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Counter measures to Sub Synchronous Resonance problems in turbogenerators

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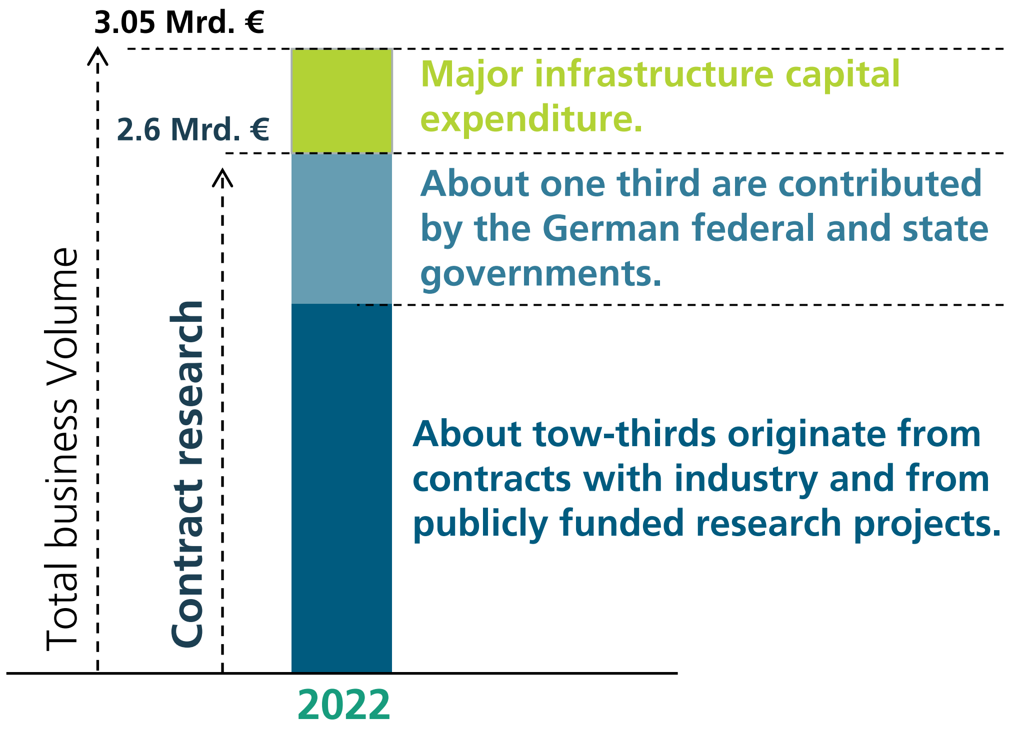

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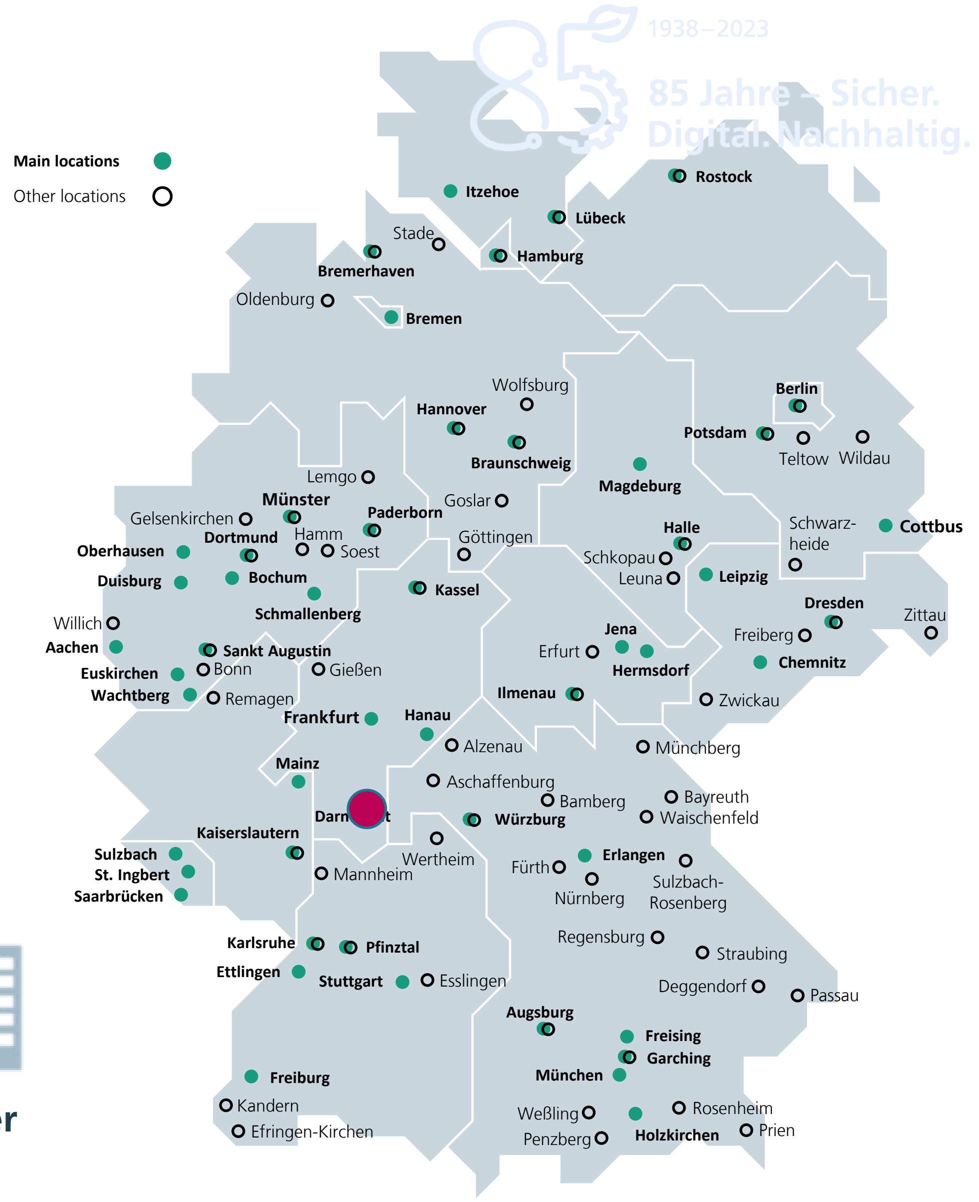

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Facts and Figures 2022

70 Work in international expert comittees and panels

362 Employes at LBF

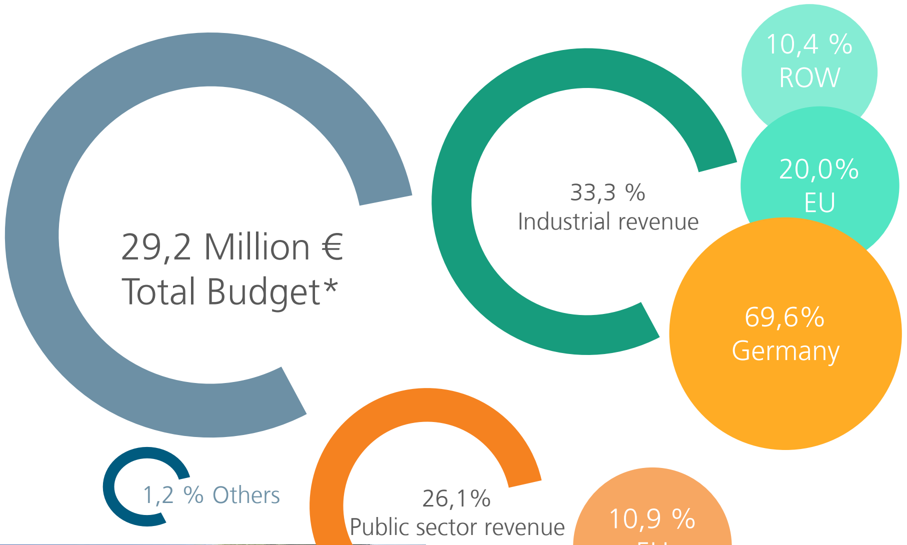
50 Lectures

27 Employes at Technical University Darmstadt

108 Scientific publications

8 New Patents

51 Academic degrees



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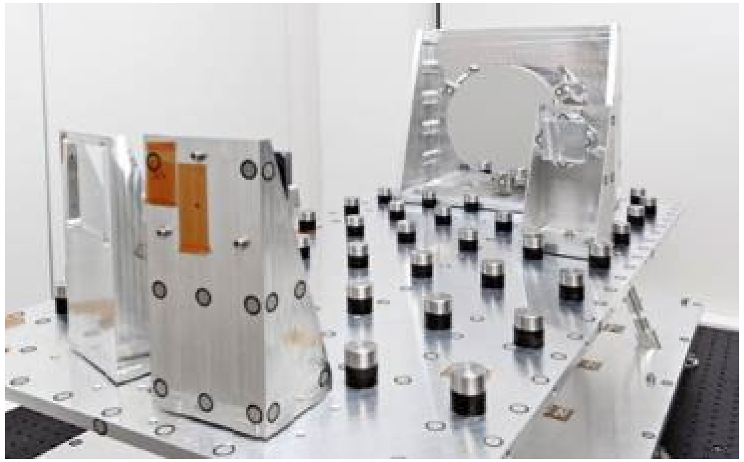

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Counter measures to Sub Synchronous Resonance problems in turbogenerators

Outline

Introduction and Motivation

Model of the overall system (mech. drive train + el.-mech. generator + el. grid)

Torsional vibrations of power trains (excited by air gap torques)

General passive and active vibration control measures

Performance evaluation of different concepts

- Electrical tuning (conventional measure)
- Mechanical rotational damper
- Mechanical rotational absorber (adaptive)
- Active Vibration Control by rotational inertial mass actuator with velocity feedback
- Digital Twin

Summary and Outlook

Counter measures to SSR problems in turbogenerators

Introduction

Resilience and availability of critical infrastructure

- stable energy supply is essential for industry, mobility, communication, private households, …
- high availability and robustness of the power supply supports the smooth operation also in critical or crisis situations

However, …

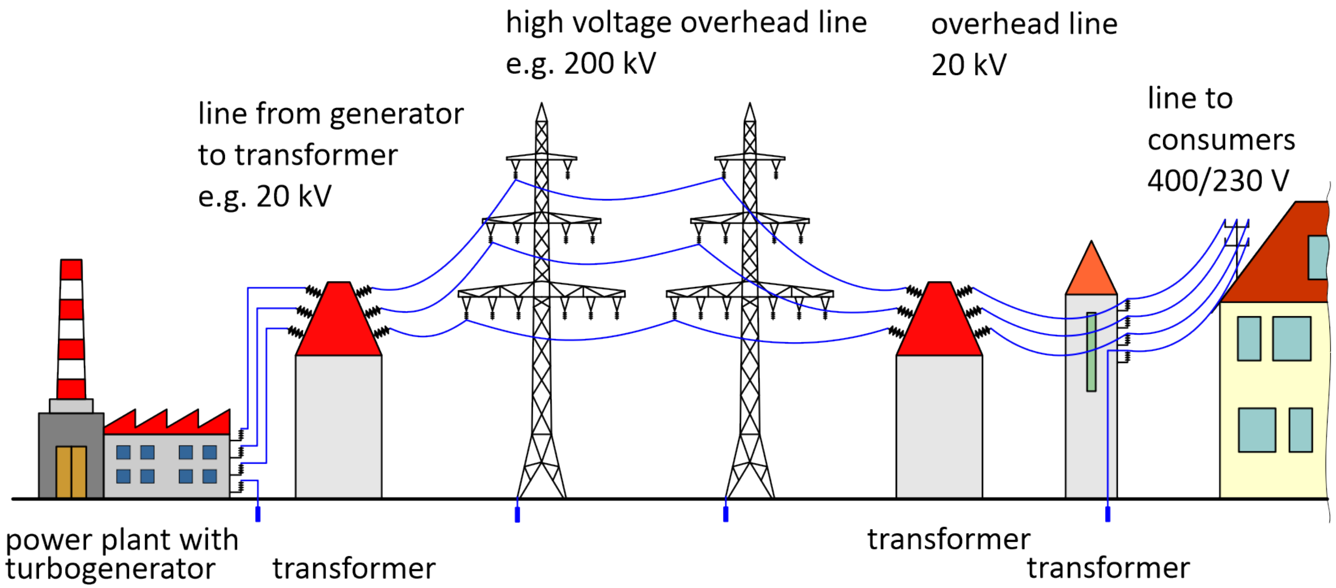
- fewer powerful systems are available to safeguard base and average loads
- alternative energy sources dependant from environmental conditions (location and time) and often not flexible
- strong variability of power requirements (location and time)

Counter measures to SSR problems in turbogenerators

Motivation

The transformation of the energy sector to decarbonized energy production leads (depending on the country) to challenging tasks:

- stable energy production without interruption
- **stabilized electrical grid** for robust energy transmission and distribution
- balancing the variable power requirements by economic storage solutions with adequate storage capacity
- high availability and robustness of all components, especially of the remaining powerful energy production systems



Reliability, availability and resilience/stability of the turbogenerators must be guaranteed.

Counter measures to SSR problems in turbogenerators

Motivation

Reliability, availability and resilience/stability of the turbogenerators must be guaranteed.
But by the situation described previously dynamic phenomena were generated:

- fault or switching operations in the resonant electrical grid coupled to the turbogenerator lead to vibration of the mechanical shaft too
- often lower frequency vibrations compared to the synchronous frequency excite the mechanical system by air gap torques, called sub synchronous resonances (SSR)
- methods to stabilize the electrical grid e.g. by electrical compensation with capacitive loads are discussed and sometimes implemented
- In this lecture counter measures concentrating on the mechanical part of the system will be investigated to prevent the drive train from long-lasting (unstable) torsional vibrations.

Application: Vibrations in turbogenerators caused by SSR problems

Different disciplines of physics are involved

Disciplines : mechanics | thermodynamics | electrodynamics

stresses, strength of material

mainly torsional vibrations (rotordynamics) ↔ **electrical vibration**

…

vibration response due **air gap torques (torsional)** ↔ vibration response due to **grid properties and faults**

stability and reliability problems (e.g. by interactions)

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How to describe holistic mechatronic systems? – a multiphysical task

Different disciplines of physics and analogies

Impedance and admittance / defined ports

		mechanical	electrical	fluid
Potential variable	$\mathcal{P}$	force F	voltage U	pressure p
Flux variable	$\mathcal{F}$	velocity v	current i	flow q
Power	$P = \mathcal{P}\,\mathcal{F}$	P = F v	P = U i	P = p q
Impedance	$Z = \mathcal{P} / \mathcal{F}$	Z = F / v	Z = U / i	Z = p / q
Admittance	$Y = \mathcal{F} / \mathcal{P}$	Y = v / F	Y = i / U	Y = q / p
Impedance model		v → [Z] → F	i → [Z] → U	q → [Z] → p
Admittance model		F → [Y] → v	U → [Y] → i	p → [Y] → q

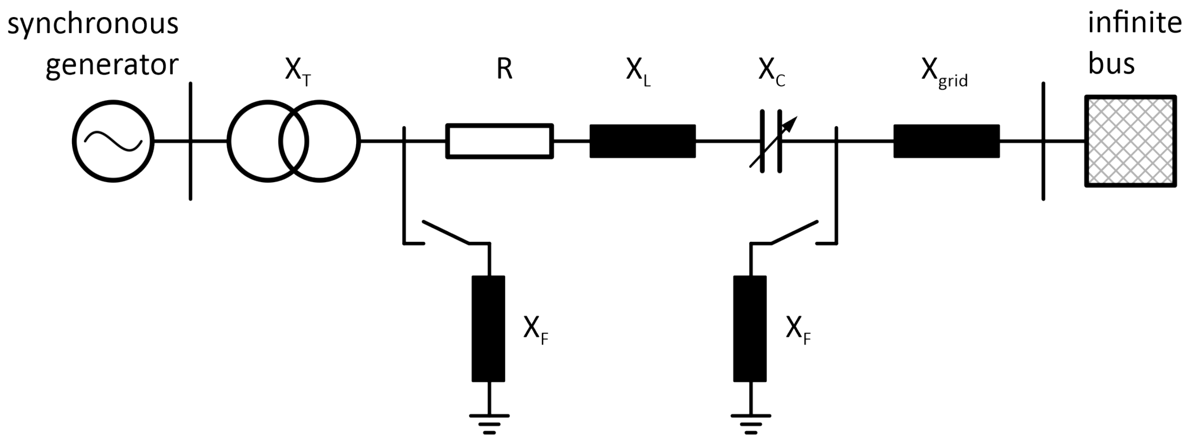
Simplified models to evaluate SSR problems

Electrical sub-system

The IEEE **first benchmark model** for SSR analysis is a simplified representation of the electrical part of the grid **including the synchronous generator**, a transformer (X_T), transmission lines (R, X_L), a compensation option (X_C), the grid load (X_{grid}) and the possibility to introduce switching faults by inductive loads (X_F).

At the generator, a coupling to the mechanical part of the system via energy exchange is necessary to investigate SSR problems holistically.

Electrical and mechanical disturbances introduce **air gap torques** on the mechanical side and **currents in the windings** (stator, rotor) on the electrical side of the generator.



IEEE first benchmark model for SSR analysis

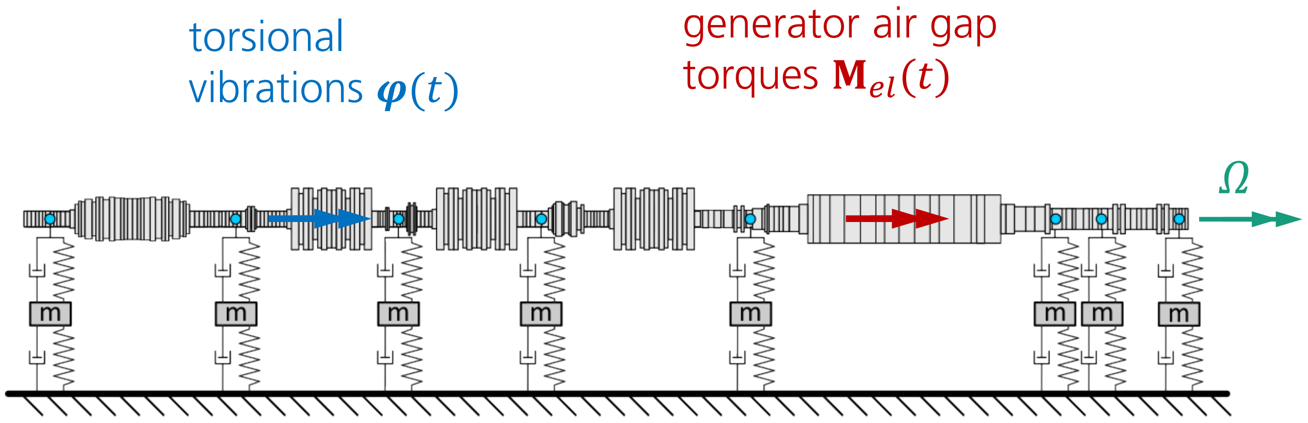
Simplified models to evaluate SSR problems

Mechanical model and equations of motion for the evaluation of torsional vibrations

The matrices $\mathbf{\Theta}, \mathbf{D}$ and $\mathbf{K}(\Omega)$ of the equations of motion for **torsional vibrations** of the **power train** contain mainly the stiffness, damping and inertia data of the shaft train. $\mathbf{K}$ depends on Ω due to the stiffening of centrifugal forces on blades. The **damping** in the torsional system is **very low**.

The main excitations are **air gap torques $\mathbf{M}_{el}(t)$** in the generator.

Torsional vibrations $\boldsymbol{\varphi}(t)$ are acting around the shaft axis.



$$\mathbf{\Theta}\,\ddot{\boldsymbol{\varphi}}(t) + \mathbf{D}\,\dot{\boldsymbol{\varphi}}(t) + \mathbf{K}\,\boldsymbol{\varphi}(t) = \mathbf{M}_{el}(t)$$

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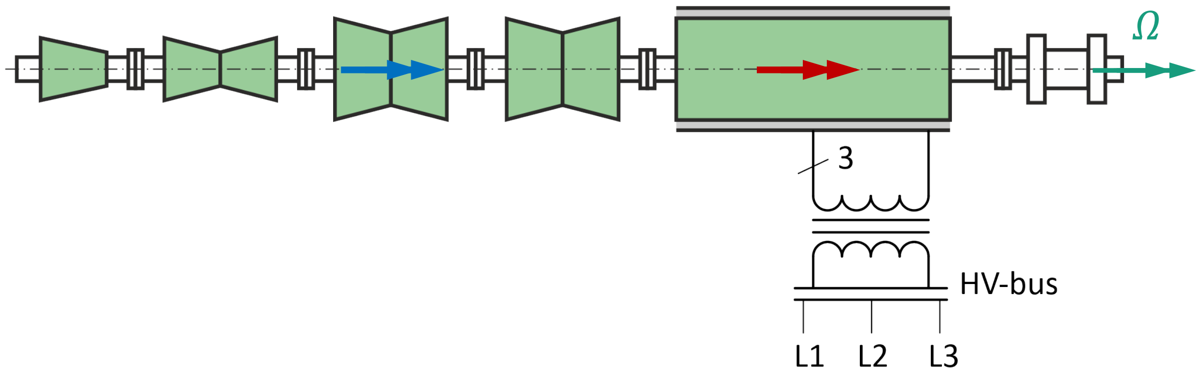
Simplified models to evaluate SSR problems

Electrical, electro-mechanical and mechanical sub-systems

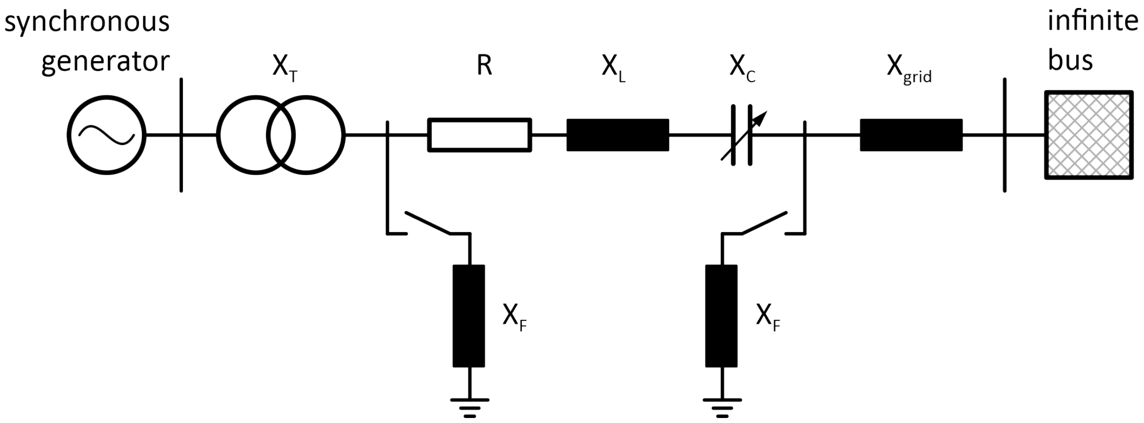
mechanical model

torsional vibrations $\boldsymbol{\varphi}(t)$

generator air gap torques $\mathbf{M}_{el}(t)$



electrical model



IEEE first benchmark model for SSR analysis

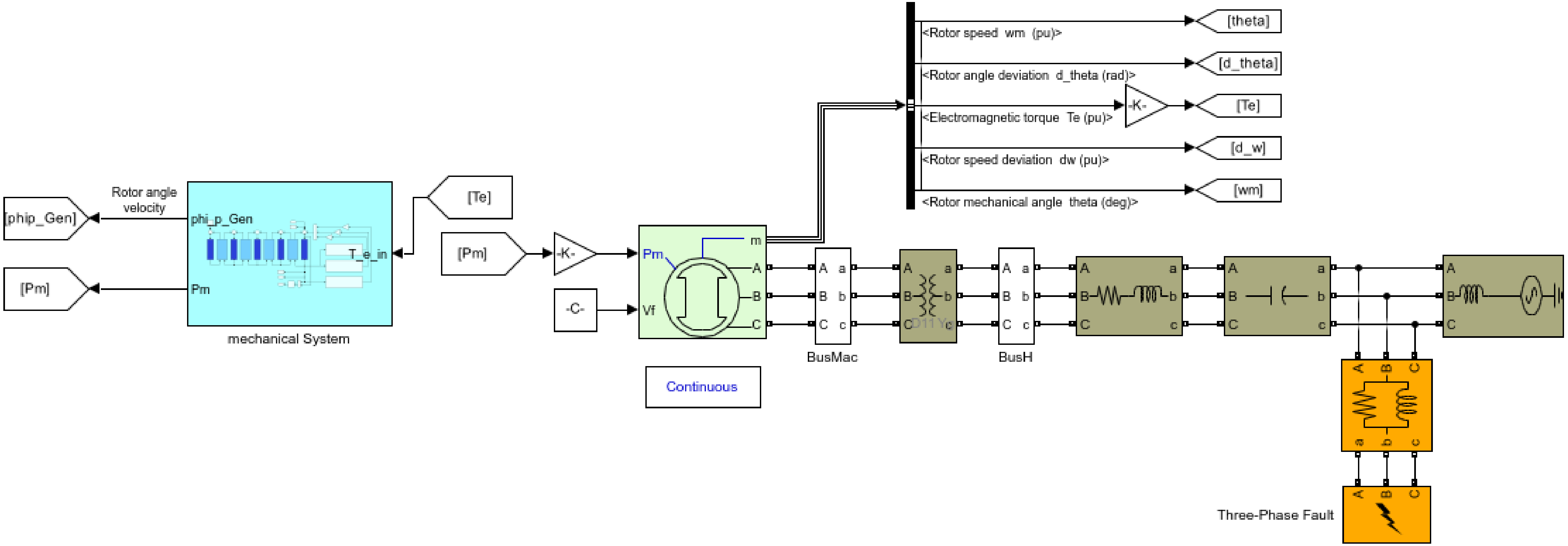
mechanical domain — $M_{el}(t)$ — $i_j^S(t), i_k^L(t)$ — electrical domain

$\varphi(t), \dot{\varphi}(t)$ — $L_{j,k}^{S,L}(\varphi)$

Simplified models to evaluate SSR problems

Implementation into simulation environment

Coupled electro-mechanical simulation model – overall system



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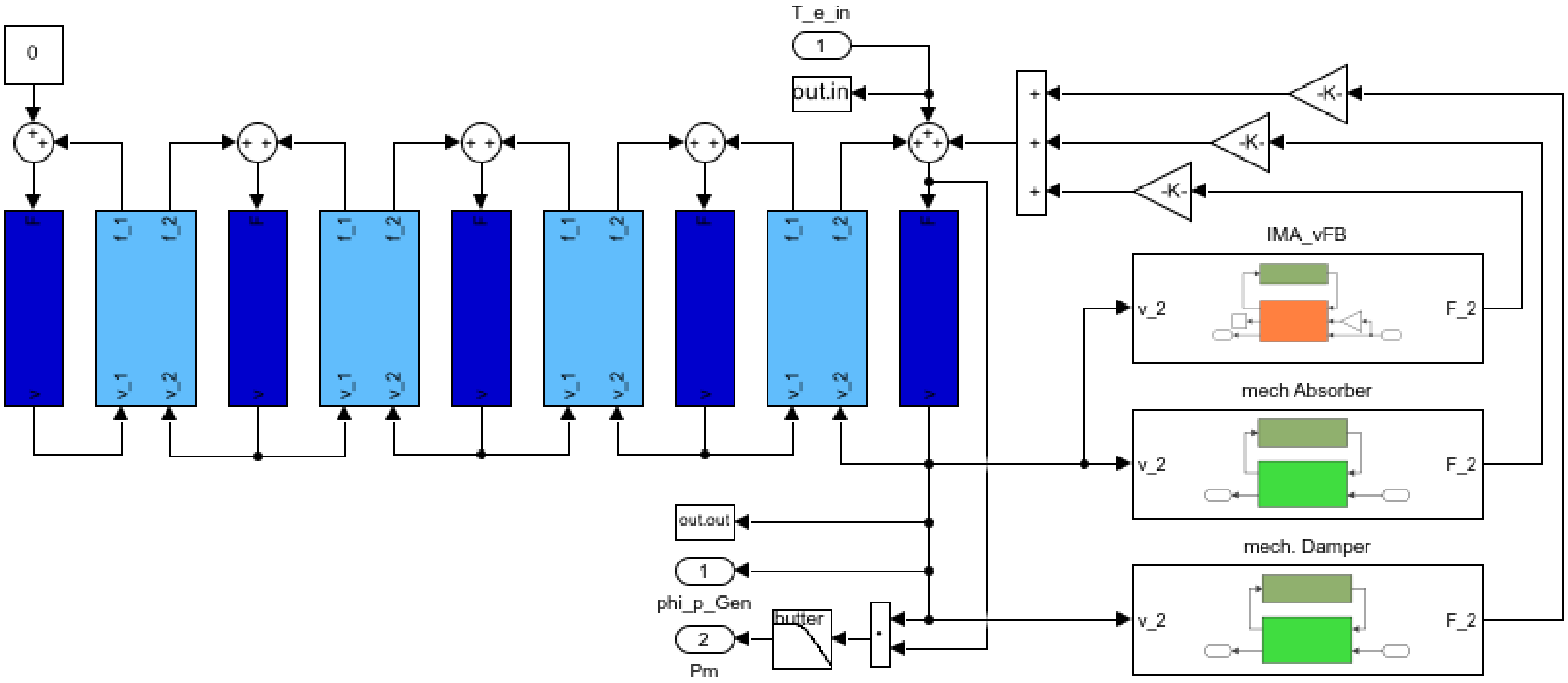
Simplified models to evaluate SSR problems

Implementation into simulation environment

Coupled electro-mechanical simulation model – mechanical system with vibration control measures



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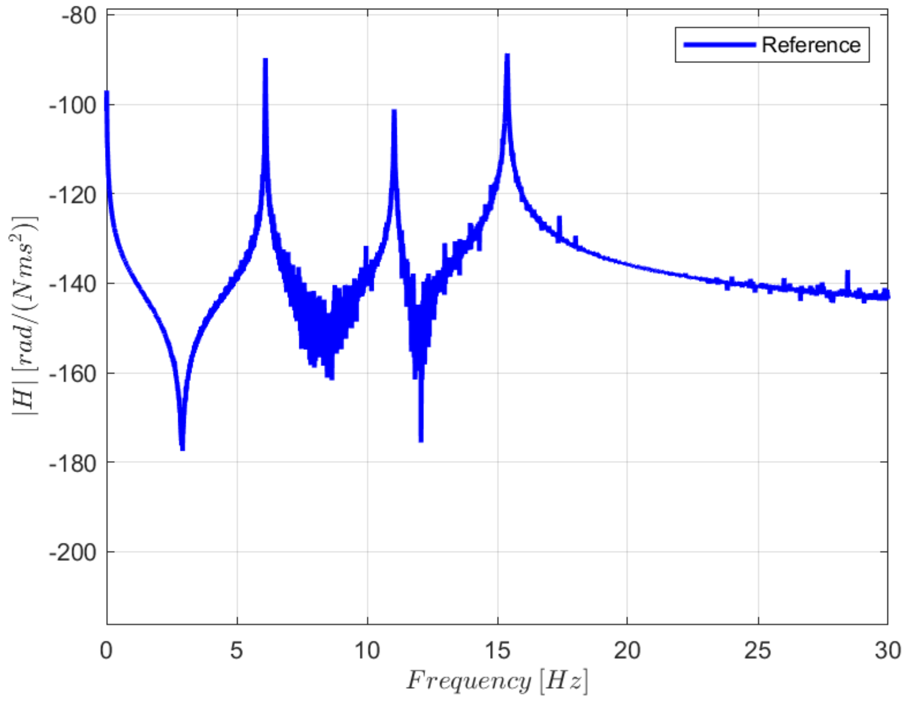
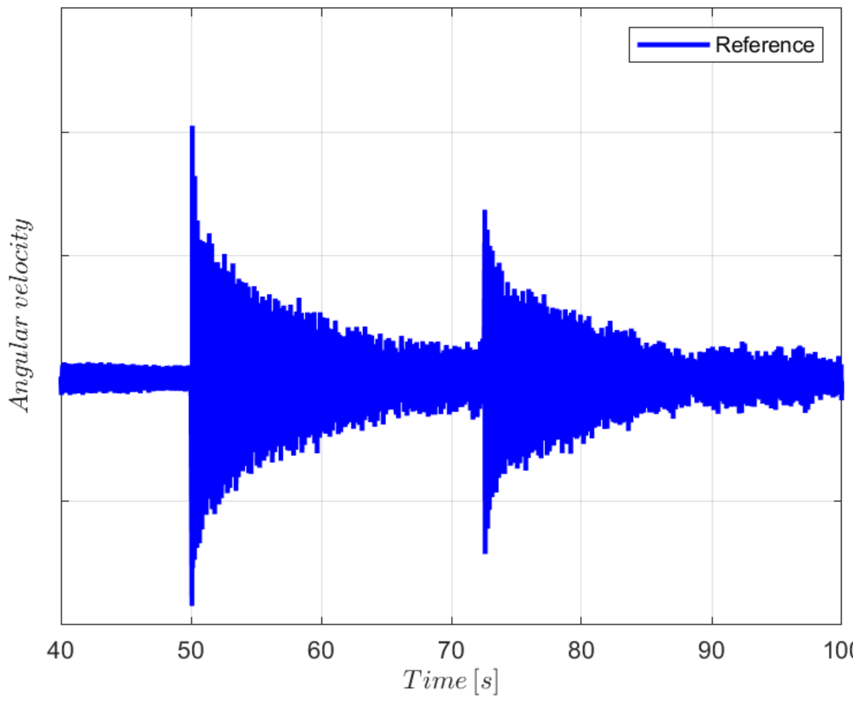
Simplified models to evaluate SSR problems

Reference results

Coupled electro-mechanical simulation → switching faults after 50 s and 72.5 s realized





Potential counter measures to SSR problems in turbogenerators

Conventional measures | Passive and active vibration control measures | Digital Twin

Conventional measures (in the electrical system)

- **system tuning** - electrical **compensation** by additional and adjustable capacitive loads
- …

Passive and active Vibration control measures (in the mechanical system)

- **reduction of excitation** – Example: active generator
- **system tuning** – modification of dynamics by **additional stiffnesses or masses**
- **damping** – modification of dynamics by **additional damping**
- **vibration absorption** – modification of dynamics by **additional resonant sub systems**
- **isolation of sources and receiver** – **decoupling of sub-systems** in a certain frequency range

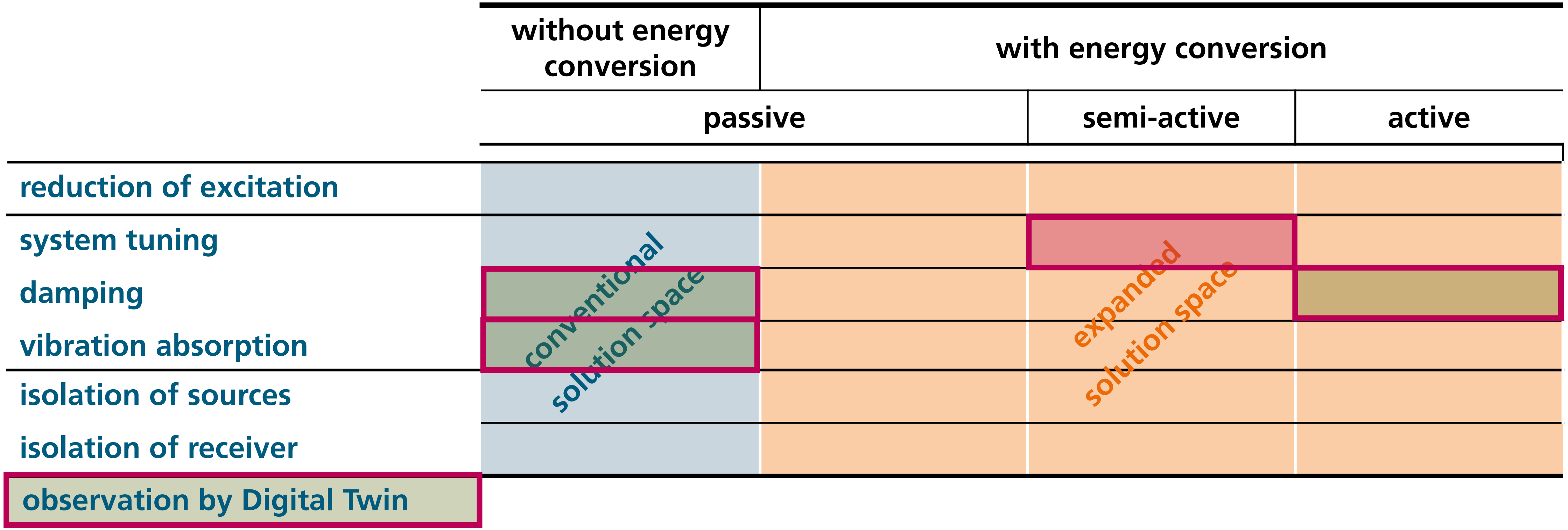
Digital Twin for decision support (applicable for both electrical and mechanical system)

- **monitoring** → **diagnosis** → **recommendations** to the plant operator → e.g. **switching off**

General passive and active vibration control measures

… with potential to counteract SSR Problems in Turbogenerators

plant measure
grid measure



In general increase of:

effectiveness, benefit, complexity, number of possible variants

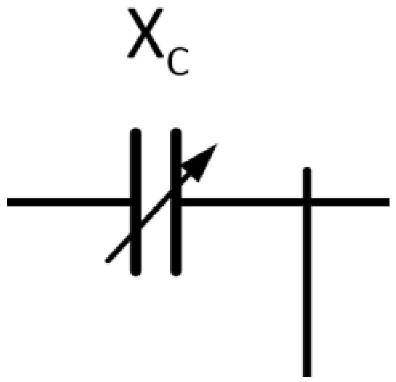
Performance evaluation of different concepts for SSR counter measures

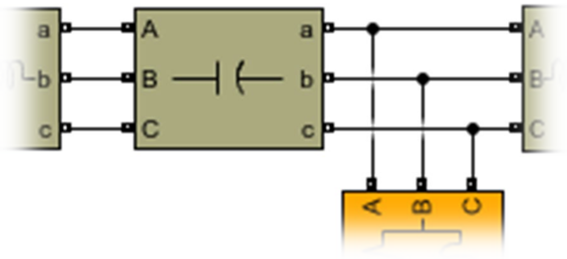
Electrical system tuning (conventional measure)

Description of measure

Electrical compensation by additional and adjustable capacitive loads

- e.g. Introducing test currents and measuring resulting voltages
- calculation of electrical impedance or admittance functions
- identification of zeros/poles (el. natural frequencies)
- calculation of critical frequencies –
  difference between electrical natural frequency and synchronous frequency of the grid
- adjustment of the capacitance X_C accordingly to shift the critical frequencies

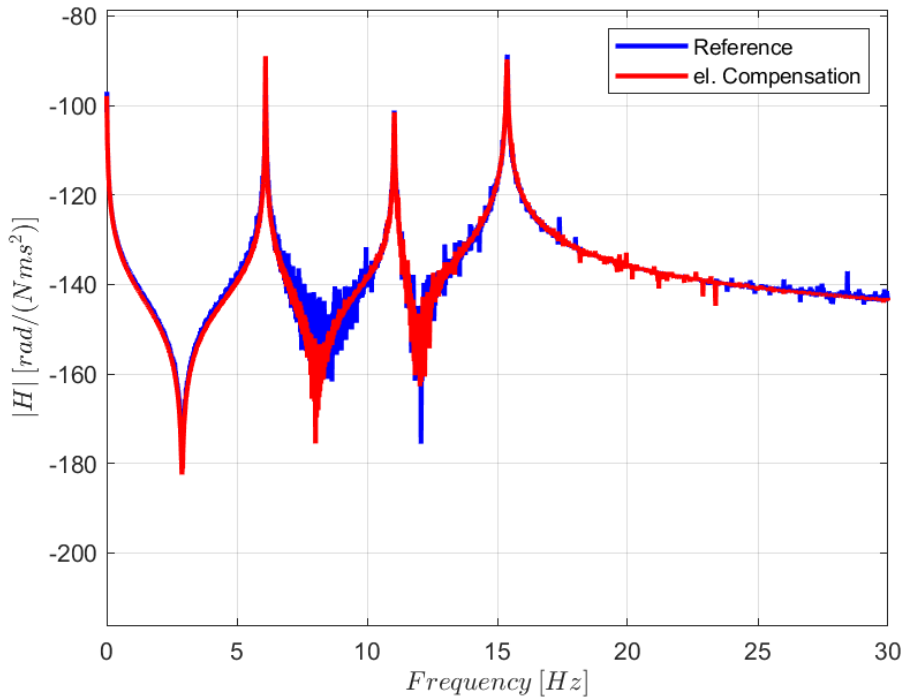




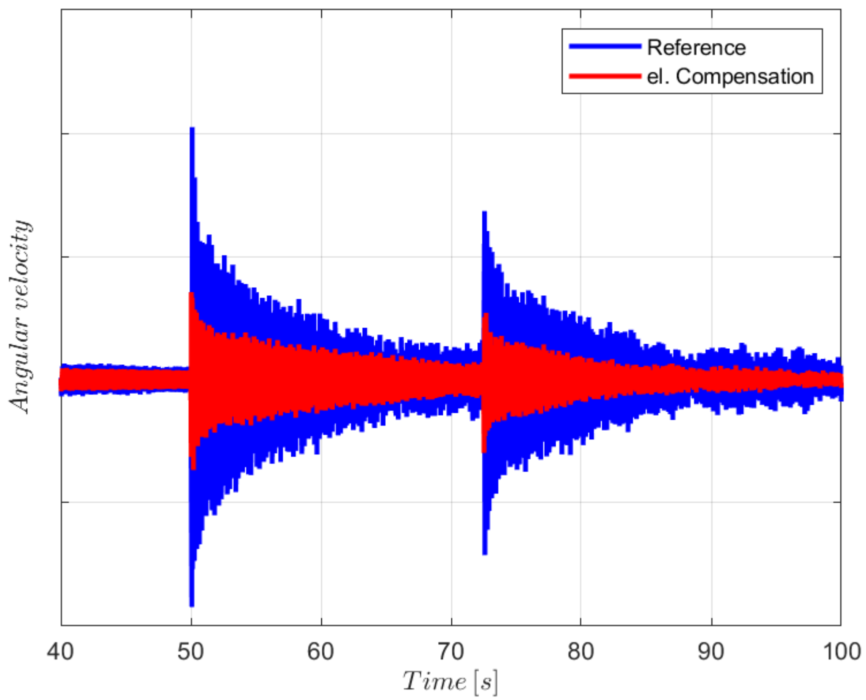
Performance evaluation of different concepts for SSR counter measures

Electrical tuning (conventional measure)

Results



nearly no influence on the mechanical side



effective reduction and relatively slow decay of vibration amplitudes

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Performance evaluation of different concepts for SSR counter measures

Mechanical rotational damper

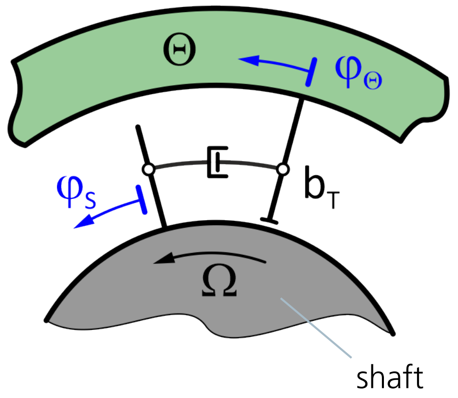
Description of measure

Modification of mechanical system dynamics by additional damping devices

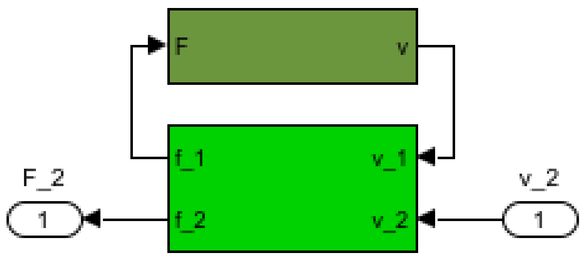
- able to add damping forces into the mechanical system
- frequency dependant behaviour – depending on the inertia and the nature of damping mechanism
- broadband measure
- passive device – no energy supply necessary
- unconditionally stable

Parameters used

$$\Theta \ = 0.05 \cdot \Theta_G$$
$$b_T = 500000 \ \mathrm{kg \cdot m^2/s}$$



mechanical scheme

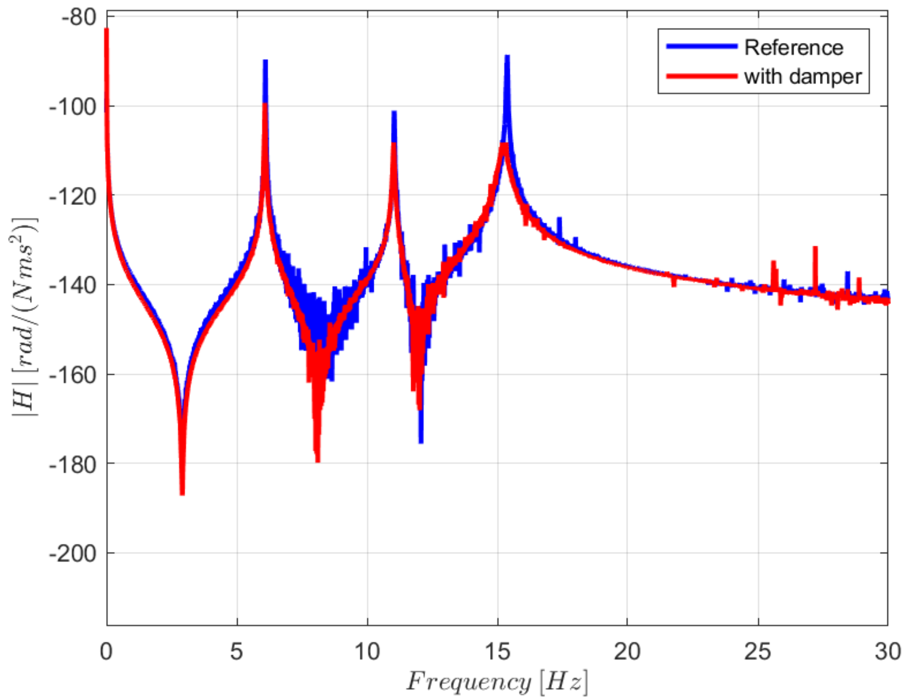


simulation model

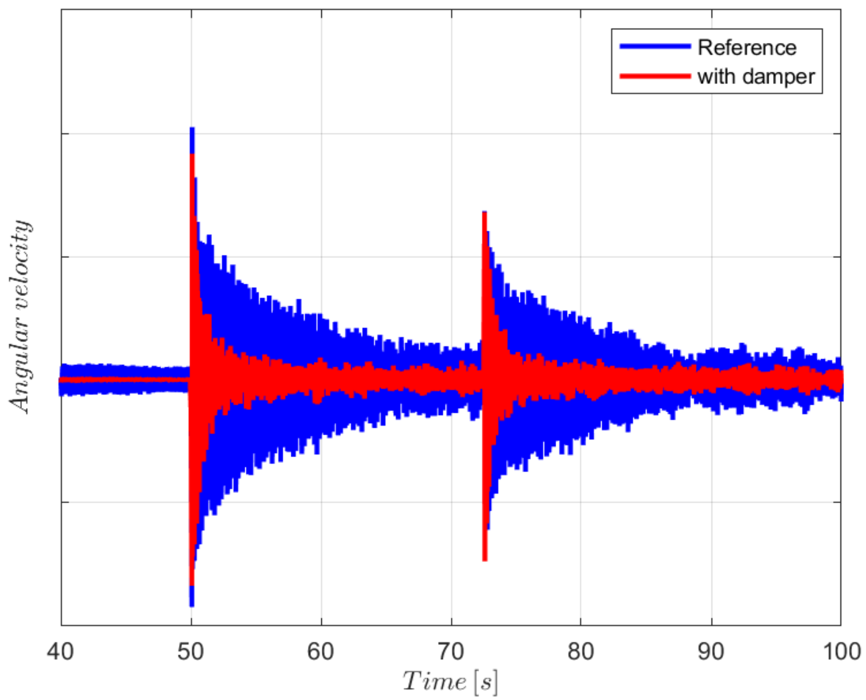
Performance evaluation of different concepts for SSR counter measures

Mechanical rotational damper

Results



broadband vibration reduction close to resonances



fast decay of vibration amplitudes

Performance evaluation of different concepts for SSR counter measures

Mechanical rotational absorber (adaptive)

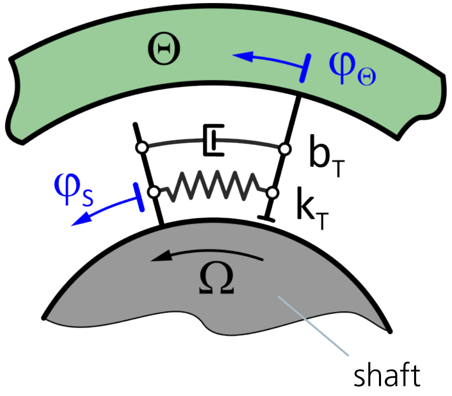
Description of measure

Modification of mech. system dynamics by an additional resonant sub-system

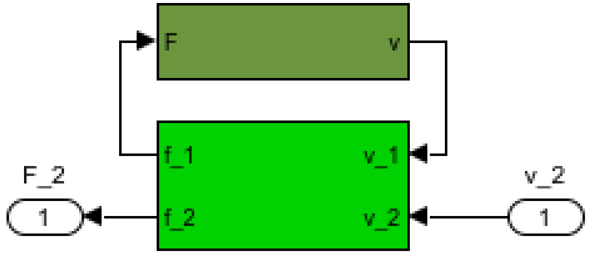
- able to absorb energy and effectively attenuate vibration amplitudes
- tuned to one natural frequency of the mechanical system (tuneable [adaptive] variants possible)
- narrowband measure
- passive device – no energy supply necessary

Parameters used

$$\Theta \;= 0.025 \cdot \Theta_G$$
$$\omega_T = 15.3 \cdot 2 \cdot \pi \;\; 1/s$$
$$k_T \;= \omega_T^2 \cdot \Theta$$
$$b_T \;= 30000 \;\; \text{kg} \cdot \text{m}^2/\text{s} \;\; (\vartheta_T \;= 0.062)$$



mechanical scheme

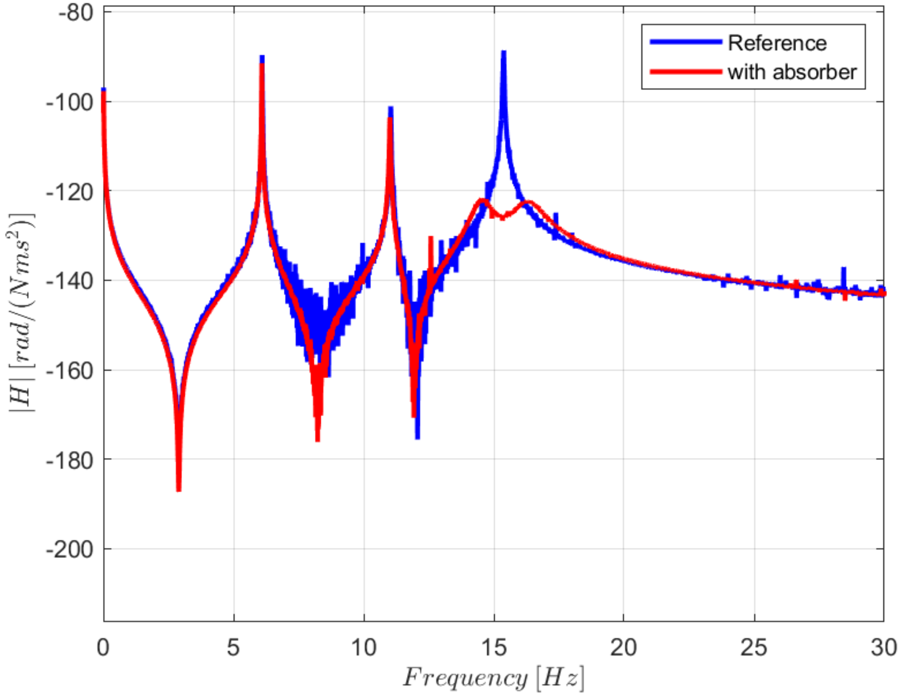


simulation model

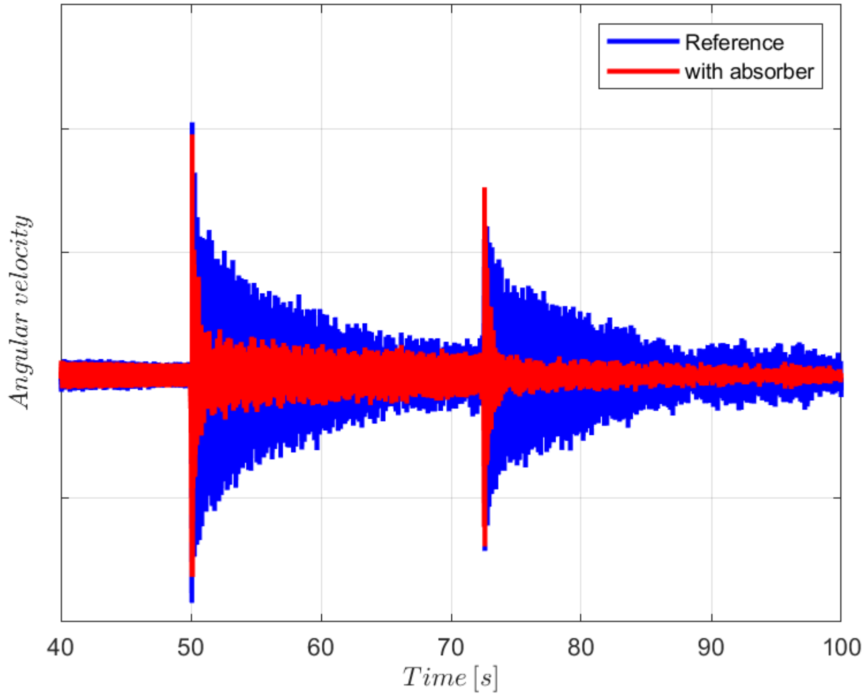
Performance evaluation of different concepts for SSR counter measures

Mechanical rotational absorber (adaptive)

Results



narrowband vibration reduction close one resonance



fast decay of vibration amplitudes

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Performance evaluation of different concepts for SSR counter measures

Active Vibration Control by rotational inertial mass actuator with velocity feedback

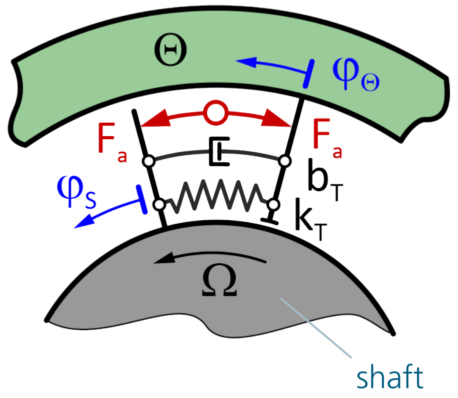
Description of measure

Integration of an actively controlled additional mech. resonant sub-system

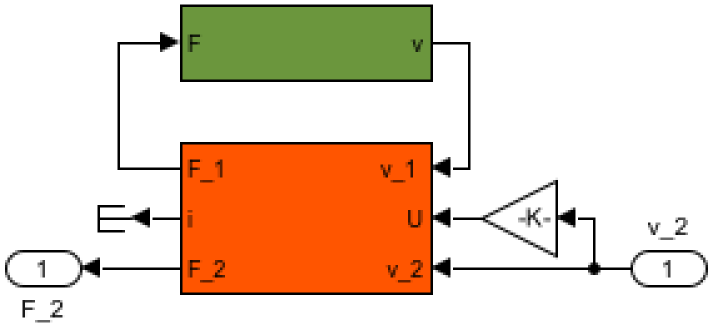
- able to actively generate dynamic forces/moments in a broad frequency range (above its own natural frequency)
- velocity feedback is implemented for demonstration – a simple unconditionally stable control approach (for control gain < 0)
- flexible – adjustable control gain and several digital control concepts possible

Parameters used

$$\Theta = 0.05 \cdot \Theta_G$$
$$\omega_T = 3 \cdot 2 \cdot \pi \ 1/s$$
$$k_T = \omega_T^2 \cdot \Theta$$
$$b_T = 20000 \ \mathrm{kg} \cdot \mathrm{m}^2/\mathrm{s} \quad (\vartheta_T = 0.106)$$



mechanical scheme

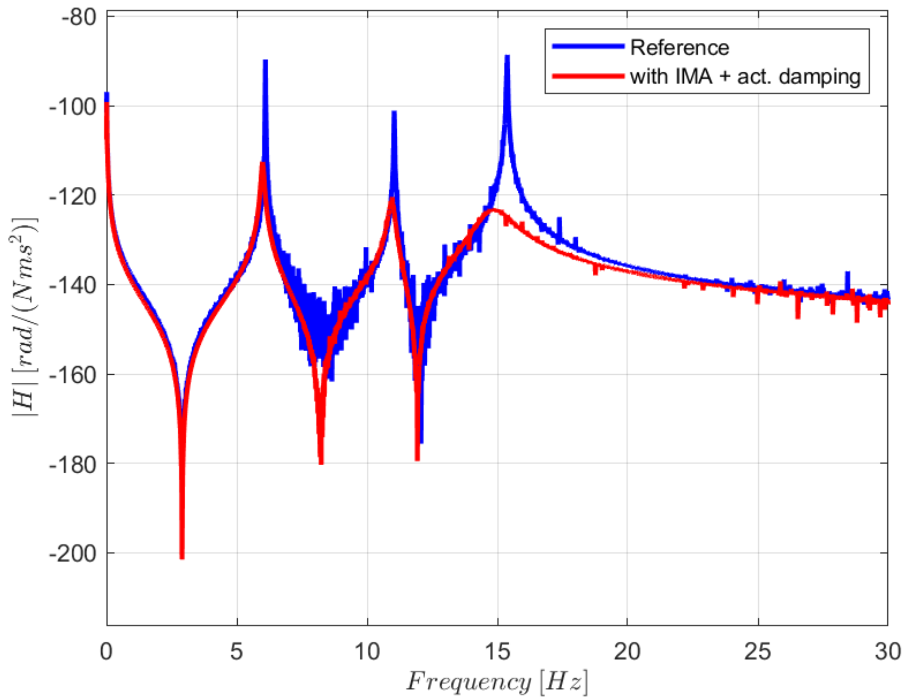


simulation model

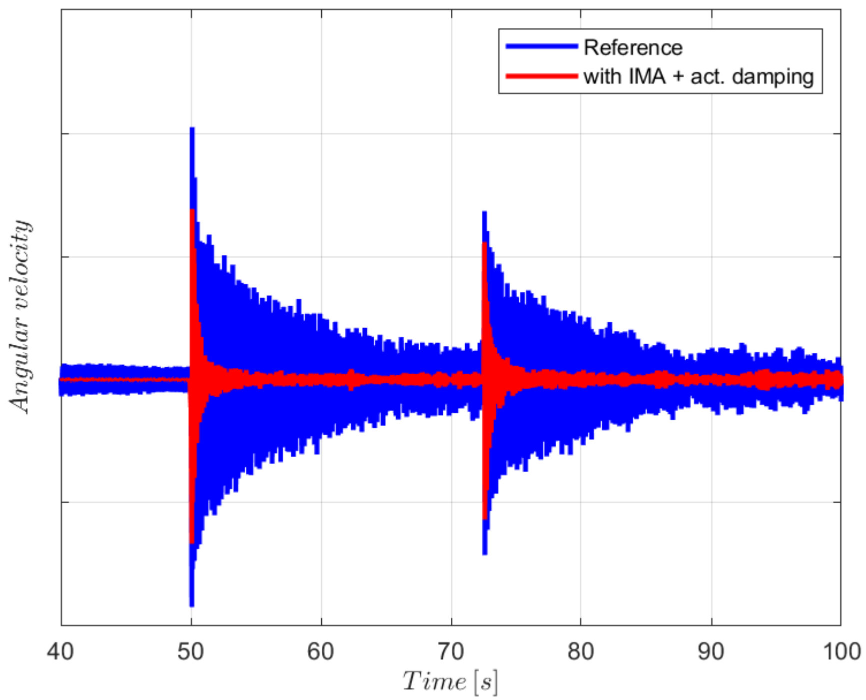
Performance evaluation of different concepts for SSR counter measures

Active Vibration Control by rotational inertial mass actuator with velocity feedback

Results



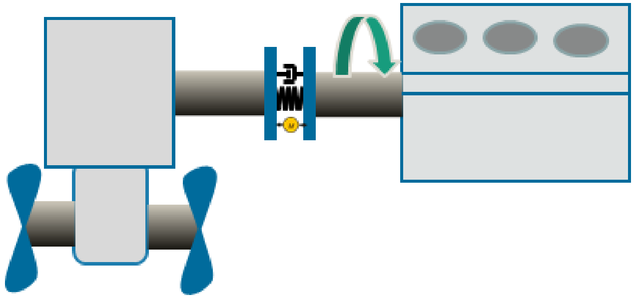
controllable broadband vibration reduction close to resonances



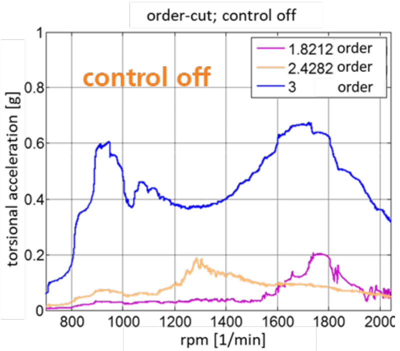
rapid decay of vibration amplitudes

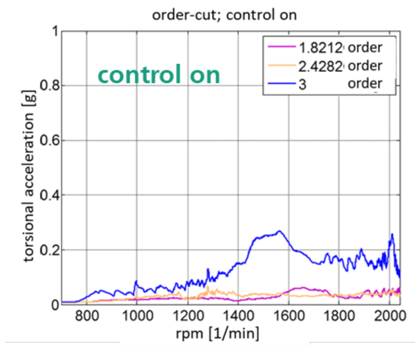
Example: Realization of AVC by IMA with adaptive control approach

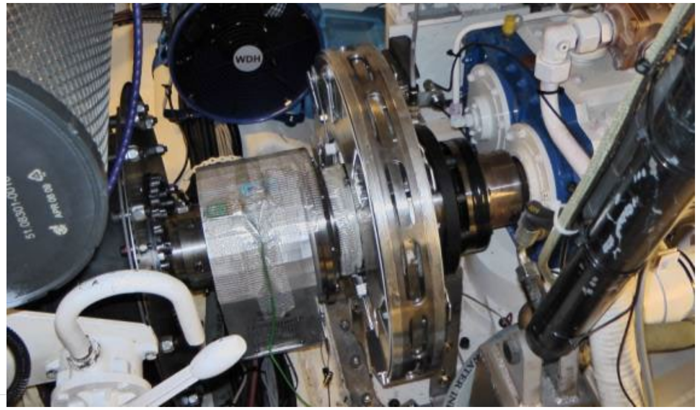
… to attenuate drivetrain vibrations in a vessel



- system integration in a motor yacht to perform tests under real operational conditions
- two V6 engines with 441 and 449 kW
- gearboxes in pod-design
- one drive train equipped with an active coupling system
- relevant periodic torsional excitations by the engine and the propeller



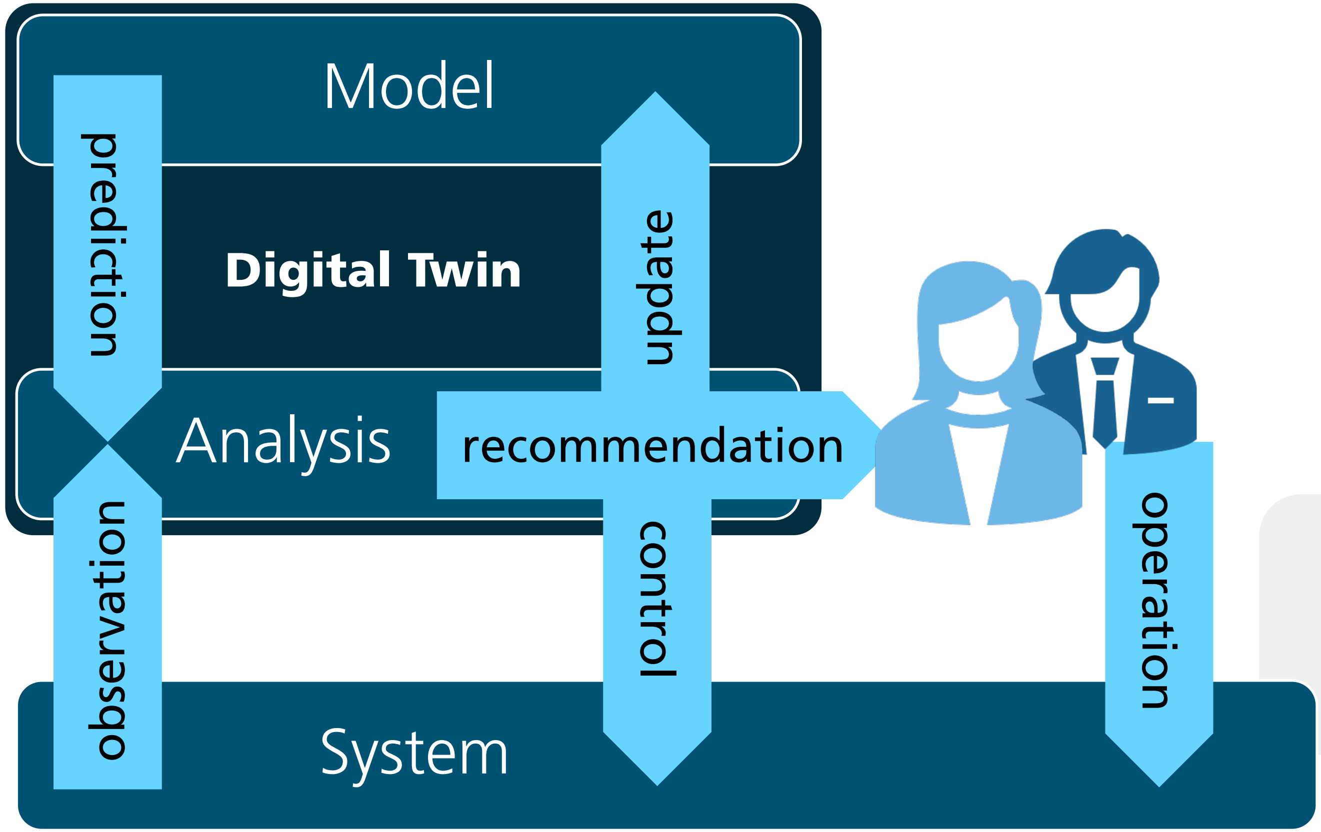




Performance evaluation of different concepts for SSR counter measures

Observation by Digital Twin

Introduction and application to a critical system at operation:



- Digital Twin receives operational conditions and sensor data from the system: Observation
- Behaviour model predicts expected state and behaviour of the system: Prediction
- Based on the deviation between prediction and observation:
  - Update behaviour model, identify system state or operational condition
  - Send signal for active system control
  - Prepare information and recommend activity to experts

Performance evaluation of different concepts for SSR counter measures

Observation by Digital Twin

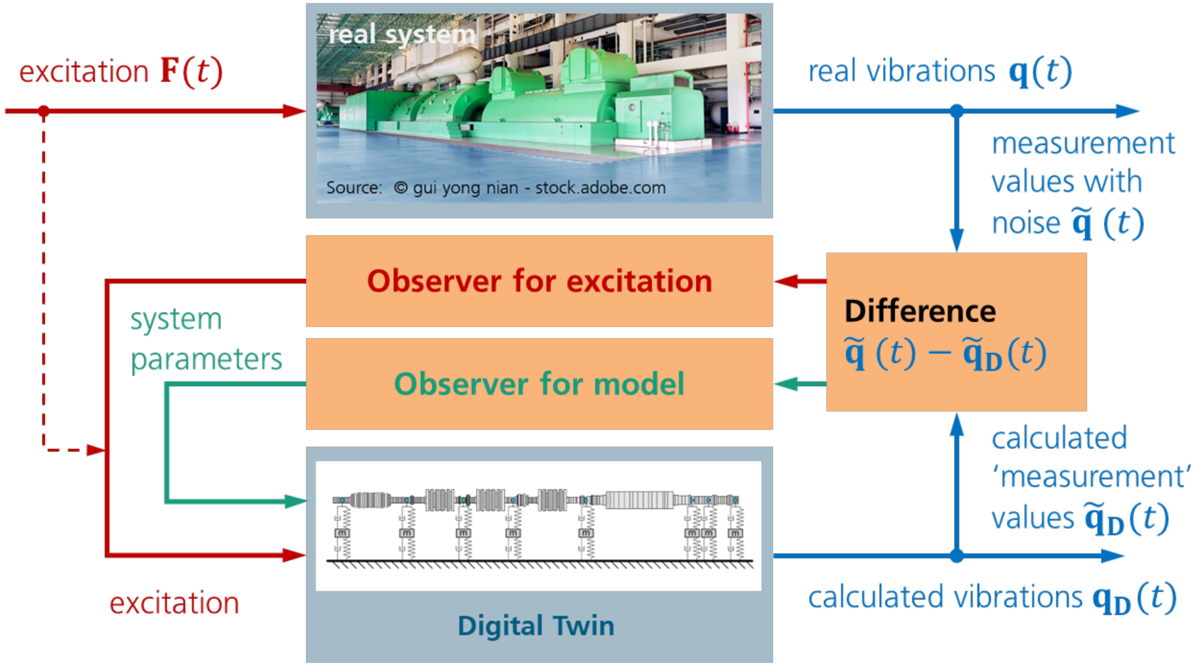
Description of measure

Monitoring the drive train → identification of parameters and diagnosis of failures

From **deviations** between the selected real vibrations $\tilde{\mathbf{q}}(t)$ and the corresponding calculated vibration $\tilde{\mathbf{q}}_{\mathrm{D}}(t)$ possible **parameter changes** or **failures** in the real system can be identified (failure diagnosis).

Events, important to detect early:

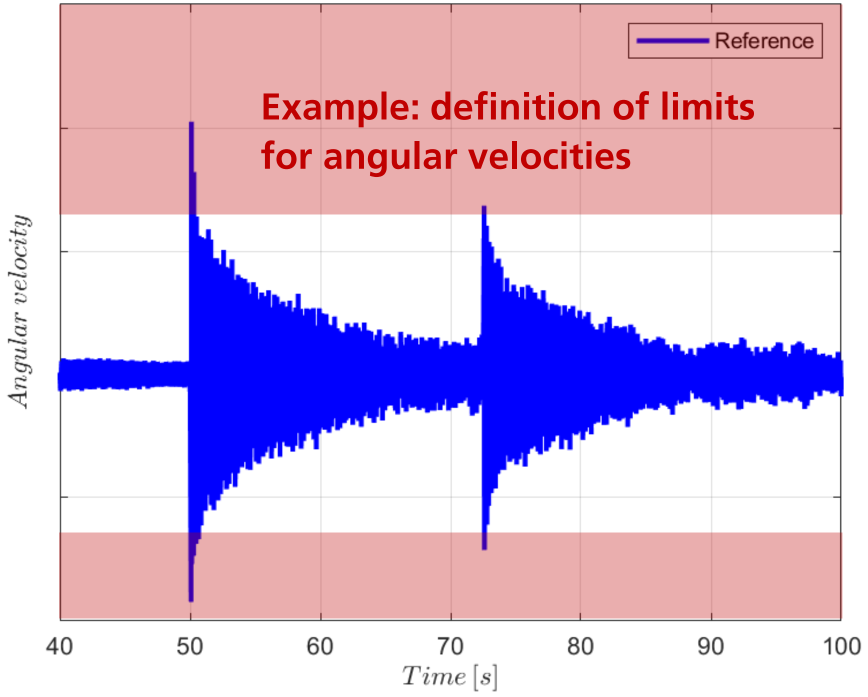
- **increase of air gap torques**
- changes of damping in torsional systems
- shaft cracks, blade failures

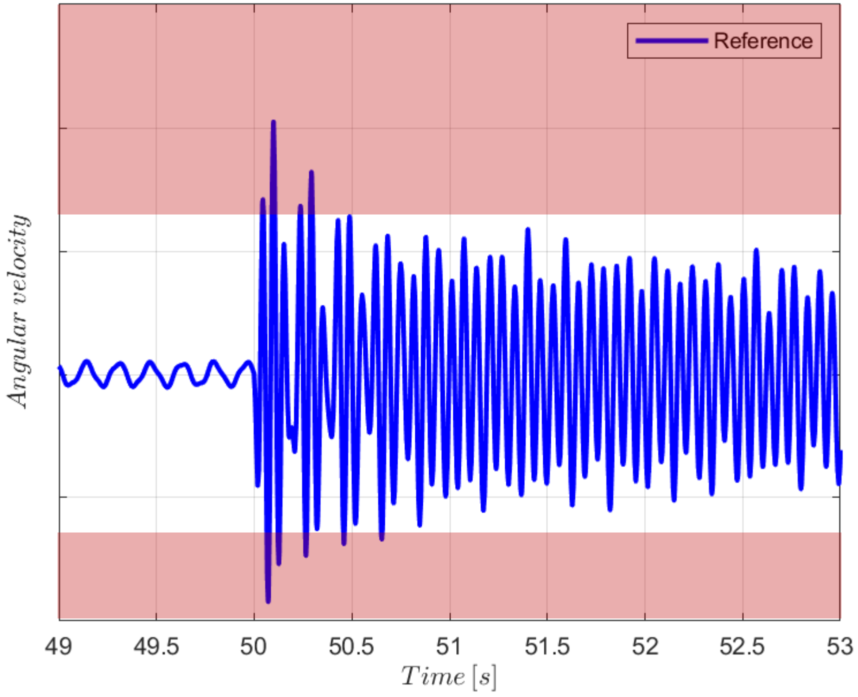


Performance evaluation of different concepts for SSR counter measures

Observation by Digital Twin

Estimation of **air gap torques** and **angular velocities** by **digital twin** to definitely **identify a SSR problem** and propose adequate recommendations to the plant operator





Counter measures to SSR problems in turbogenerators

Evaluation of the concepts investigated

	effectivity (h → l , ++ → --)	effort (h → l , -- → ++)	installation space (h → l , -- → ++)	energy required (h → l , -- → ++)	managed by
electrical tuning (conventional measure)	+	0	0	+	network operator
mechanical rotational damper	+	+	+	++	power plant operator
mechanical rotational absorber (adaptive)	0 (+)	+ (0)	+	++ (+)	power plant operator
AVC by rotational inertial mass actuator with velocity feedback	++	-	+	0	power plant operator
Digital Twin	+	0	++	+	power plant operator

Counter measures to SSR problems in turbogenerators

Summary and Outlook

Summary

- mechanical measures significantly contribute to a reliable operation of the turbogenerator
- such measures can be integrated directly into the rotating system and can be configured/managed by the plant operator
- installation space and maintenance costs are low (energy consumption is 0 for passive and low for active mech. measures)
- Digital Twins are useful for decision support during SSR events in addition to other advantages

Outlook

It's proposed to investigate a specific system and SSR protection approaches for it by e.g. a feasibility study to

- consider the **whole system** (drive train, generator, grid, protection methods) for specific turbogenerator/grid combination
- evaluate protection methods with more detailed modelling
- derive a first design of the most promising protection concept

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