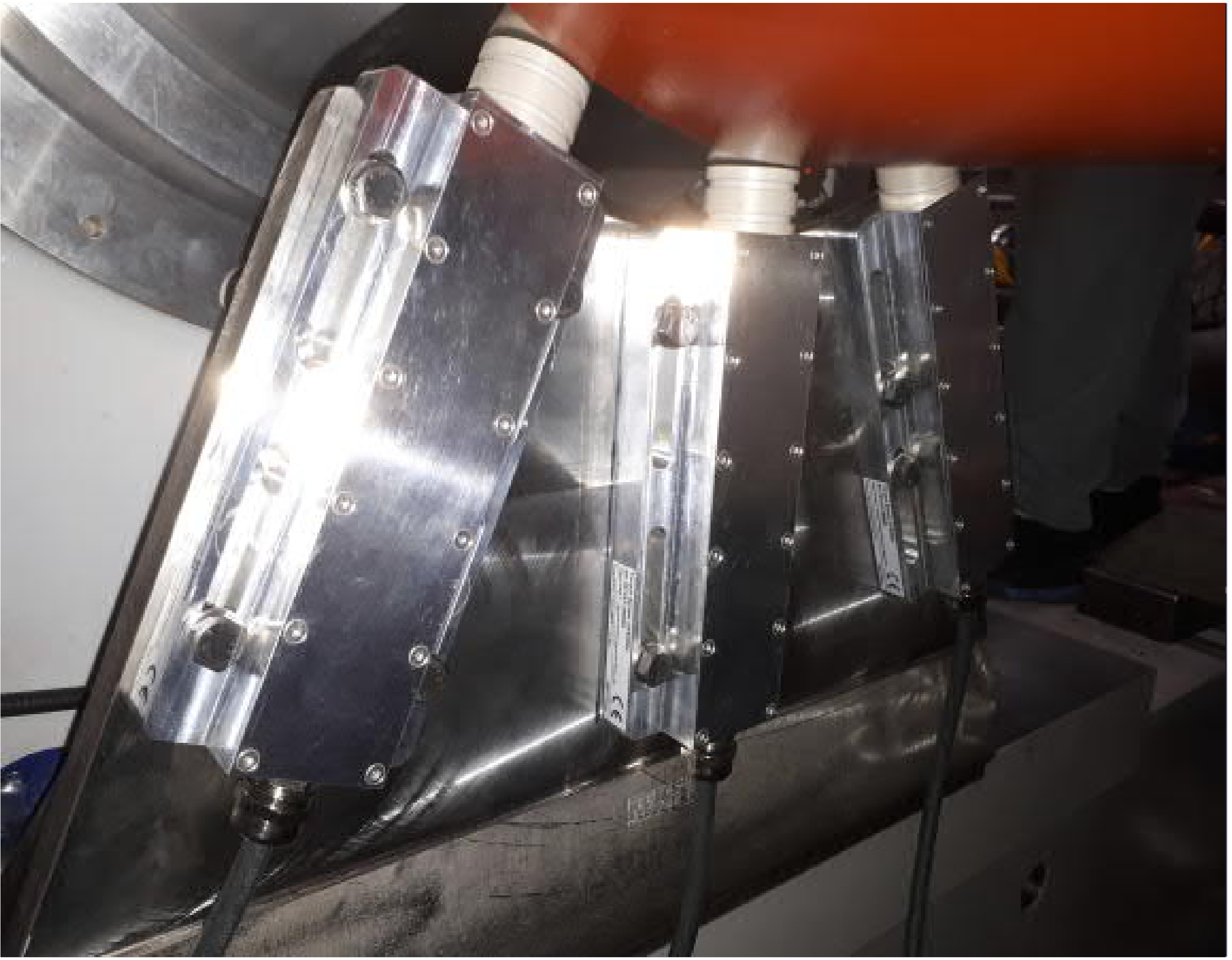

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