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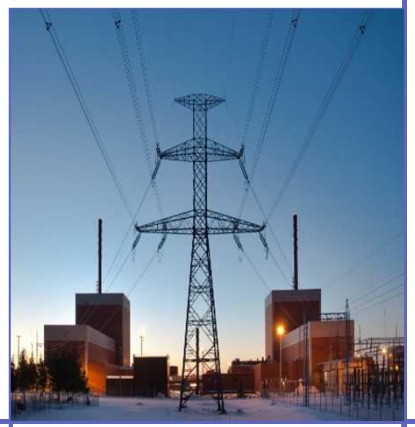

Challenges and Solutions for Numerical Sub-Synchronous Resonance Protection

KTH-Stockholm
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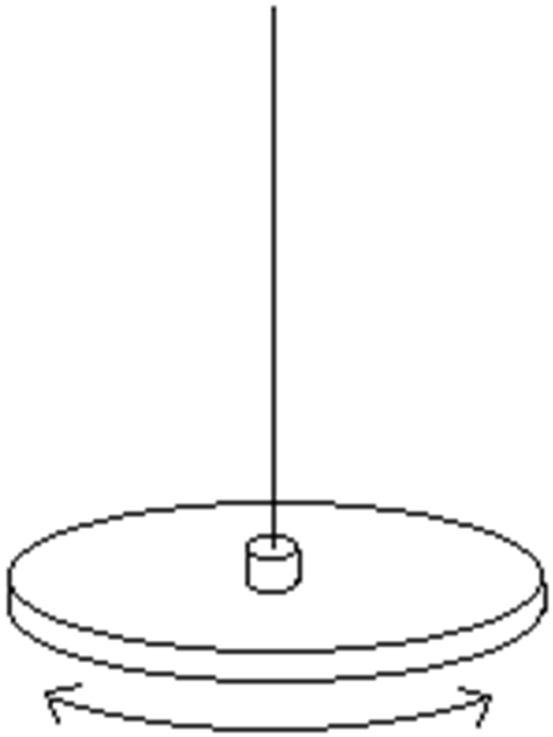
Presentation Content

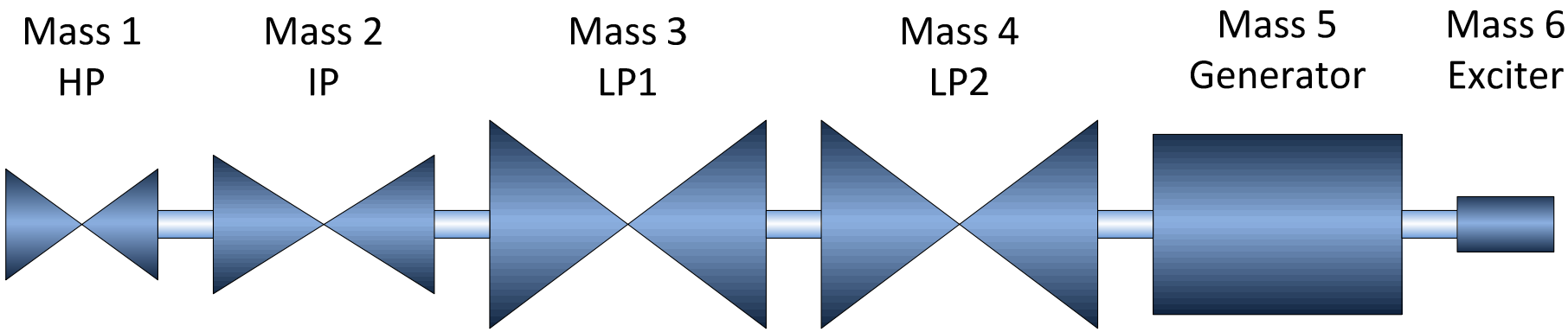
- Short introduction
- Basic SSR Principles
- SSR Relay Trials
- Numerical SSR Relay Installations
- Conclusion

Torsional Oscillations

Back to basics of Mechanical Engineering



How Shaft of a Turbo Machine Look Like



Properties of Turbo Machines
Several items (N masses) on the shaft
Long shaft / axle from 30m up to 100m
These masses can oscillate against each other
N-1 oscillation modes will be present.

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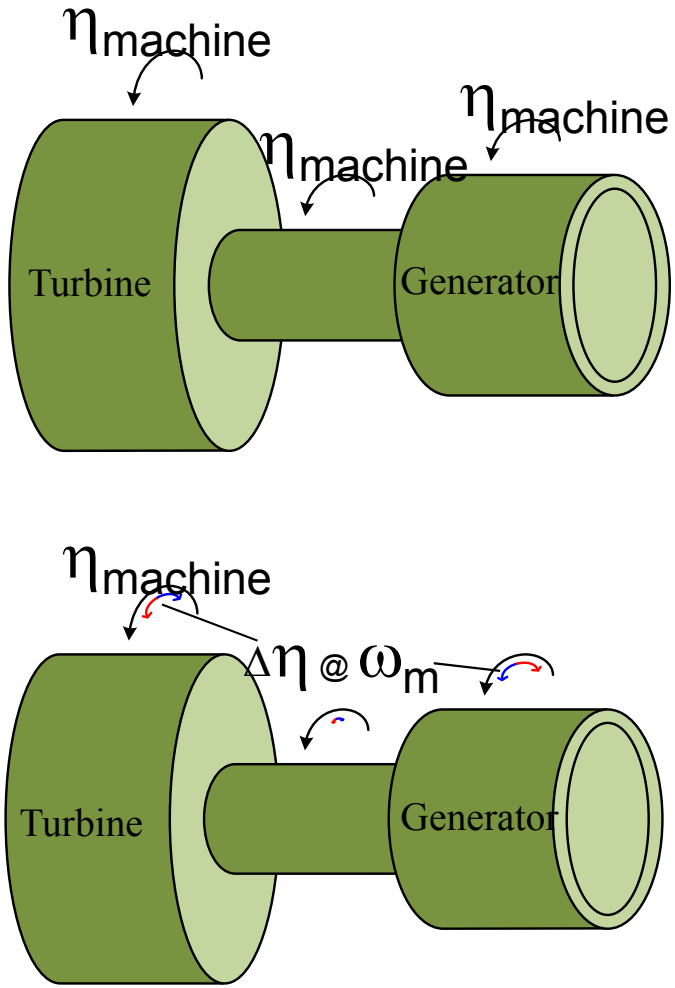
Sub-synchronous Phenomena

Generation of Sub-synchronous Currents



- Under normal conditions

  $\eta_{machine} = \eta_{synchronous}$

  $\omega_{electrical} = \omega_b$

- When perturbed, masses oscillate against each other at natural frequencies of mechanical system (ω_{m1}, ω_{m3}, ω_{m3} …)

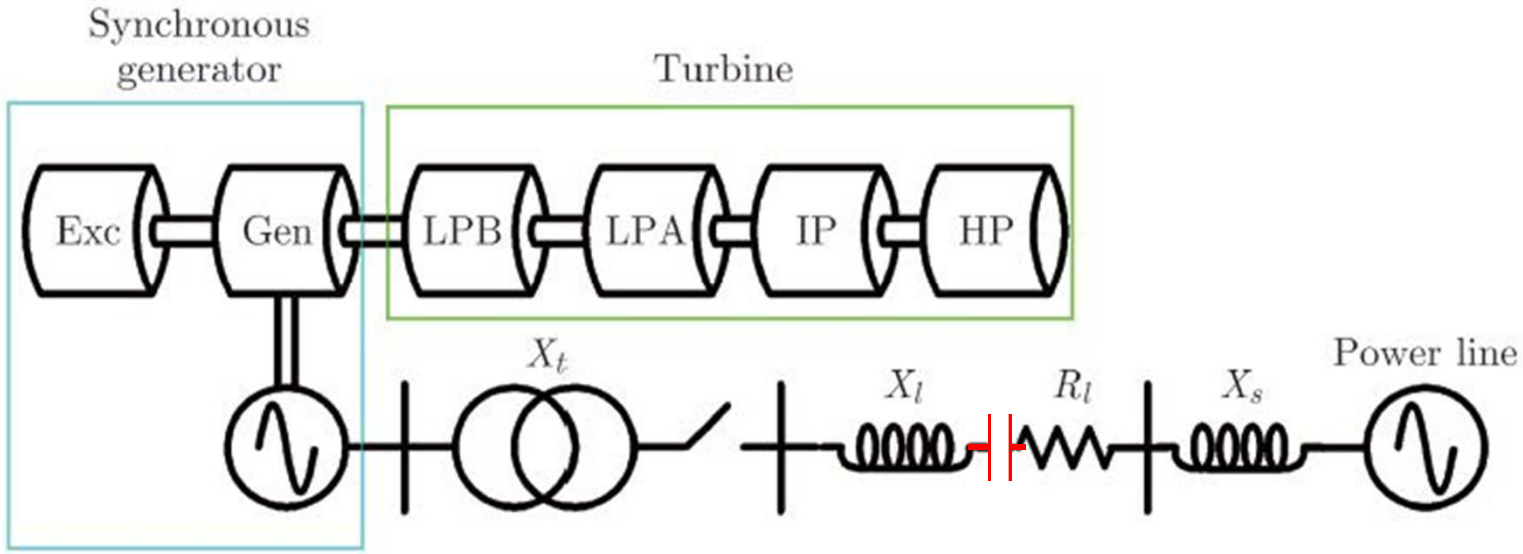
- These natural modes of oscillation modify generator speed and result in currents at new frequencies*

  $$\omega_{em} = \omega_b \pm \omega_{mx}$$

  $$f_{em} = f_b \pm f_{mx}$$

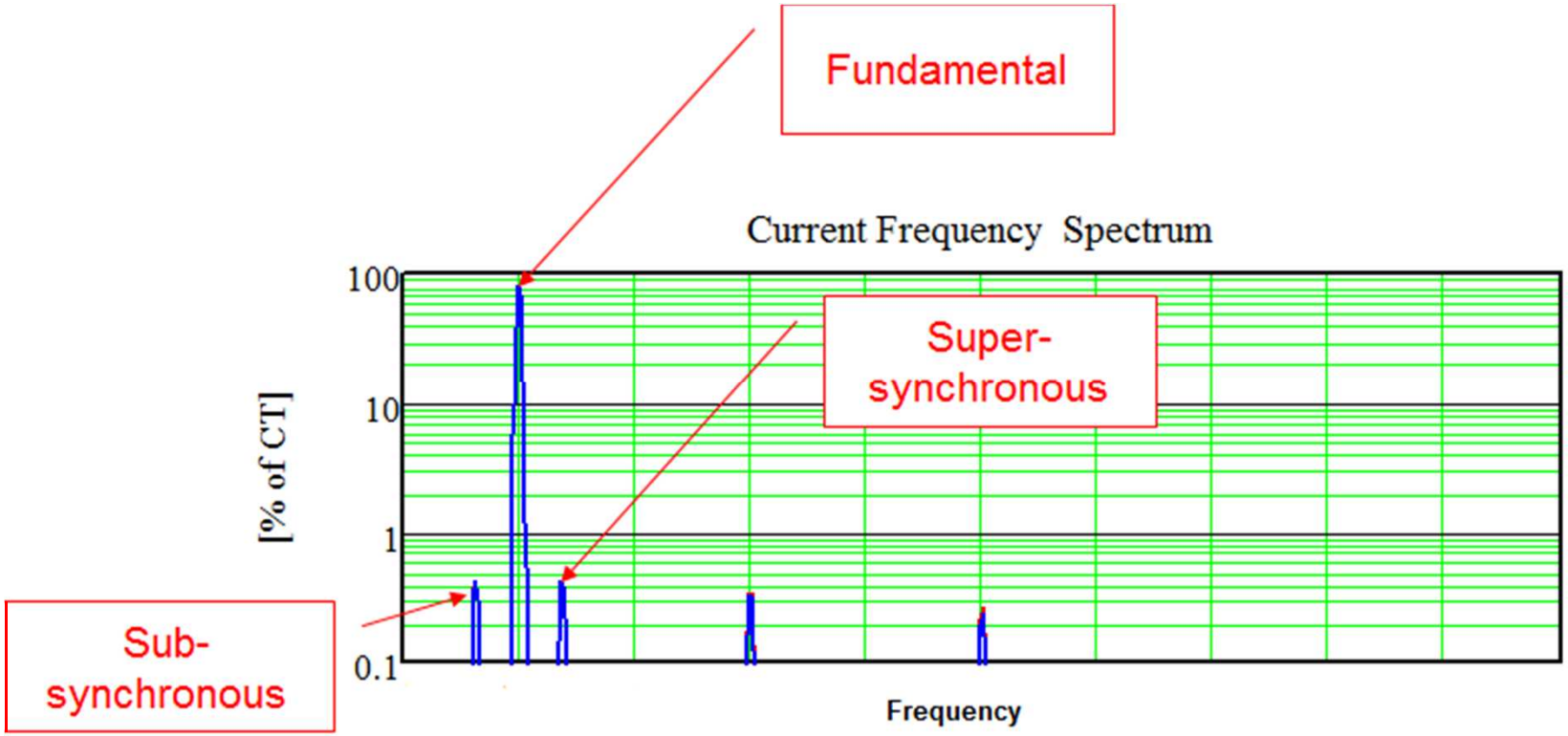
* Other sideband frequencies may also occur but these are the dominant frequencies

SSR is an Electro-Mechanical Process



Danger that this SSR sub-synchronous frequency of U & I can get in resonance with the connected power network
Series compensation of OHLs can cause such resonances

Example of Current Frequency Spectrum during SSR



$$f_{SSR} = f_{Fundamental} \pm f_{mechanical}$$

SSR can be caused by

- Series compensation (series capacitors)
- But also possible to be caused by some controllers:
  - Excitation control
  - Speed governor control
  - Nearby HVDC links control
  - Network switching
- Info from book: “Power System Stability and Control”; P. Kundur; ISBN 0-07-035958-X
- The main concern with SSR is the possibility of rotor damage due to excessive shaft torques.

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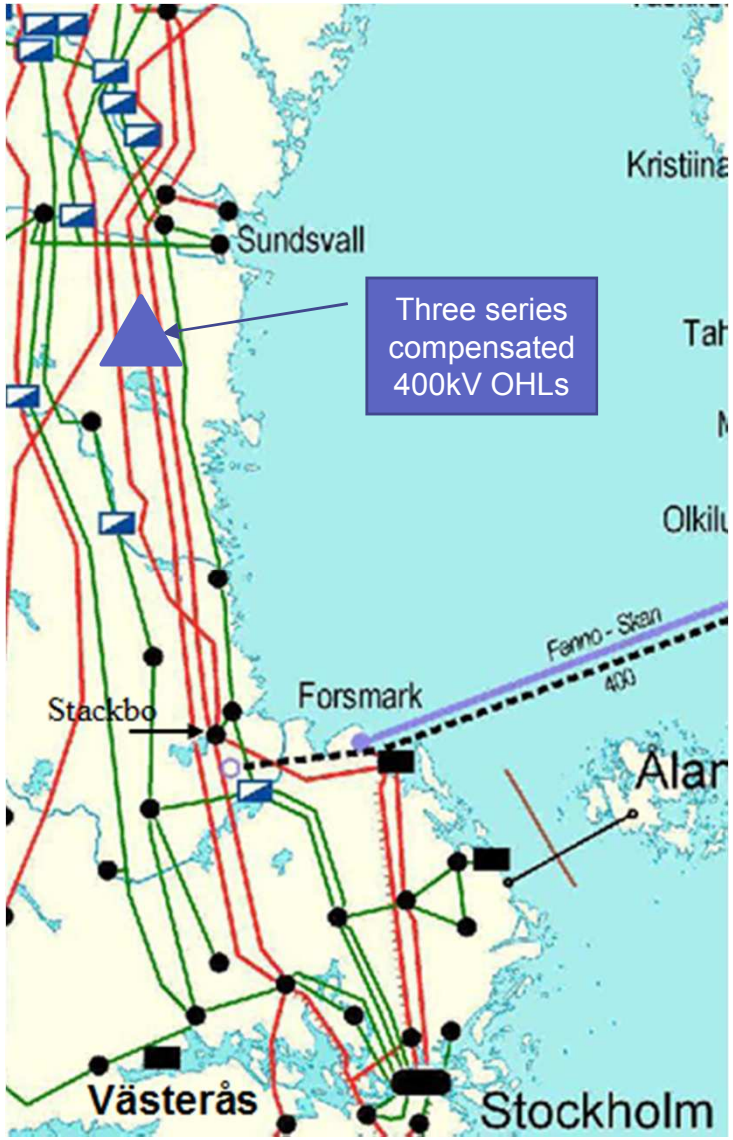
NPP Forsmark 3 Information

- In operation since 1985
- Reactor Type: BWR
- 1190MW; 20,5kV
- Located close to HVDC connection to Finland: Fenno-Skan
- 400kV OHL going north from the NPP are series compensated
- Analogue SSR relay installed in 1985
- Due to shaft change the mechanical frequencies have been moved
- Analogue relay becomes obsolete

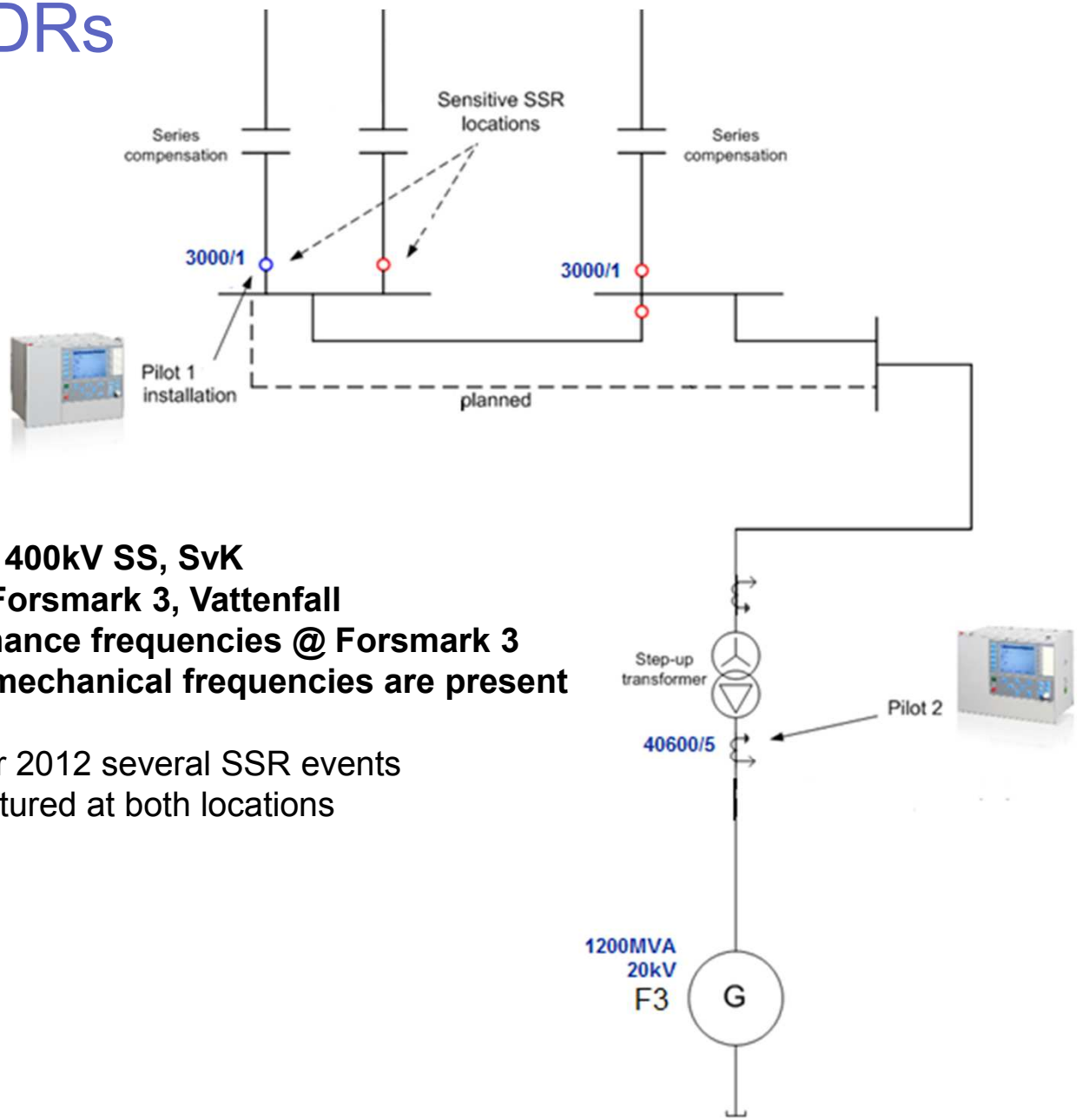
SSR can happen in Swedish Network

- During development of the numerical SSR protection functionality trial installation was used to gather data:
  - Two IEDs were installed which first just recorded Comtrade files when triggered externally due to an SSR event
    - One at 400 kV SS going north
      - Operative since May 2012
    - One in NPP Forsmark 3, on 1190MW generator
      - Operative since July 2012
  - No interaction/communication between the two IEDs



SSR in Swedish Network

Field data from DRs



Pilot1 – 400kV SS, SvK
Pilot2 – NPP Forsmark 3, Vattenfall
Sub Synchronous Resonance frequencies @ Forsmark 3
Two dangerous shaft mechanical frequencies are present

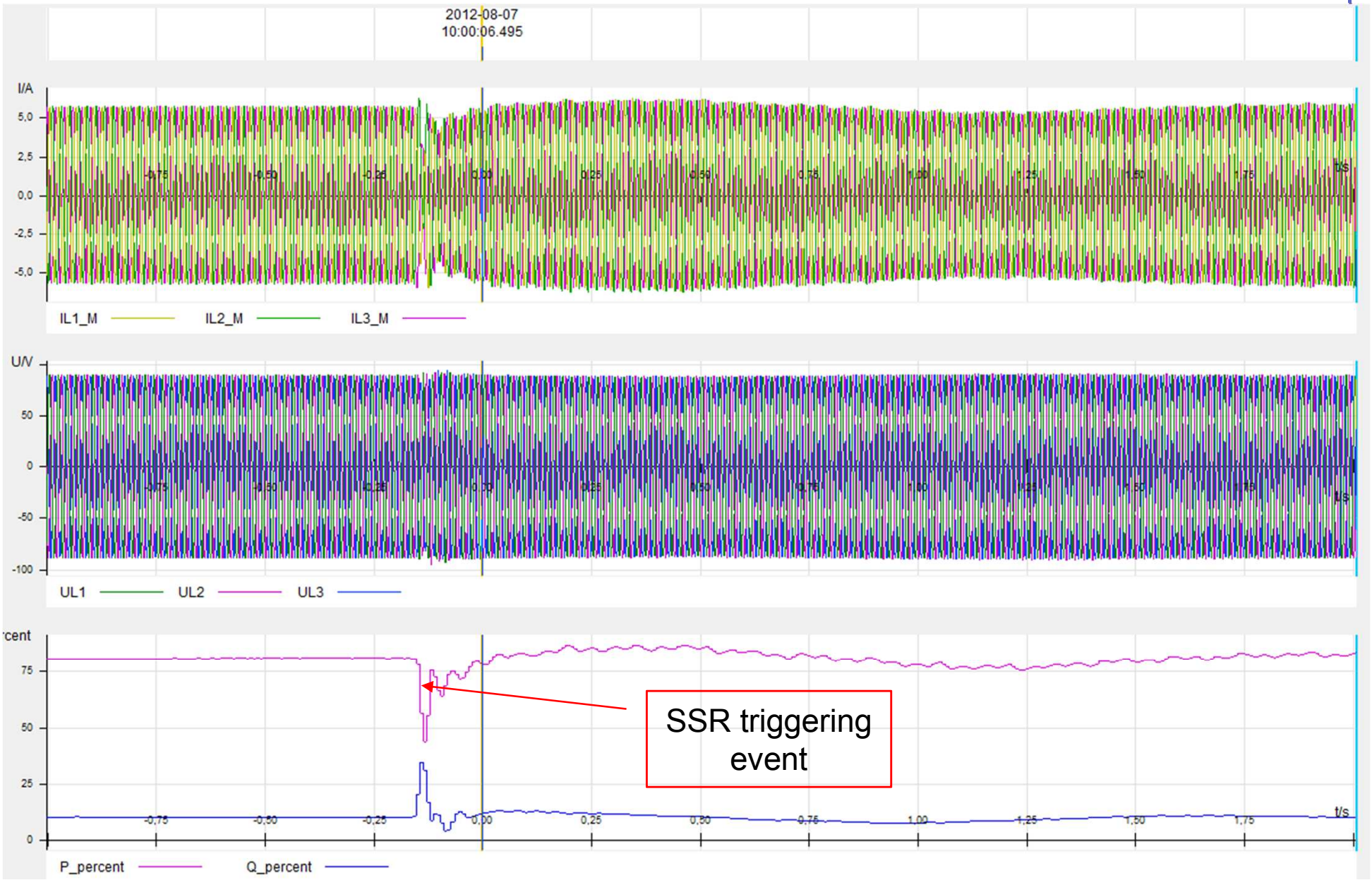
From summer 2012 several SSR events
were captured at both locations

Numerical SSR Pilot Evolution

- From summer 2012 several SSR events were captured at both locations using built-in DR in IED (1kHz sampling rate). Such recordings were analyzed off-line in a software running on a stand-alone PC.
- During Spring 2013 both IEDs were upgraded with new prototype software containing the new filter. From then the captured DRs contained SSR quantities and SSR frequencies estimated by the new filter installed within the IED.
- At the same time logging PC was added in both installations to log every 5s the SSR quantities from the IED filters into the files on the PC hard disk.
- Permanent new SSR protection installation in summer 2015

Event captured on 2012-August-07

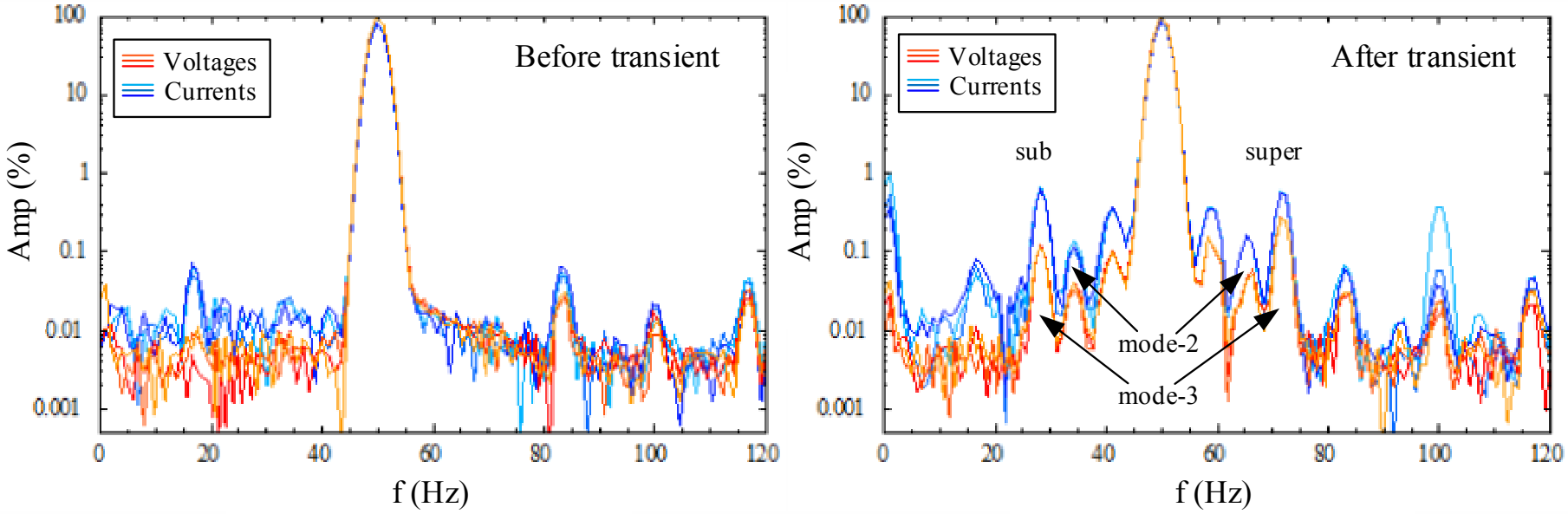
I & U waveforms @ Forsmark 3 machine



SSR event 2012-August-07

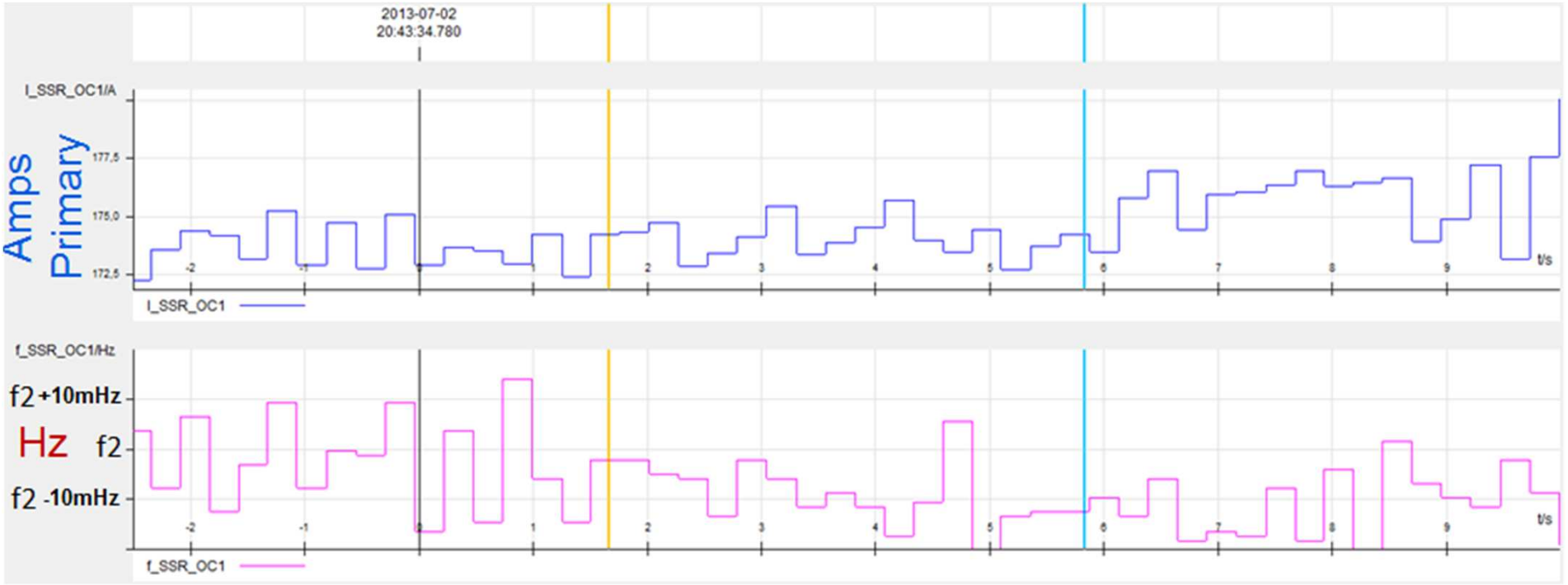
Three resonance frequencies observed

- Clearly appear three frequency pairs:



SSR event captured on 2013 - July - 02

Values from the filter captured by the IED in Forsmark



Note precision with which filter estimates SSR frequency and current magnitude!
Limitation of 11s per DR record
Up to 30 records can be stored in the IED memory (FIFO principle)

SSR event captured on 2013-July-02

Current Values from the PC log file during whole event

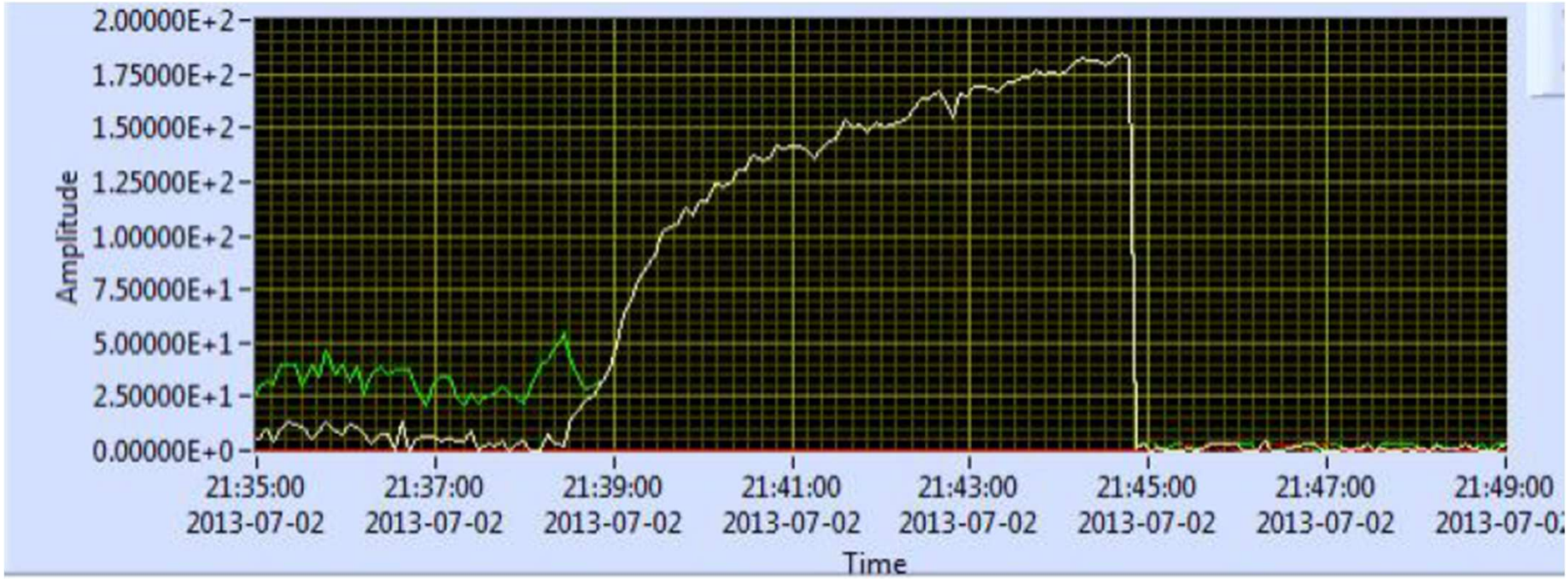
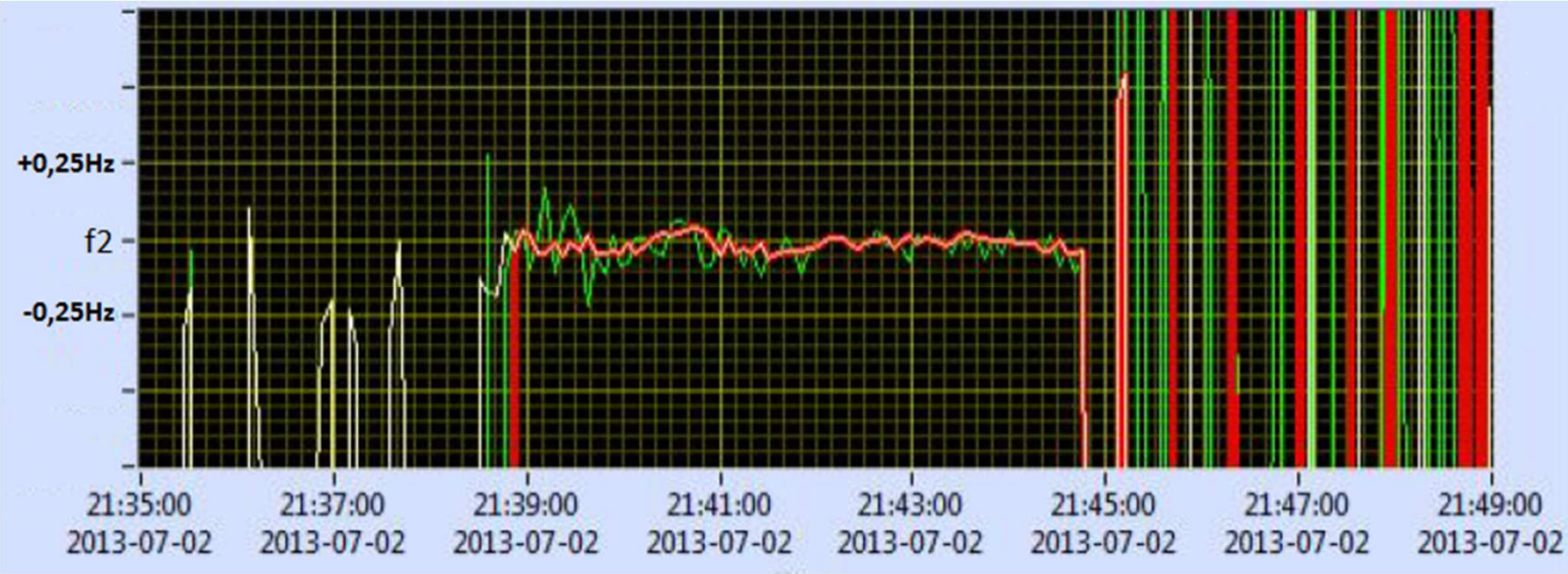


Figure 10: The event at 21:40, June 02 which caused Forsmark 3 to trip.

Note that CT ratio is 40600 / 5 (filter precision !!!)
Such trends can be recorded on a stand-alone PC which logs the SSR current magnitude from the filter implemented within the IED.
SSR events which lasted even for an hour were recorded.

SSR event captured on 2013-July-02

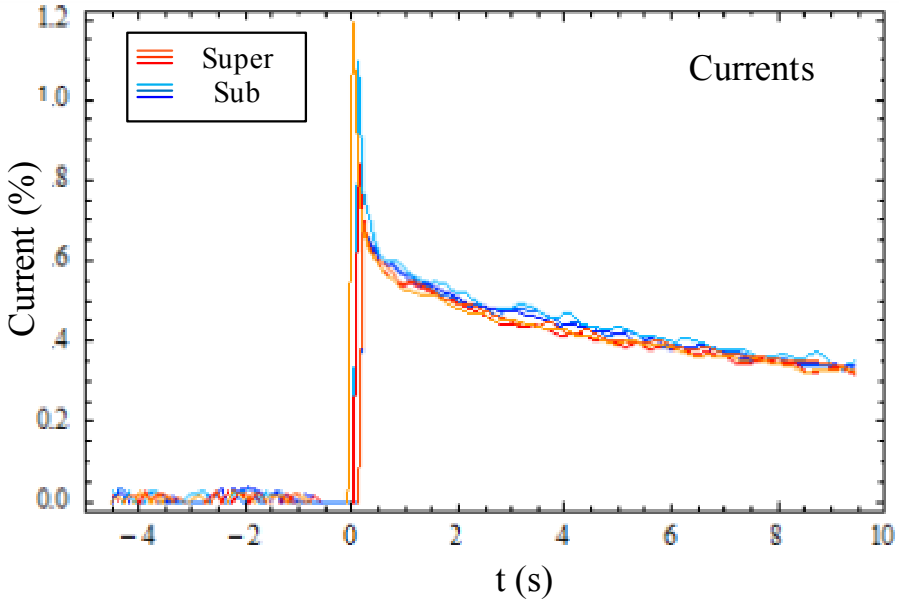
Observed frequency values during whole event

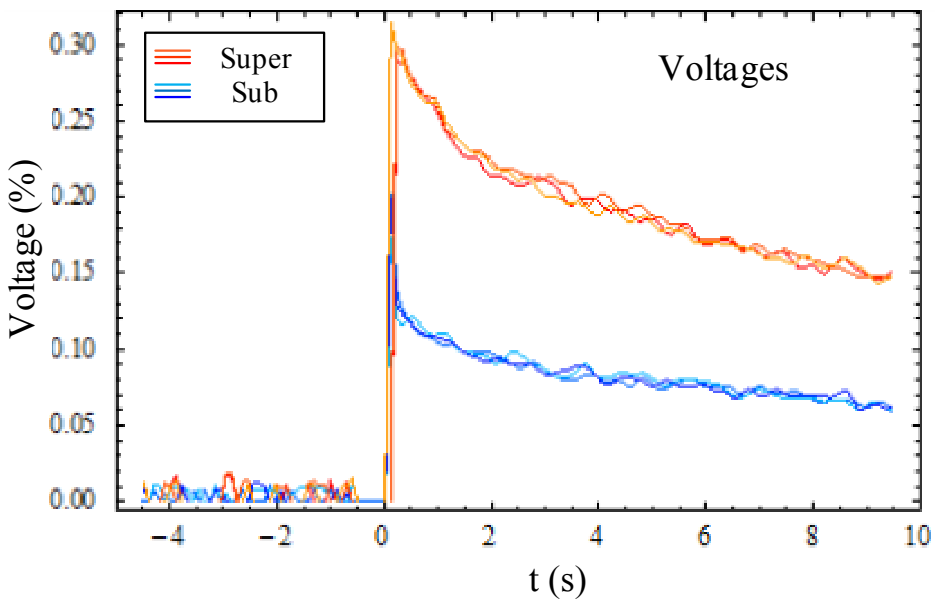


Note that estimated SSR frequency stays during all incident within:

Mode_2_Freq ± 0.1Hz

SSR U& I Relationship at Generator Terminals





$$\frac{|U\_SSR_{Sup}|}{|U\_SSR_{Sub}|} \approx \frac{|E\_SSR_{Sup}|}{|E\_SSR_{Sub}|} = \frac{Freq_{Sup}}{Freq_{Sub}}$$

$$|I\_SSR_{Sup}| \approx |I\_SSR_{Sub}|$$

These relationships do not hold out in the network!

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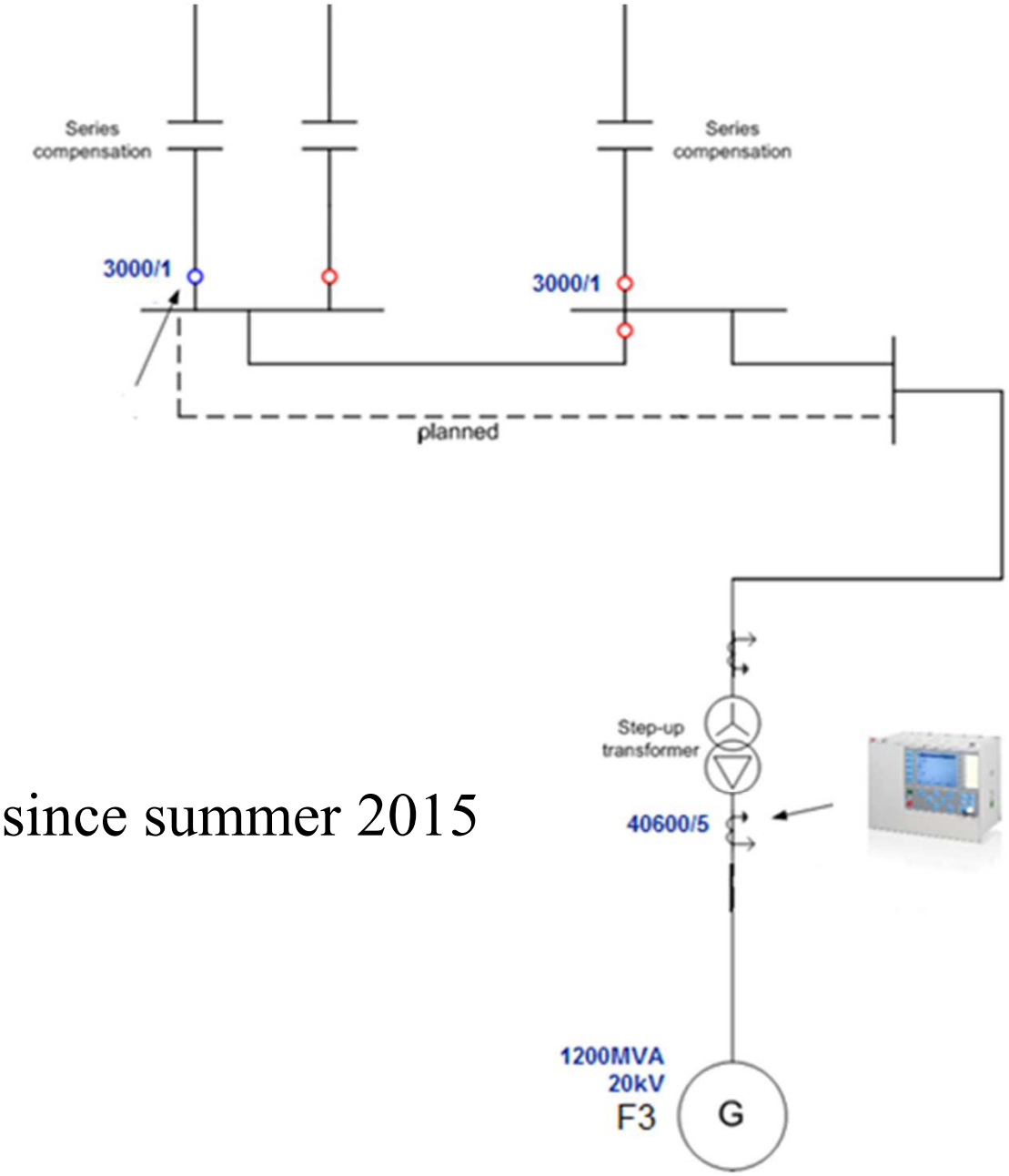
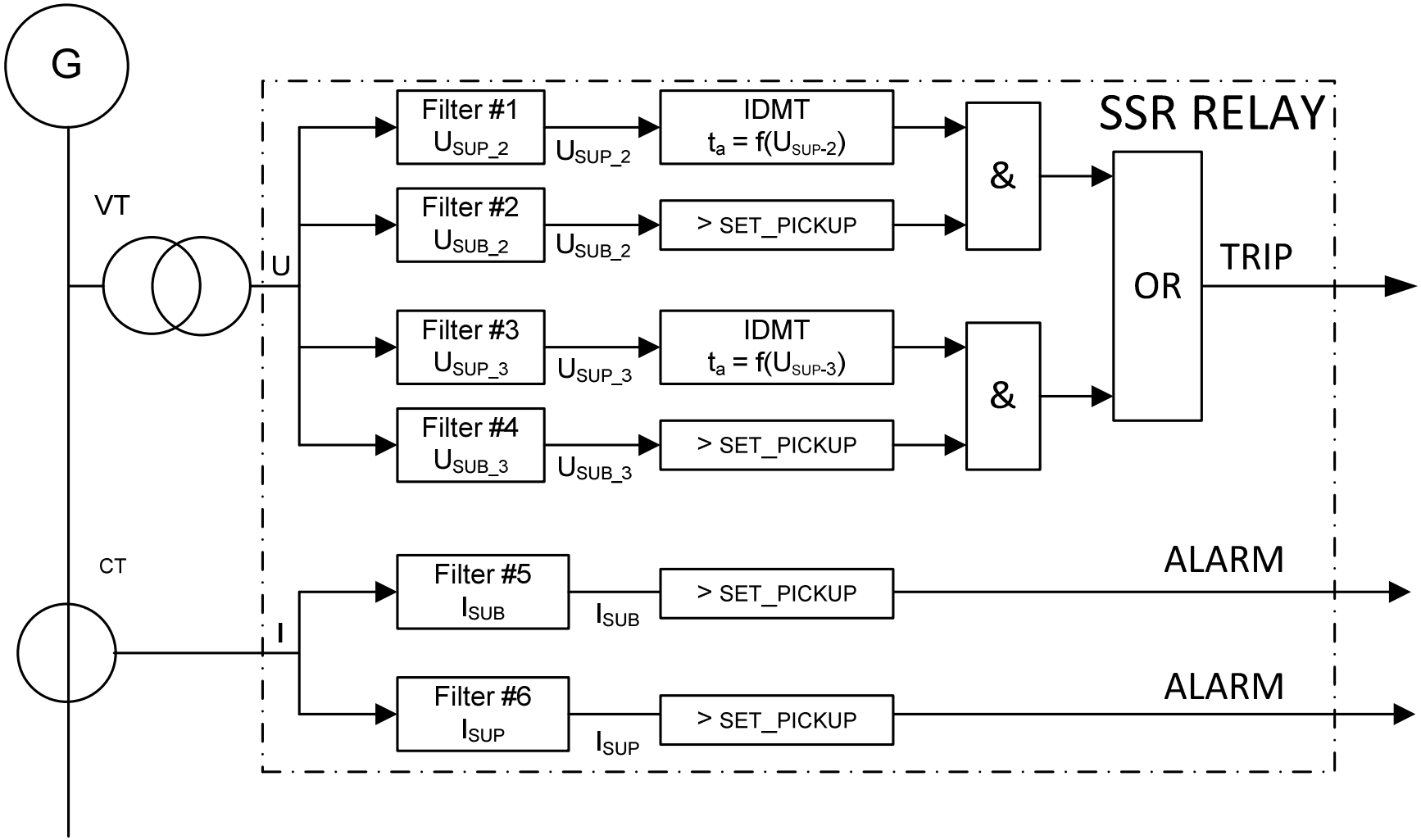
One SSR IED Installed at Forsmark 3



In service since summer 2015

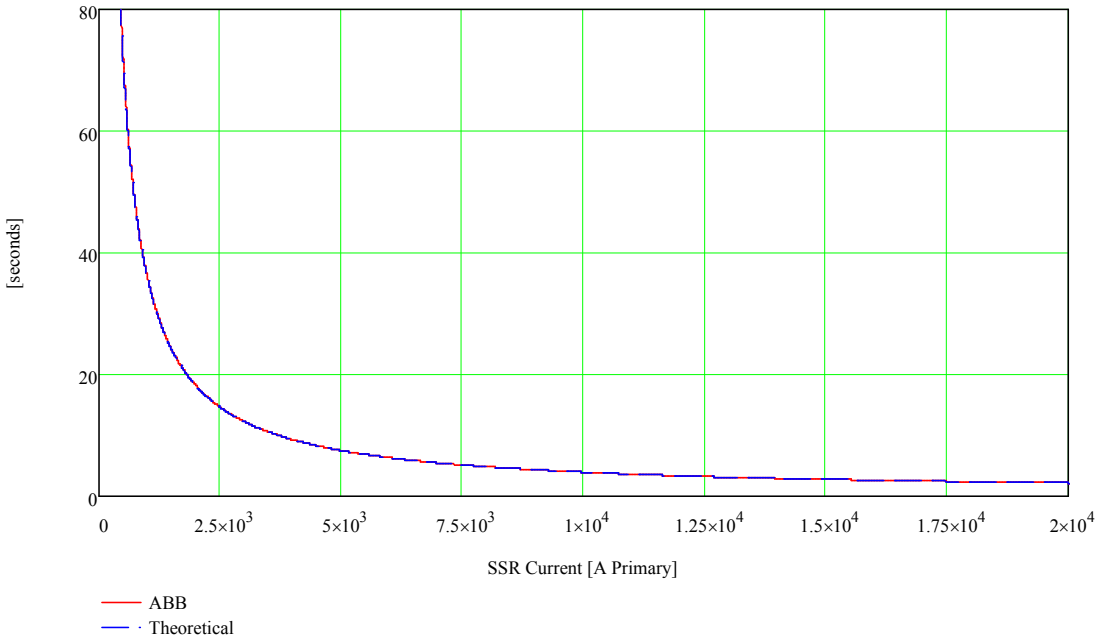
New SSR Protection Scheme in NPP Forsmark 3



Actual IDMT OC Curve is Used toTrip

Curve from Analogue Relay

$$t\_Theory = 0.64s + \frac{35566[A \cdot s]}{I_{SSR}[A]}$$



$$t[s] = \left(\frac{A}{\left(\frac{i}{in>} \right)^{p} - C} + B \right) \cdot k$$

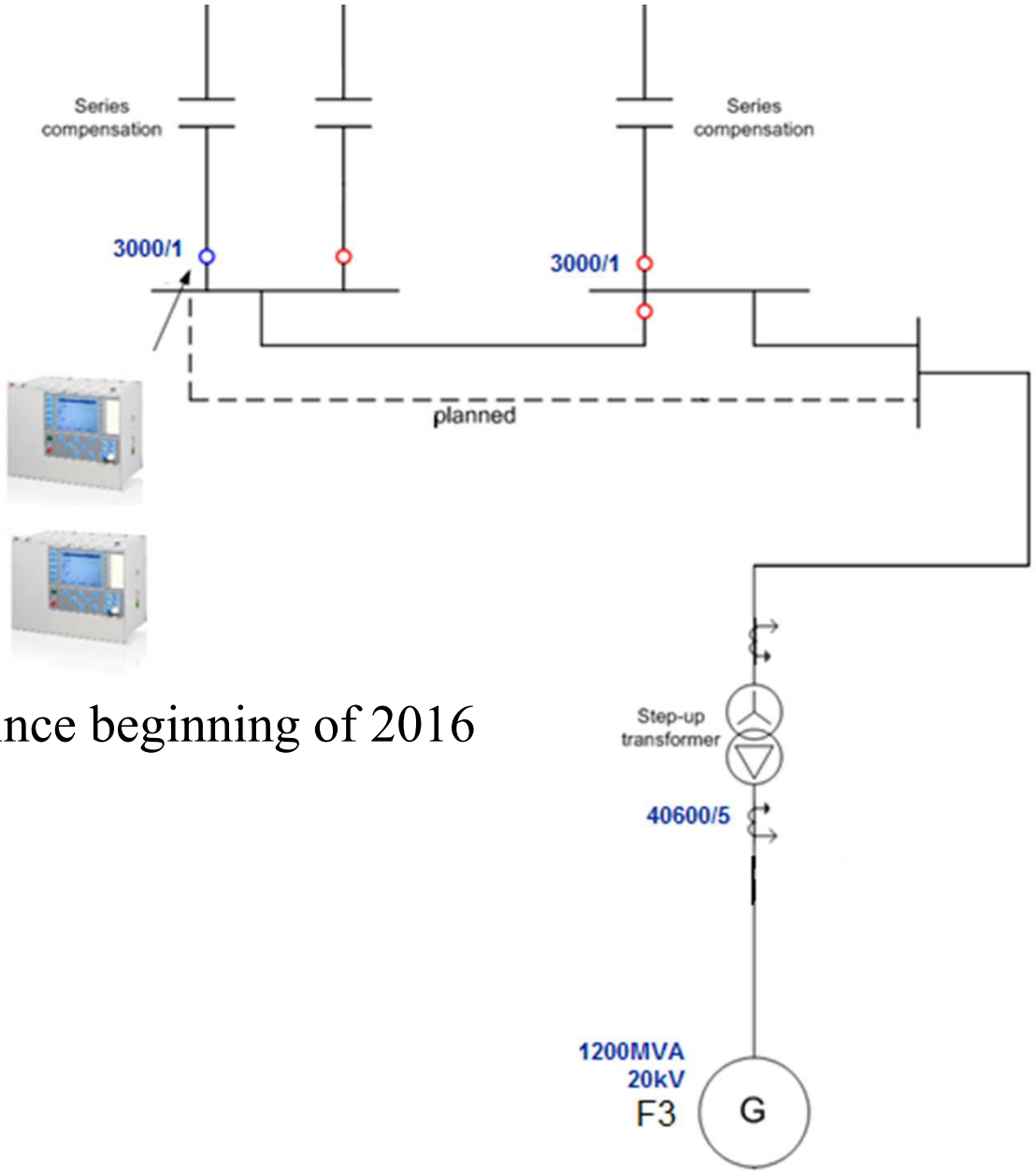
- in>=299A; A=35566/299; B=0.64; C=0.0; p=1.0; k=1.0
- tMin = 1.4s

SSR Panel for NPP Forsmark 3

1) SSR protection IED REG670*2p0
2) MicroSCADA Hystorian used for logging of all relevant SSR data and other generator measurements onto a PC hard disc. More than one year of data can be stored. Data stored once every 2s. Data logged over IEC61850.

In service since summer 2015.

Two SSR IED Installed on each compensated OHL



In service since beginning of 2016

Six IEDs installed in 400kV Network

- These IEDs measure sub-synchronous current magnitudes only
- Sub-synchronous current must exceed the set value in all three phases for a certain time in order to send by-pass command to the series capacitor
- In service since beginning of 2016

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Conclusion

- Sub-synchronous resonance protection for turbo generators available
- Developed on commercially available hardware platform
- Biggest challenge to properly measured the relevant U&I signals
- Phenomenon not properly understood (my personal opinion)
  - What causes it
  - How it starts
  - How it stops
  - How it can be damped
  - Errors in the books
  - U and I relationship at generator
  - Why differs in the 400kV grid
- A lot of data shall be available in F3 (Vattenfall)
  - Possibility for cooperation with Universities?

Questions