SSO in inverter dominated systems and concepts for a new protection

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Agenda

- Introduction
- SSR @ generator (torsional resonance)
- Function for detecting torsional resonance
- Detecting converter driven instability (slow)

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Motivation & Challenges

- SSR/ SSO occurs due to interaction between electrical and mechanical system frequencies below the nominal grid frequency (i.e., below 50/60 Hz).
- Common in series-compensated lines and renewable energy systems
- Risks include mechanical stress, equipment damage, and blackouts
- Increased inverter-based resources (IBRs) raise SSR risks
- Instability in power system operation. Risk of cascading failures if not mitigated
- Traditional methods struggle with noise and dynamic conditions
- Need for real-time, robust, adaptive protection algorithms

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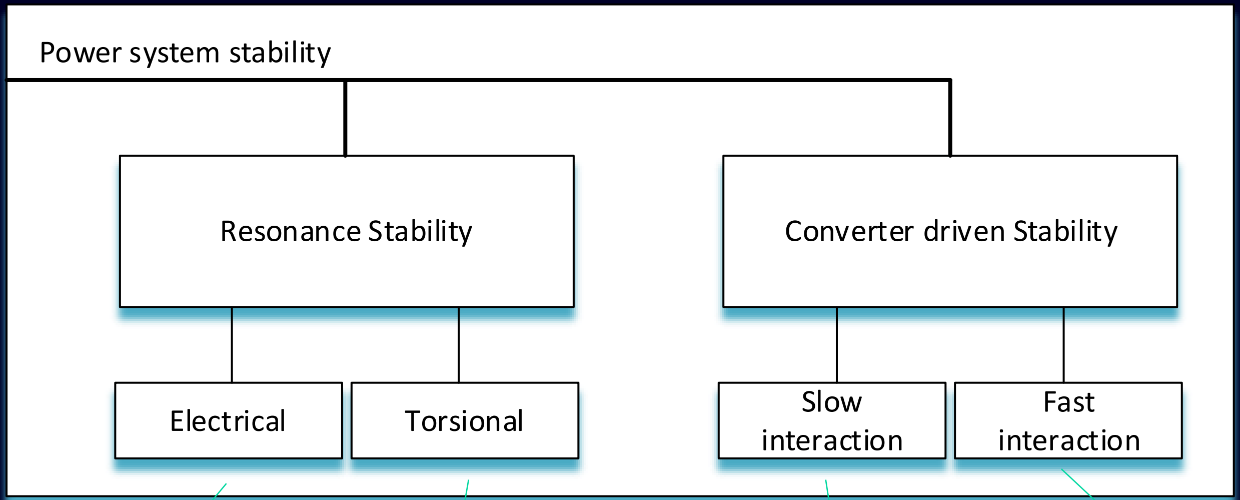
Motivation & Challenges

These interactions can amplify oscillations instead of damping them, potentially causing:

- Voltage and power oscillations
- Excessive torsional stress in rotating machines (in classical SSR)
- Grid instability or protection trips
- Flicker and harmonic interactions
- Localized grid disturbances, especially near large, rapidly varying loads

New power system stability classes



A resonance between **series compensated network** and electrical characteristics of a **DFIG type wind power plant.** Typically occurs in frequencies of 5-40 Hz.

A resonance between **series compensated** network and mechanical torsional frequencies of a **turbine-generator shaft**

Slow dynamic interactions of the **control systems** of power electronic-based devices with network. Typically occurs in frequencies 40-60 Hz.

Fast dynamic interactions of the **control systems** of power electronic-based devices with power system. Typically occurs in frequencies >100 Hz.

SSR @ generator (torsional resonance)

SSR @ generator dominated networks with series compensated lines

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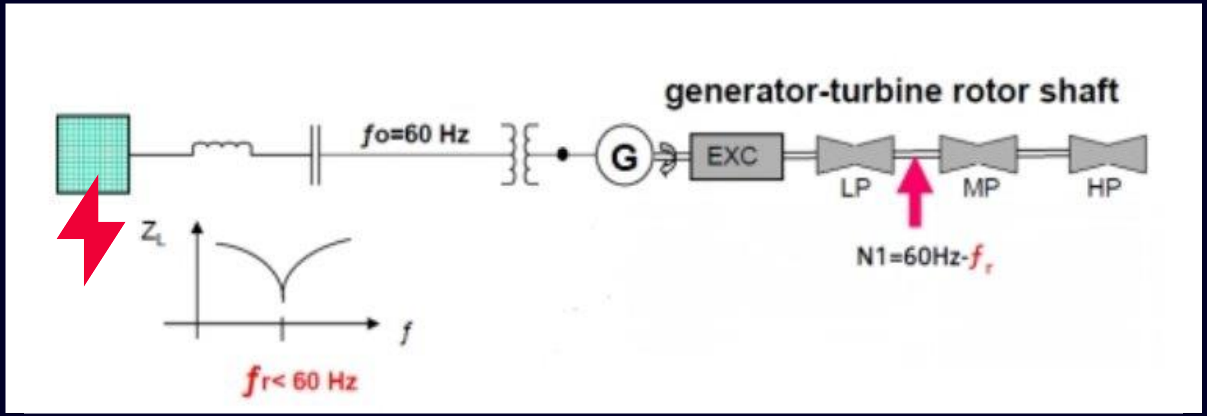
SSR @ generator
Torsional stability (generator)

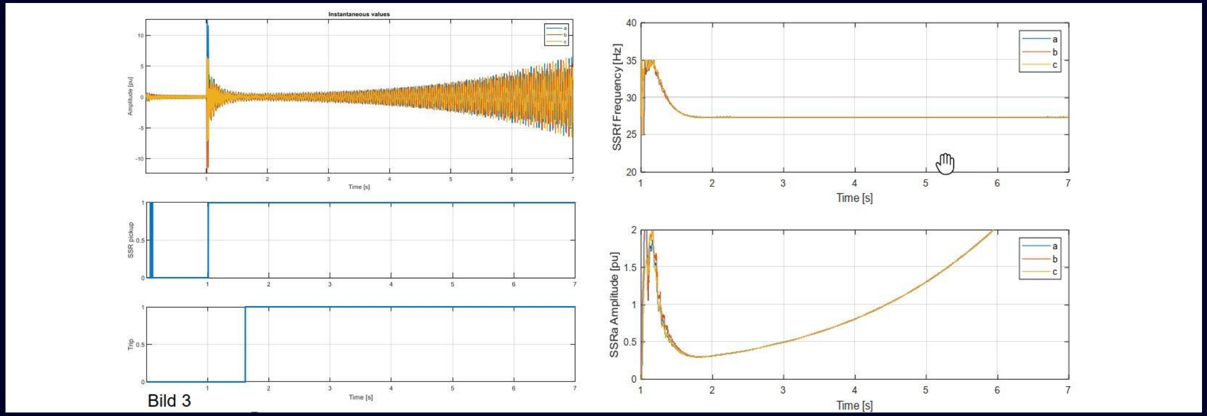
Prevent your installation from **being damaged** by **Subsynchronous Resonance (SSR)** using by a fast fault detection for SSR

SSR is a complex and dynamic phenomenon in power systems where electrical networks interact with power plants.

SSR refers to the condition where the electric network exchanges energy with a turbine-generator shaft at a frequency lower than the fundamental frequency of the system and **can cause serious mechanical and electrical problems**.

SSR leads to **oscillations at a frequency below the synchronous frequency of the system**, which is typically 50 Hz or 60 Hz.





Simulation of SSR

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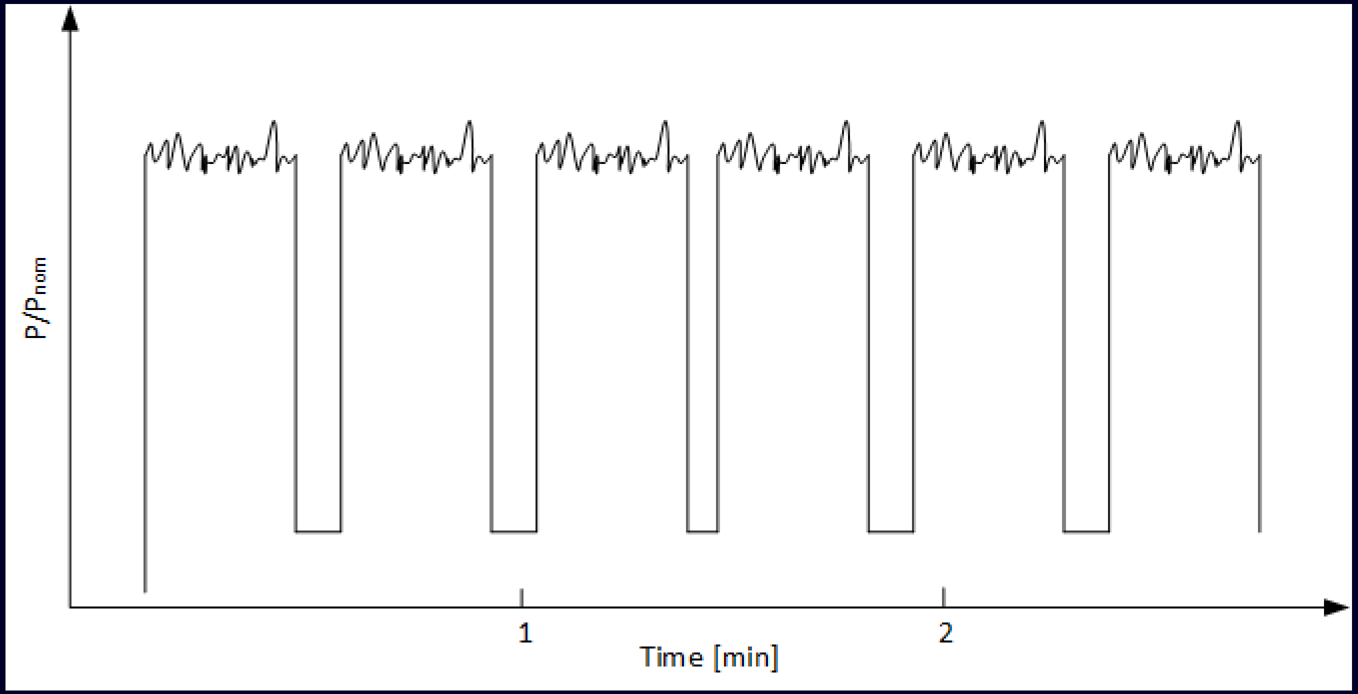
SSR @ generator
AI Training Datacenter

- Training process of large AI models produces a cyclic load i.e. 600 MW.
- Pulsing load can force resonances with the network
- Problems:
  - < 1 Hz inter area oscillations
  - 1 Hz-2.5 Hz power swings
  - 7-100 Hz torsional instability



- Details in: Power Stabilization for AI Training Datacenters https://arxiv.org/abs/2508.14318v2

Function for detecting torsional resonance

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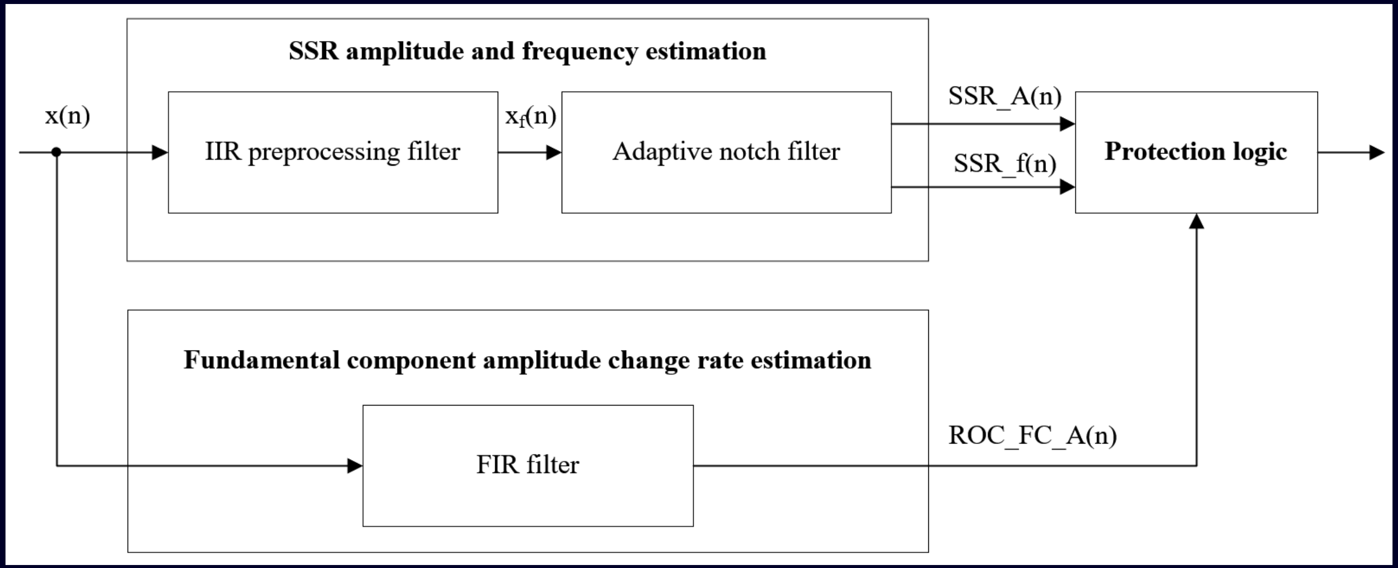
Methodology functional Overview

Three-stage signal processing:

1. IIR Filter – isolates SSR frequencies range
2. Adaptive Notch Filter (ANF) – tracks dominant frequency and amplitude
3. FIR Filter – estimates rate of change of fundamental component



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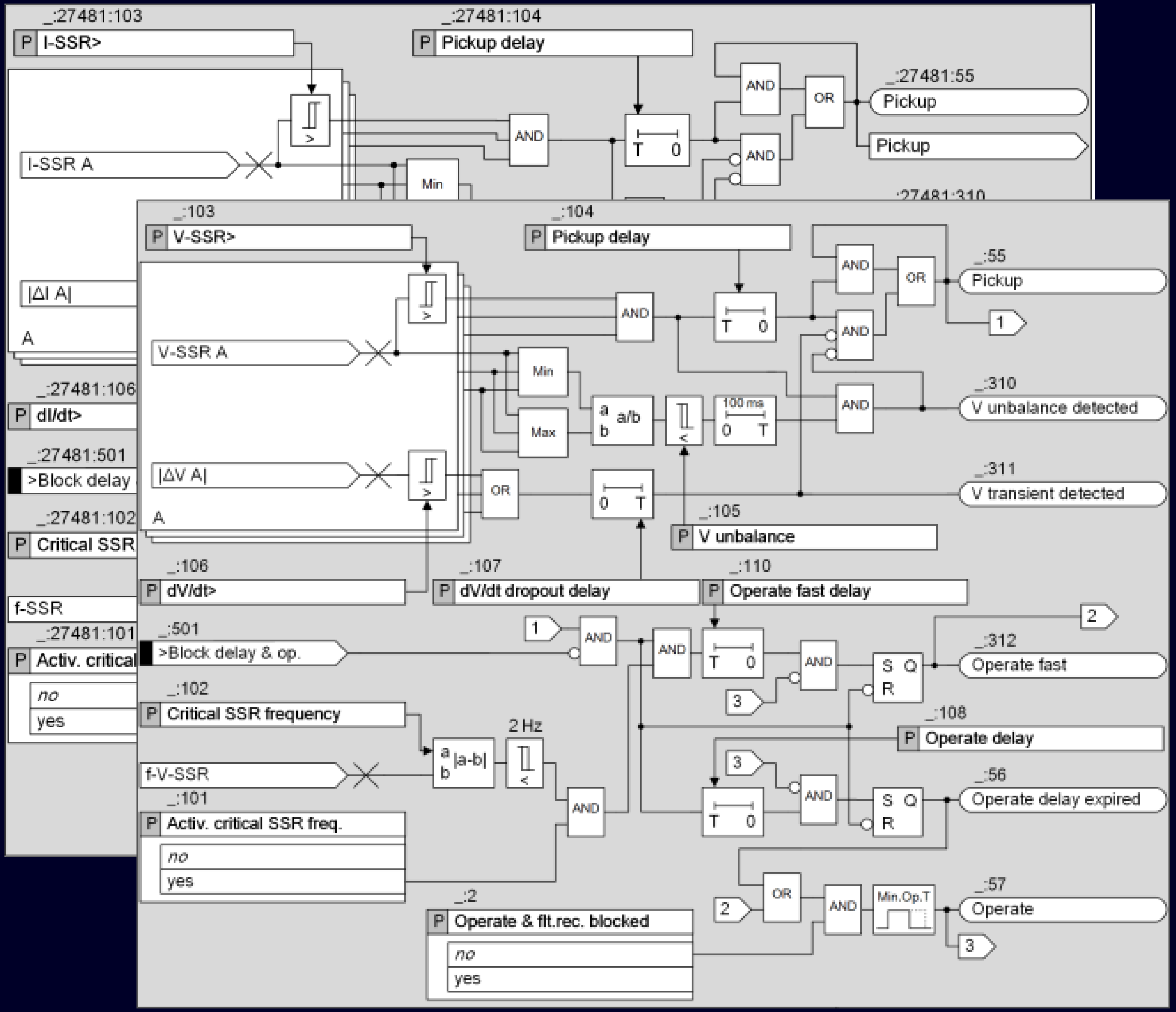
SSR Detection Logic

Four logical elements:

- SSR start detection
- Asymmetry check
- Transient blocking
- Critical frequency check

- Combined to form pickup and operate
- 2 stages current and voltage based

logic



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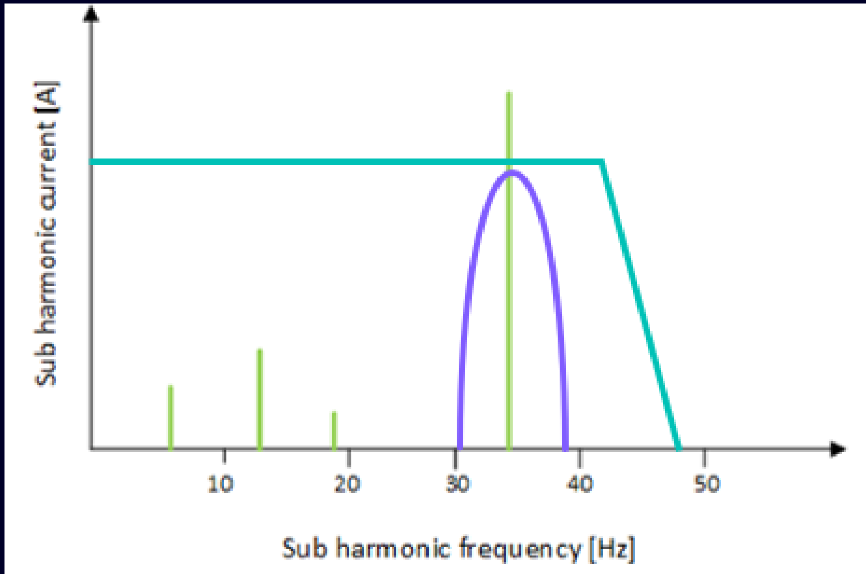
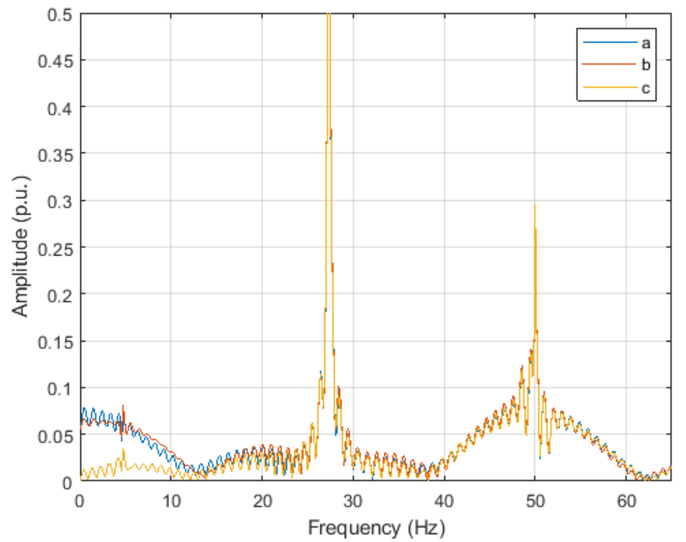
SSR @ generator



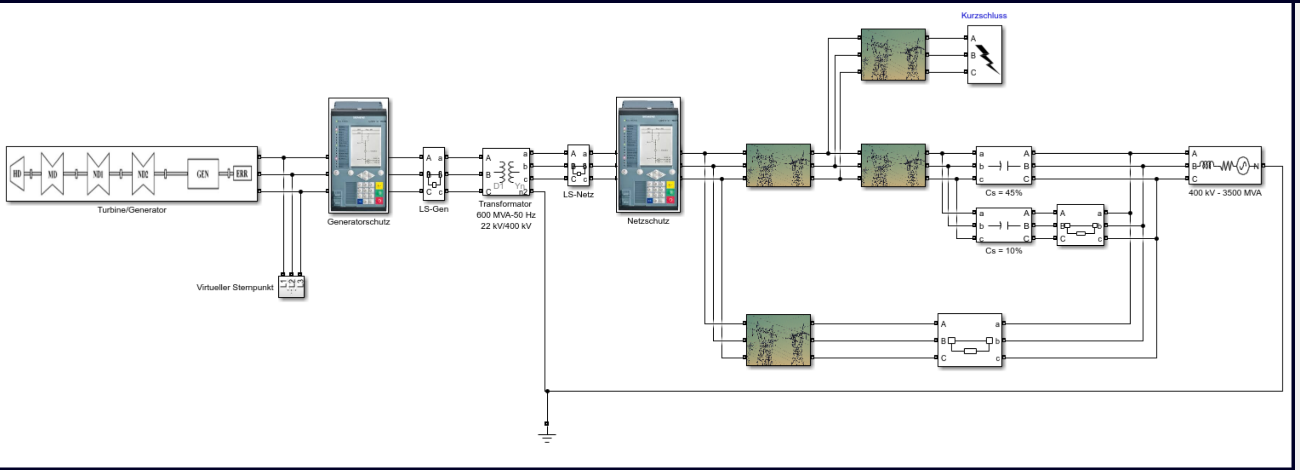


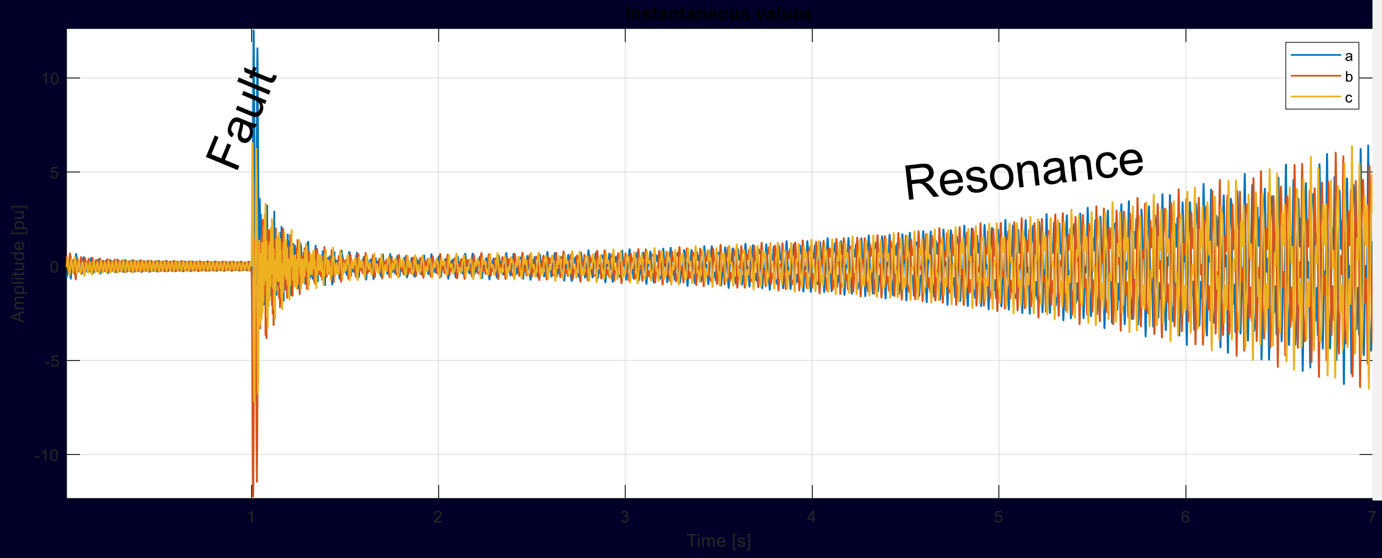
Frequency Spectrum of generator currents.

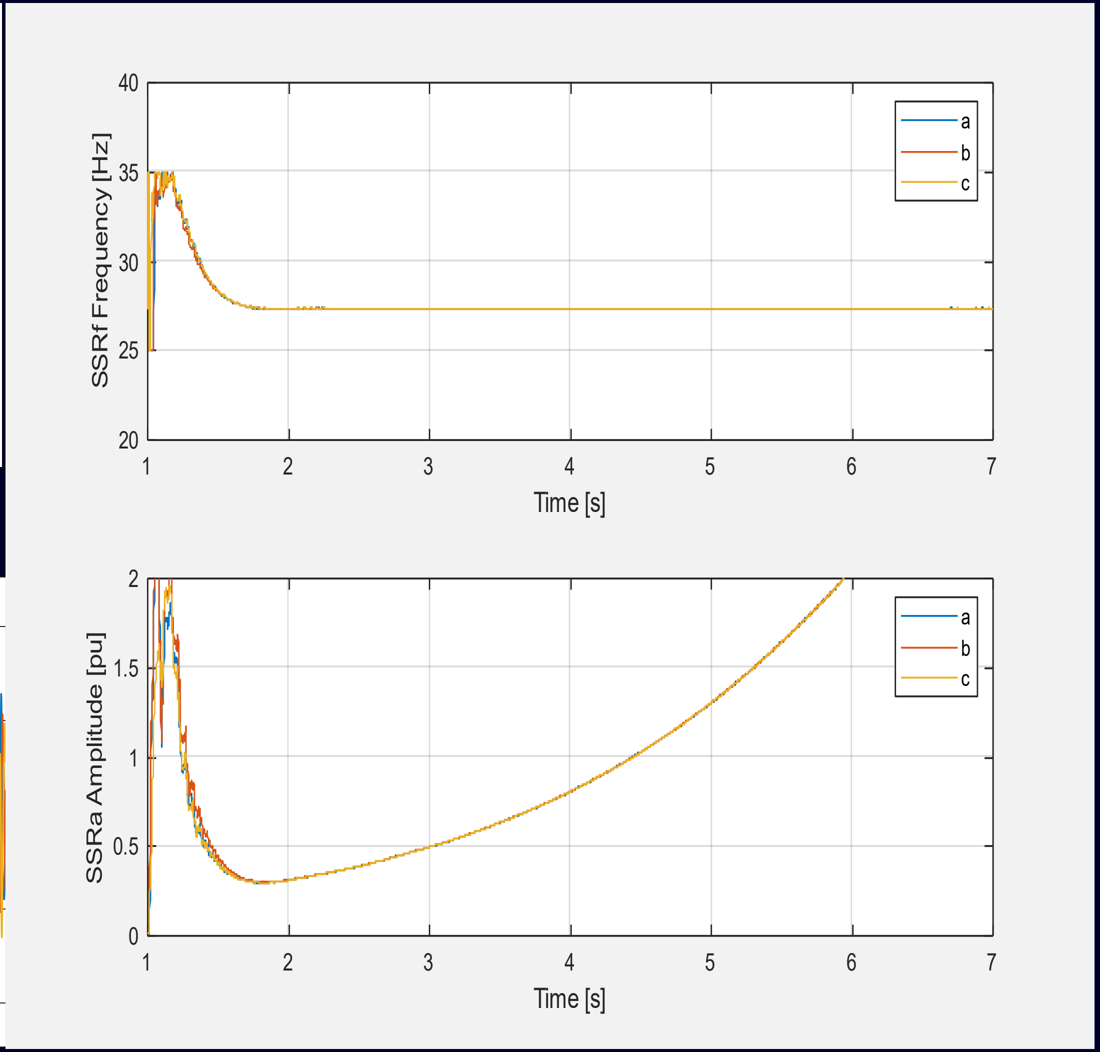
Simulation Validation

- IEEE SSR First Benchmark Model used in MATLAB/Simulink
- Validated algorithm performance under various SSR scenarios
    - Normal operating conditions without SSR.
    - Conditions with varying levels of series compensation, which are known to induce SSR.
    - Disturbances such as sudden load changes or faults that could trigger SSR phenomena.
    - Field Validation – real data from DFIG wind farm in Finland
- Variation: amplitude, frequency, asymmetry, rate of change
    - Generator Parameters: Inertia constant (H), damping coefficient (D), and rated power.
    - Transmission Line Parameters: Length, series compensation level, and line resistance.
- Filter Parameters:
    - IIR filter cut-off frequencies and order.
    - ANF adaptation rates and notch depth.
    - FIR filter coefficients for rate-of-change detection.

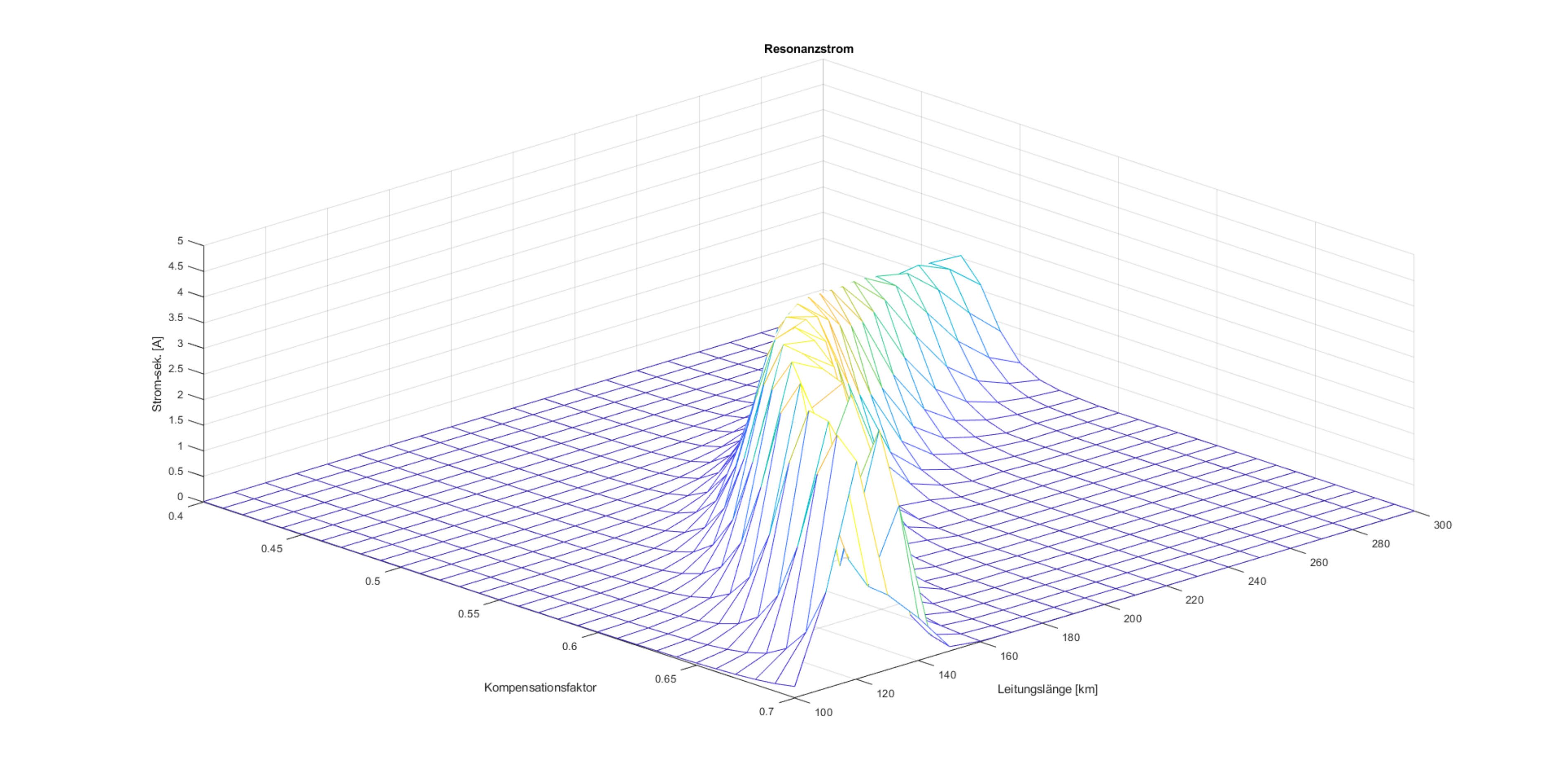
SSR @ generator
IEEE simulation model







SSR @ generator
simulation example: resonance current as function of line length and compensation factor



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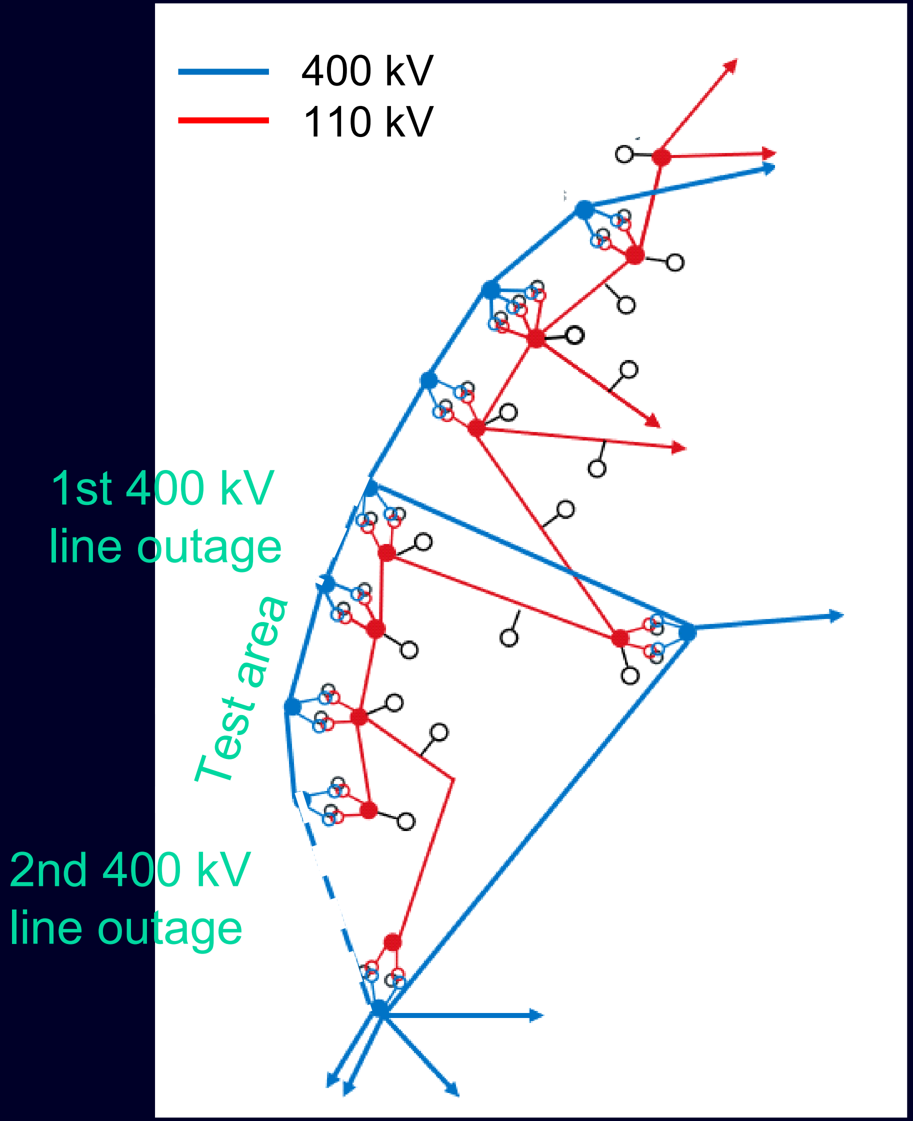
Detecting converter driven instability (slow)

Network tests in 2025

- Two 400 kV line outages were conducted which weakened the grid at the test area.
- Test area was connected to the transmission grid with two 110 kV lines.
- Nominal wind power capacity at the test area is about 1600 MW.
- Wind power production is low in the beginning of the test.
- Oscillations started when wind power level reach 24% of the nominal power at the test area.
- Network test was operated for 2.5 hours.



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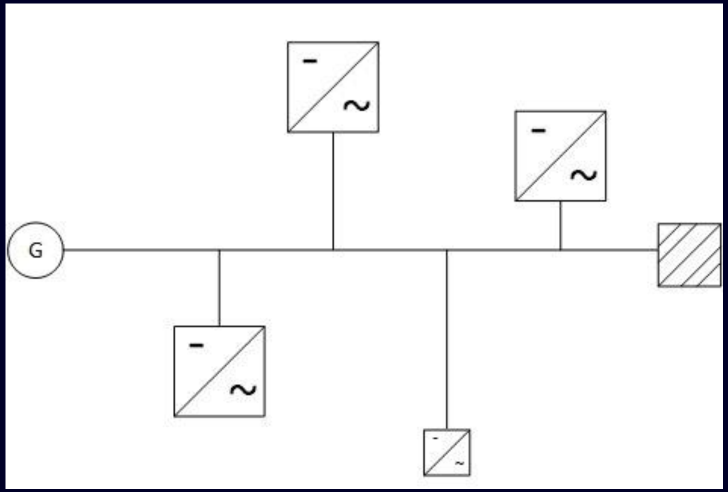
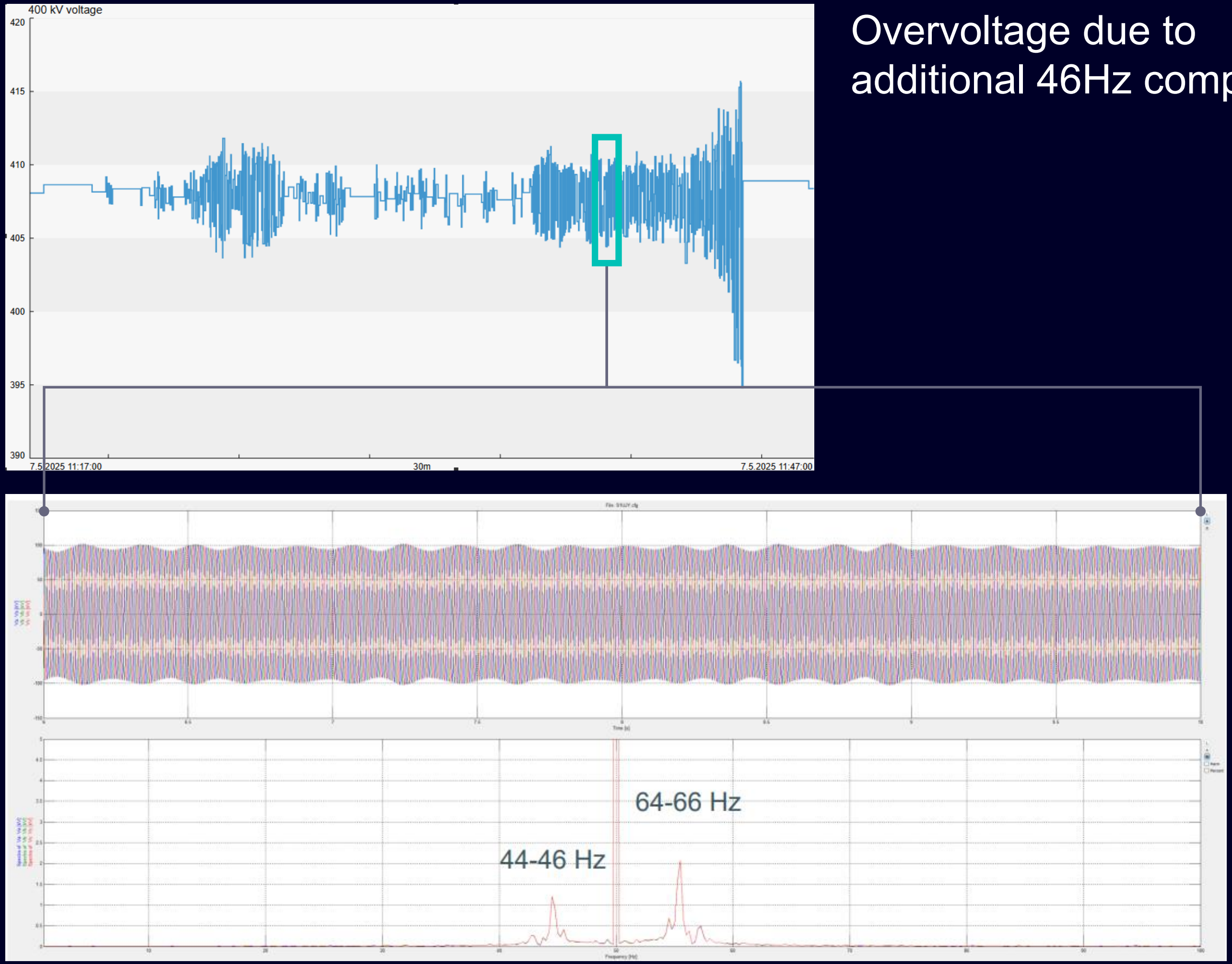
SSO @ inverter
Converter driven - slow (Inverter dominated SSO)

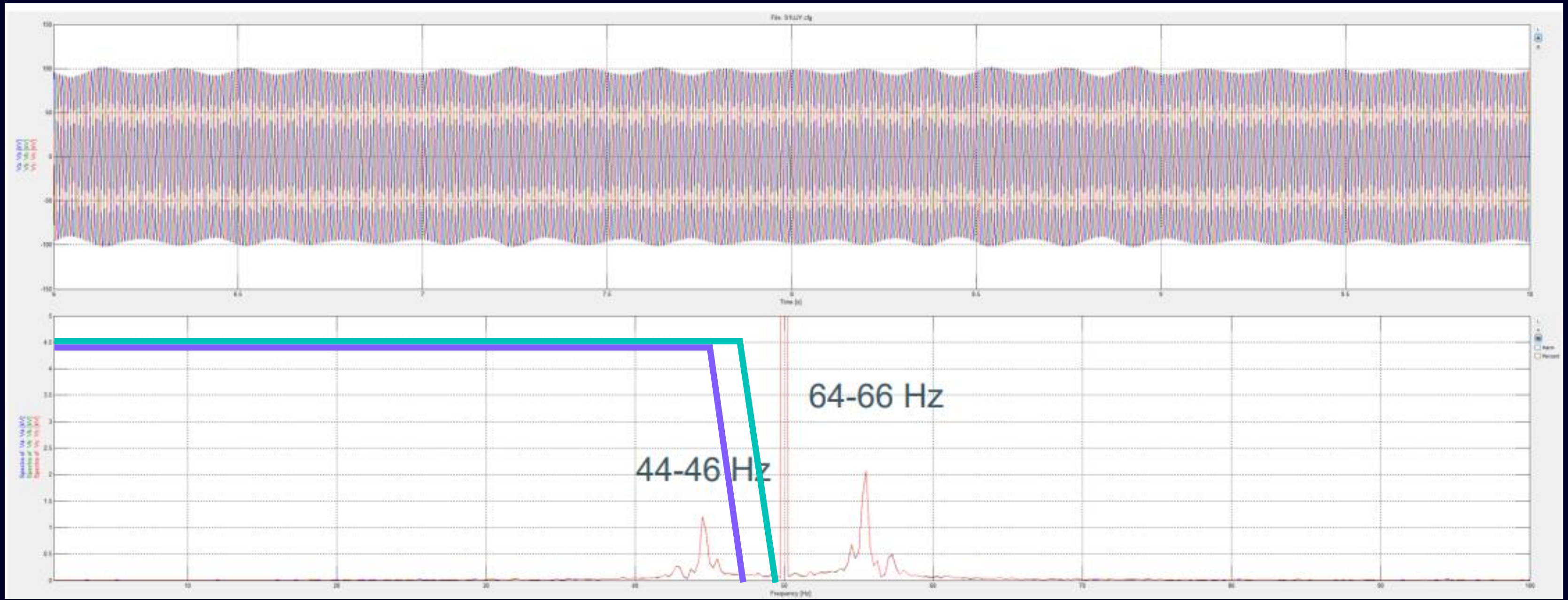


- Less conventional infeed
- More inverter infeed



Overvoltage due to additional 46Hz component

SSO @ Converter
Challenge



SSO Generator

SSO Converter

Overvoltage's due to additional 46Hz component

Challenge separate

- 48 Hz from 50 Hz
- 58 Hz from 60 Hz

Special filter design necessary

Value of the Application parameter	Setting range of the Critical SSR frequency parameter
generator dominated	5.0 Hz to 45.0 Hz at f_{rated} = 50 Hz 5.0 Hz to 55.0 Hz at f_{rated} = 60 Hz
converter dominated	5.0 Hz to 48.0 Hz at f_{rated} = 50 Hz 5.0 Hz to 58.0 Hz at f_{rated} = 60 Hz

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SSO improvements, enhancements

- Generator SSO U> stage
- Generator SSO P> stage
- P ~ electrical moment

- Inverter SSO I> stage
- Inverter SSO U> stage

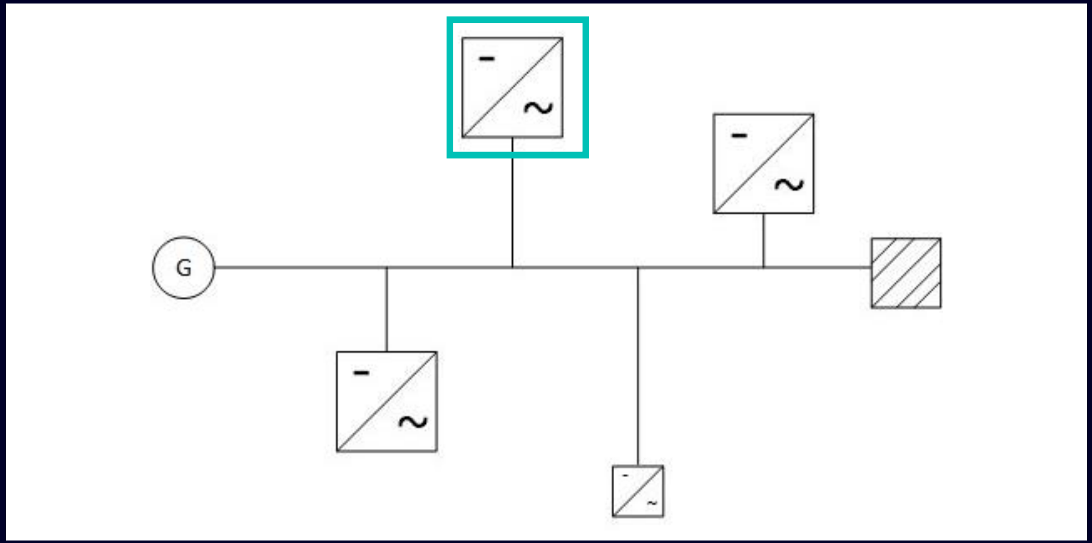
- Inverter SSO P stage
- Inverter SSO Q stage

Determination of the source

SSO with super harmonics $f_{SSO} > f_n$

! **Research necessary**

Determination of the source of SSO (direction)



Experiences, fault records, cooperation are welcome

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Conclusion

- The Novel SSR protection algorithm improves grid stability
- Future development will focus on enhancing signal analysis, designing new filters for detecting SSR frequencies in the sub and super harmonic range
- Initial deployments with operators such as Fingrid (Finland) and AEMO (Australia) demonstrate the relevance and effectiveness of the solution
- Validated in simulations and field deployments
- Supports safe integration of renewable energy
    - Integration of IBRs with advanced control systems/ strategy
    - Wide area SSR protection based on PMU data/ special protection schemes
- Ongoing research to address evolving grid challenges
- SSR protection detects sub synchronous oscillations early and isolates or dampens the affected generation, preventing damage and stabilizing power flow.

Thank you

for your attention

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