SSR Analysis and Design of SSR Protection in Sweden

Per-Olof Lindström

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Sub-Synchronous Resonance

There are three different SSR phenomena that can occur for a synchronous generator connected to the grid.

> **Torsional Interaction**. Undamped resonance between a torsional frequency in a turbo-generator and an electrical resonance in the grid.

> **Induction Generator Effect**. As the generators behave as asynchronous generators towards a sub-synchronous resonance frequency on the grid, negative resistance is supplied. If this resistance is greater than the positive resistance of the grid, the resultant resistance can be negative, causing self-induced electrical oscillations to arise in the grid.

> **Shaft Torque Amplification**. Switching sequences close to the turbo-generator unit can subject it to high instantaneous stresses. Resonances in the grid can result in these stresses becoming many times greater.

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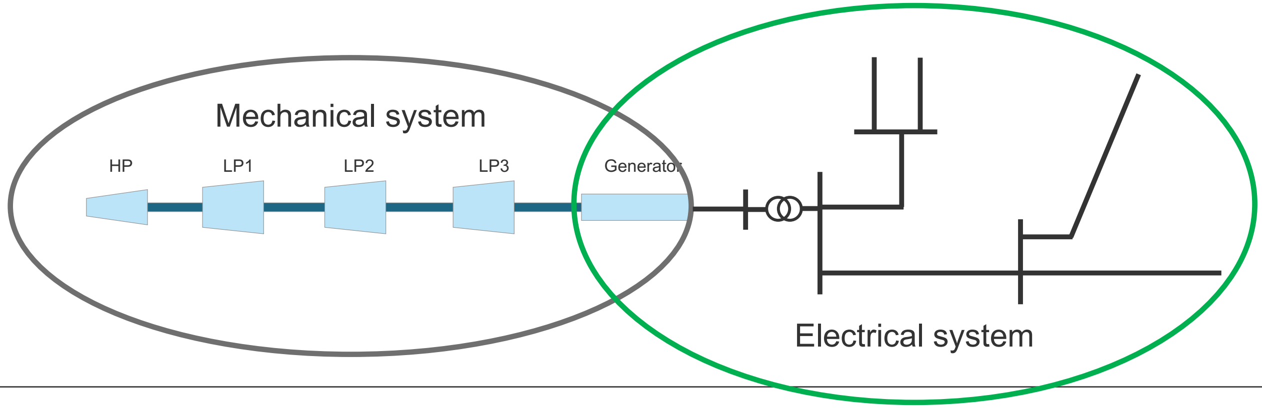
Analysis of Torsional Interaction

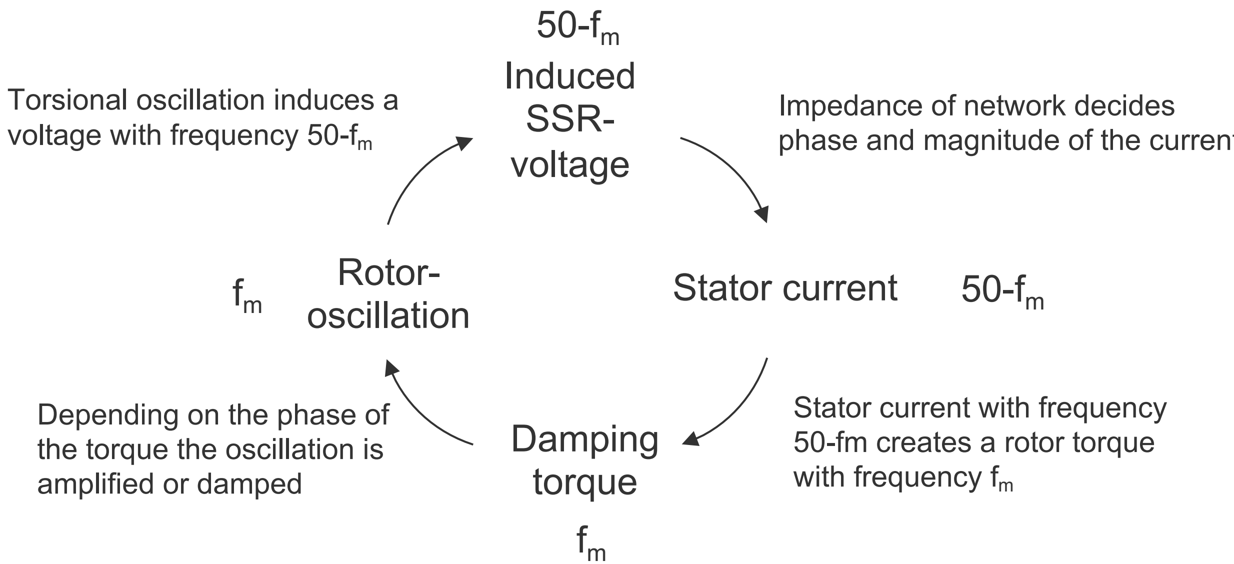
In this presentation analysis and protection against **Torsional Interaction** (TI) is discussed.

- The analysis method was introduced by Vattenfall around 1980.
- Mechanical and electrical system are analysed separately.



Torsional Interaction

SSR can occur if a torsional frequency in the generator interacts with a resonance frequency in the grid, and creates an undamped oscillation.



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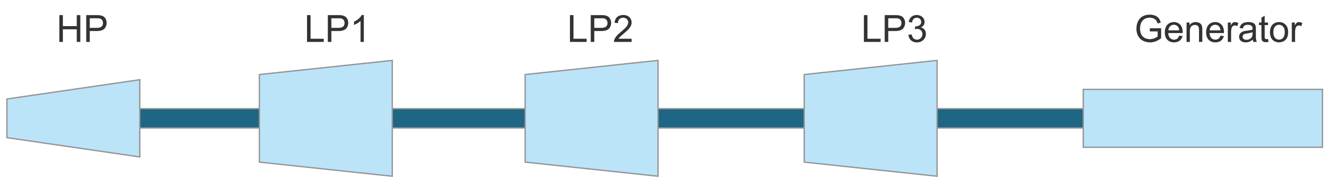
Torsional Frequencies

A turbo-generator can be represented with a mass-spring model

Input data

- Masses: moment of inertia, J [kgm^2]
- Shafts: spring constant, K [Nm/rad]



Results

- 4 torsional frequencies
- Alstom´s och Siemens´s calculations are made with a detailed model with more masses

Mode	Alstom	Siemens	Simplified
1	6,7	6,7	6,7
2	12,5	12,5	12,3
3	17,1	17,0	17,1
4	18,7	19,0	18,7

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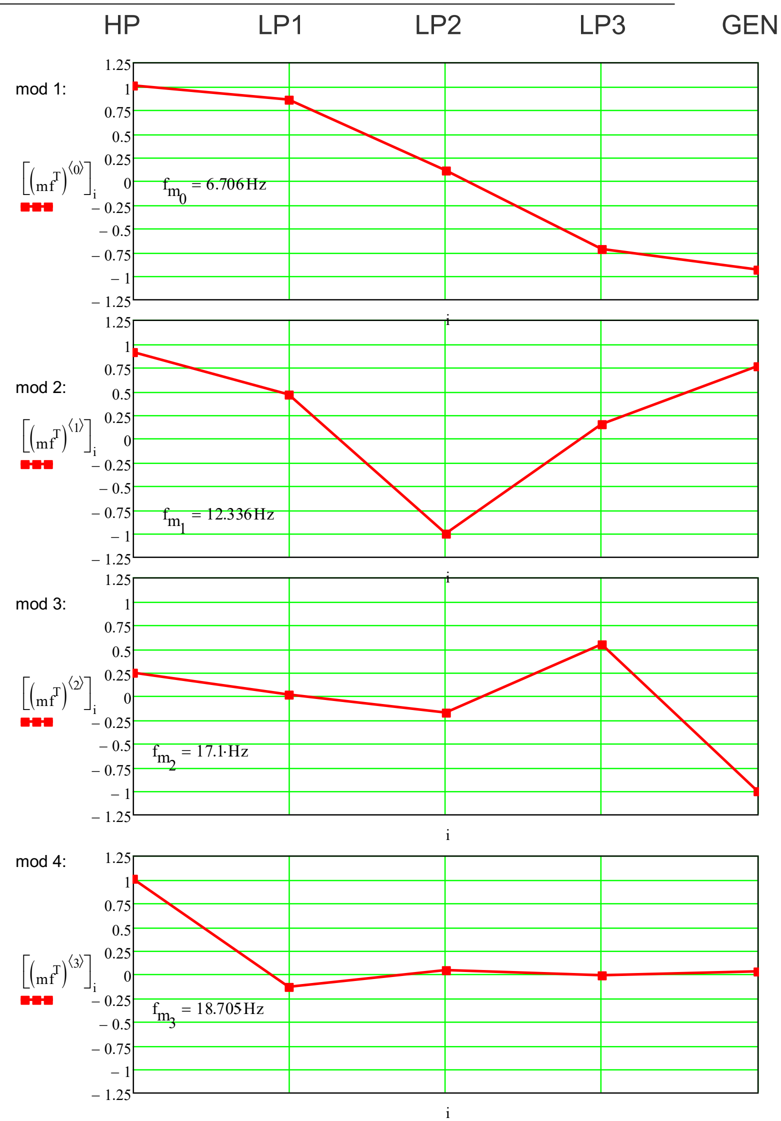
Mode Shape

A mode diagram shows how the masses are oscillating in each mode.

Calculated from the Spring-Mass model

The oscillation of the generator rotor decides the interaction with resonances in the grid.

Each shaft has a different torsion in respective mode, one of them will be most critical.



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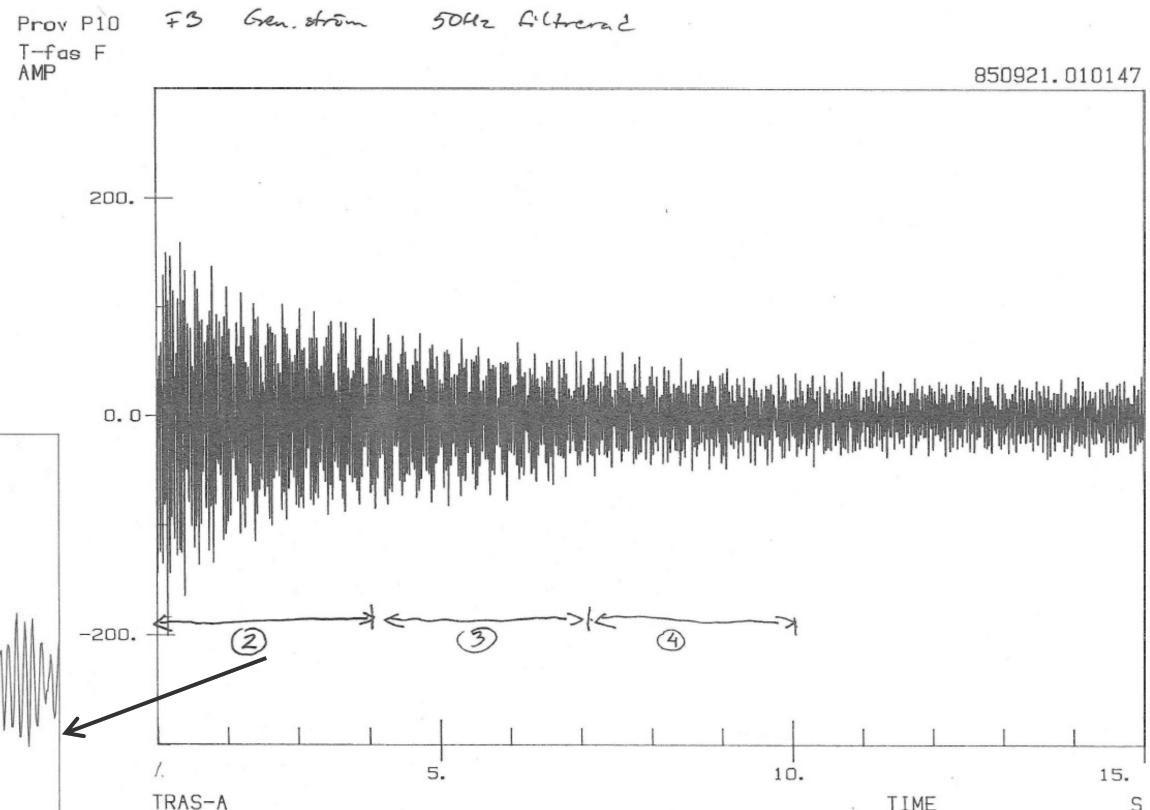
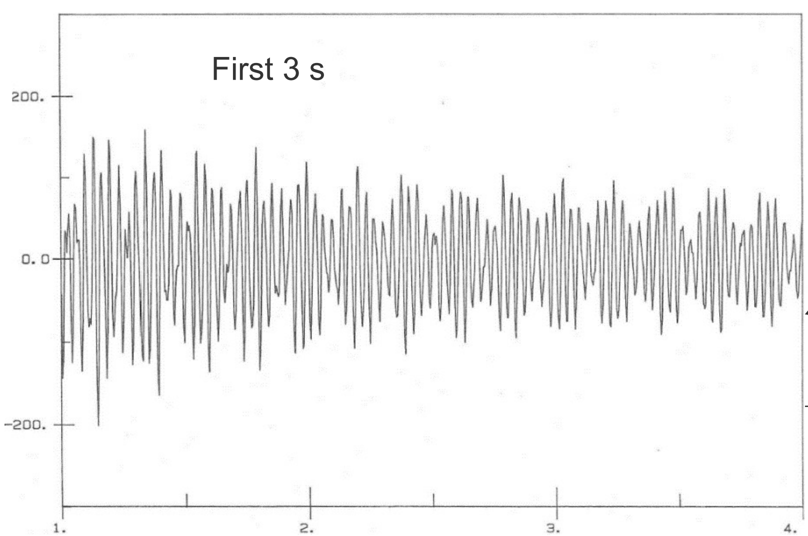
Short circuit field test of F3, 1985 (P10)

Subsynchronous generator current

Interference between several torsional frequencies seen





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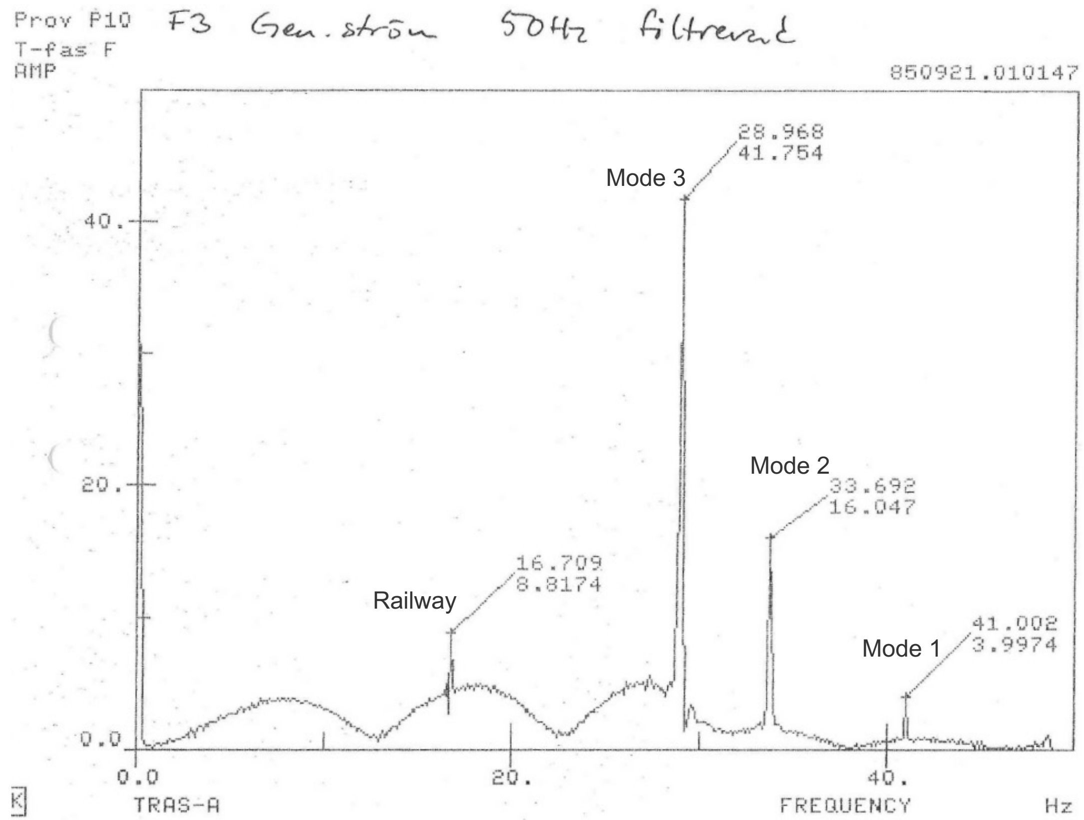
P10: Fourier-analysis of the current

Torsional modes are seen

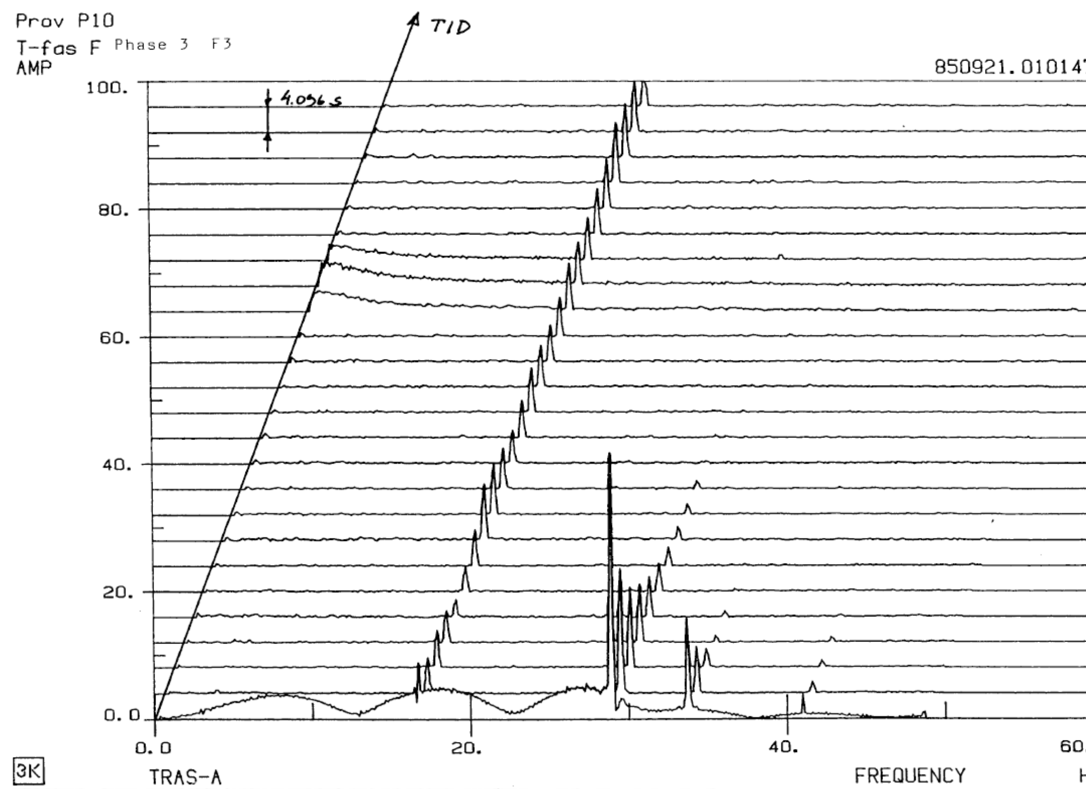
Electric railway operates at 16 2/3 Hz



P10: Consecutive Fourier-Analyses

Consecutive Fourier-analyses with 4 s time frame are shown.

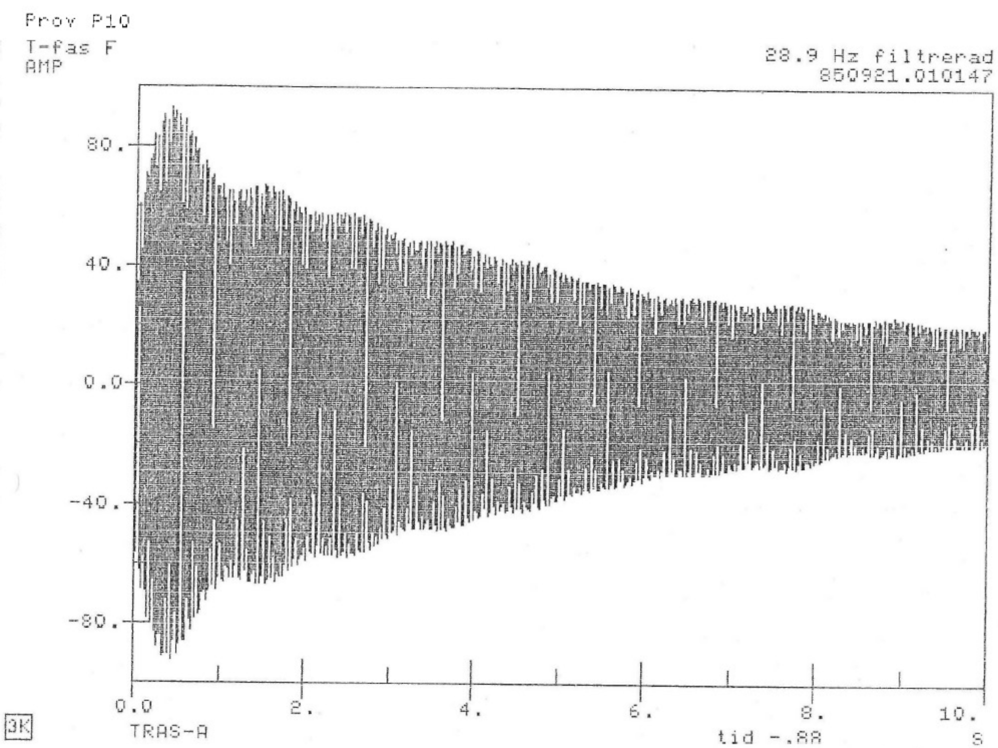
Damping of each torsional mode is illustrated.



P10: Time plot

Filtered current, 28.9 Hz.

Interference seen between mode 3 and mode 4.

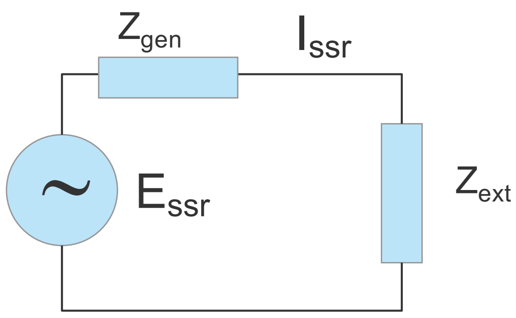


Mechanical --- Electrical Frequency

A torsional mode with frequency f_m induces voltages in the stator:

Sub-synchronous frequency: $50 - f_m$

Super-synchronous frequency: $50 + f_m$



Mode, f_m	Sub-synchronous	Super-synchronous
2, 12.5 Hz	37,5 Hz	62,5 Hz
3, 17.1 Hz	32,9 Hz	67,1 Hz

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Analysis Method

Calculation of grid damping, seen from studied generator (rotor)

Sub-synchronous damping: $D_1 = -\frac{f_e}{2f_m}\frac{R}{R^2+X^2}$ Supersynch.: $D_2 = \frac{f_e}{2f_m}\frac{R}{R^2+X^2}$

Mechanical damping D_r is always positive, but rather small. Can be measured at field test. (Has not been done for F3 after 1990)

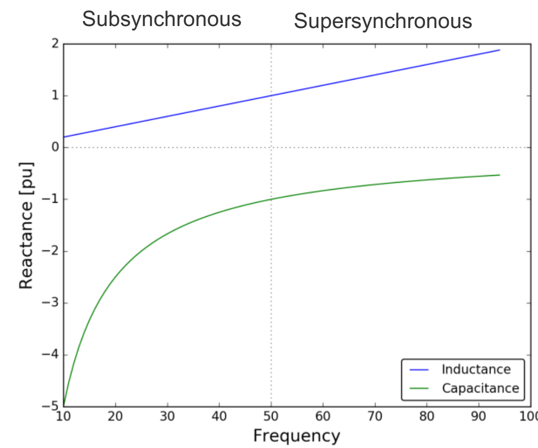
D_1 , D_2 and D_r can be compared in pu. Damped if $D_r + D_1 + D_2 > 0$

D_1 depends on grid impedance at frequency f_e

D_r depends on turbo-generator design and loading

Resonances in the Grid

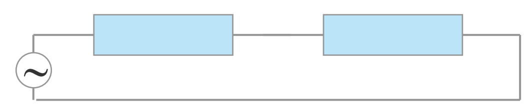
Series resonance. A series compensated line gets higher compensation degree at sub-synchronous frequencies



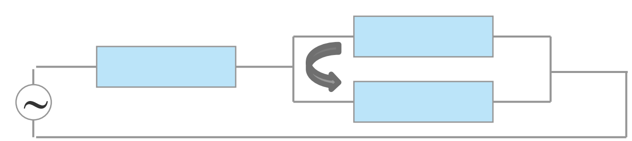
Line reactance decreases: x= ωl

Series capacitor reactance increases : $x_C = -\frac{1}{\omega C}$

Series resonance: (R+j0)



Parallel resonance: (R>>0)



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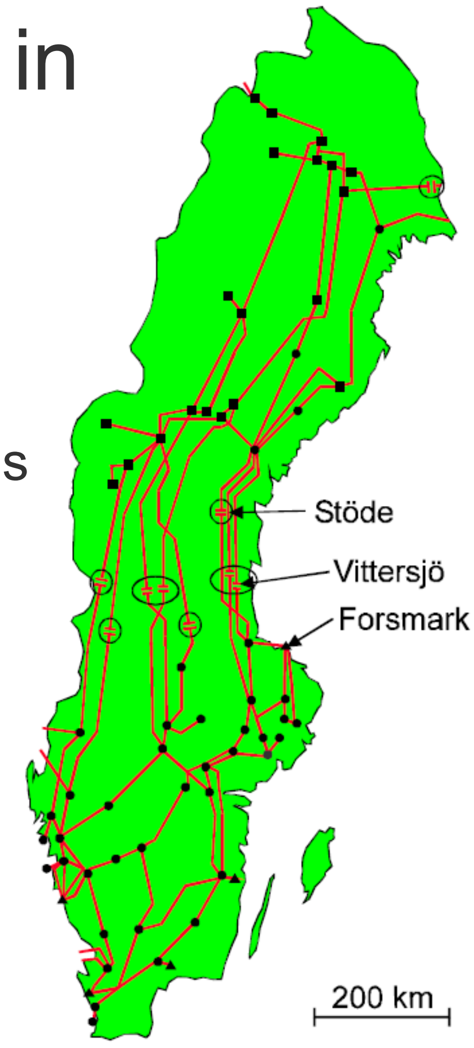
Torsional Interaction Problem in Sweden

Forsmark 3 is connected to Stackbo/Ängsberg

Strong electrical coupling to the 3 eastern, series compensated lines in transfer section 2



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Development of Analysis Tools

> Late 70’s: FRERED, frequency reduction program. Calculating network impedance for sub- and supersynchronous frequencies. Results: R,X → D_1

> 1982: Master Thesis by Carl Johan Dahlgren. Analysmetod för beräkning av subsynkrona strömmar i kraftnätet, SD-5125

> This led later to the idea to use PSS/E for the SSR analysis!

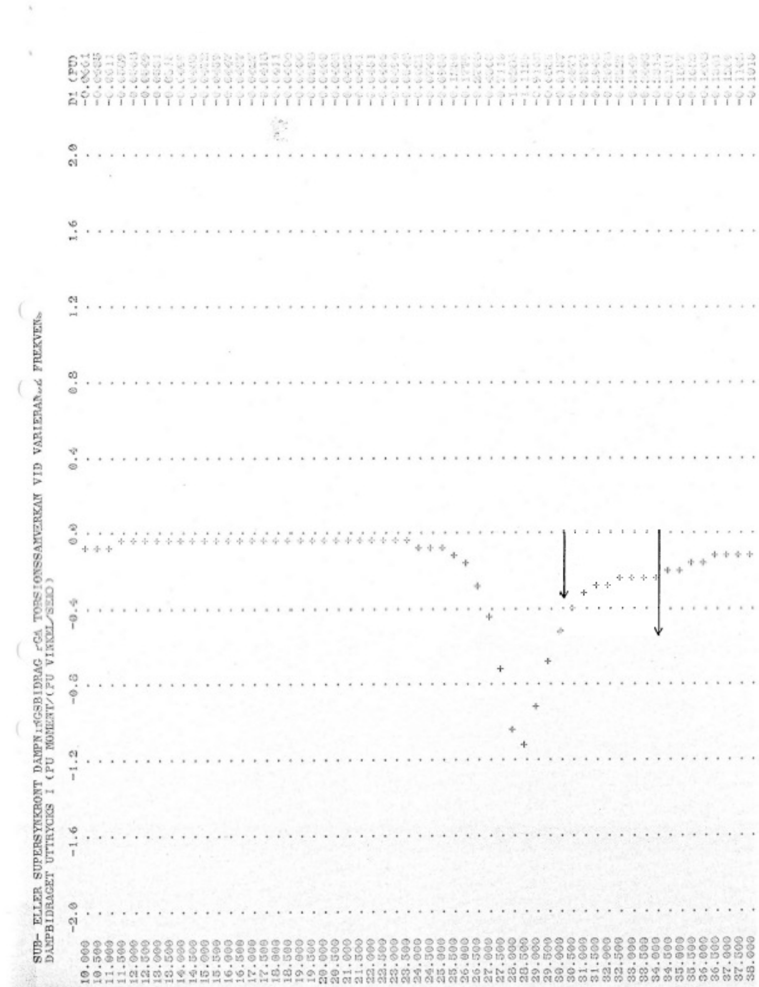
> Iplan-program was developed for SSR-scanning in PSS/E. Results: R,X, D_1, I_{gen}, I_{line}, U_{ssr} .

Example of FRERED Result from 1984

> Frequency scanning from 10 to 38 Hz (electric frequency)

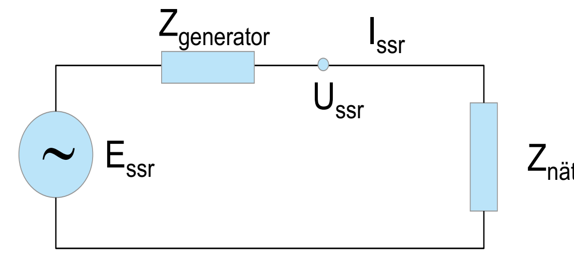
> Electric damping, D_1, is printed with “line printer plotting”.

> Assumed mechanical damping is indicated with arrows



Analysis of SSR and Line Currents

- Analysis in PSSE
- Frequency scanning: network model recalculated from 50 Hz to studied frequency
- Study of one selected generator. E.g. F3
- Normal operations and several contingencies
- Sub-synchronous damping and line currents are calculated



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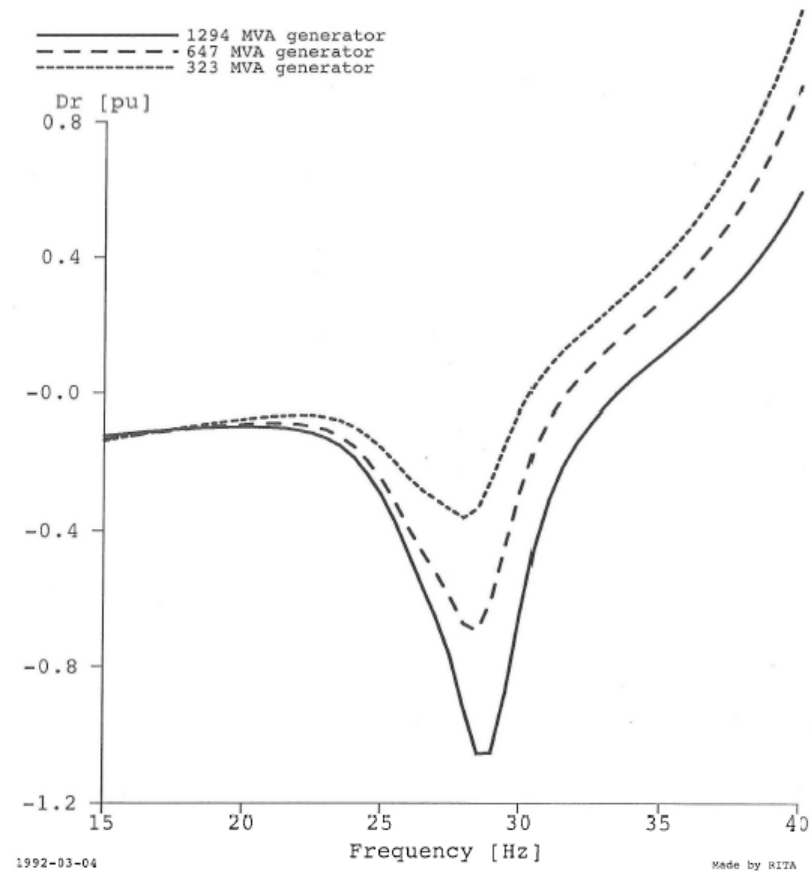
SSR damping as function of generator rating

> Damping becomes worse with increasing generator size



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Results from SSR analysis year 2015

In the following slides some results from an SSR-study are shown.

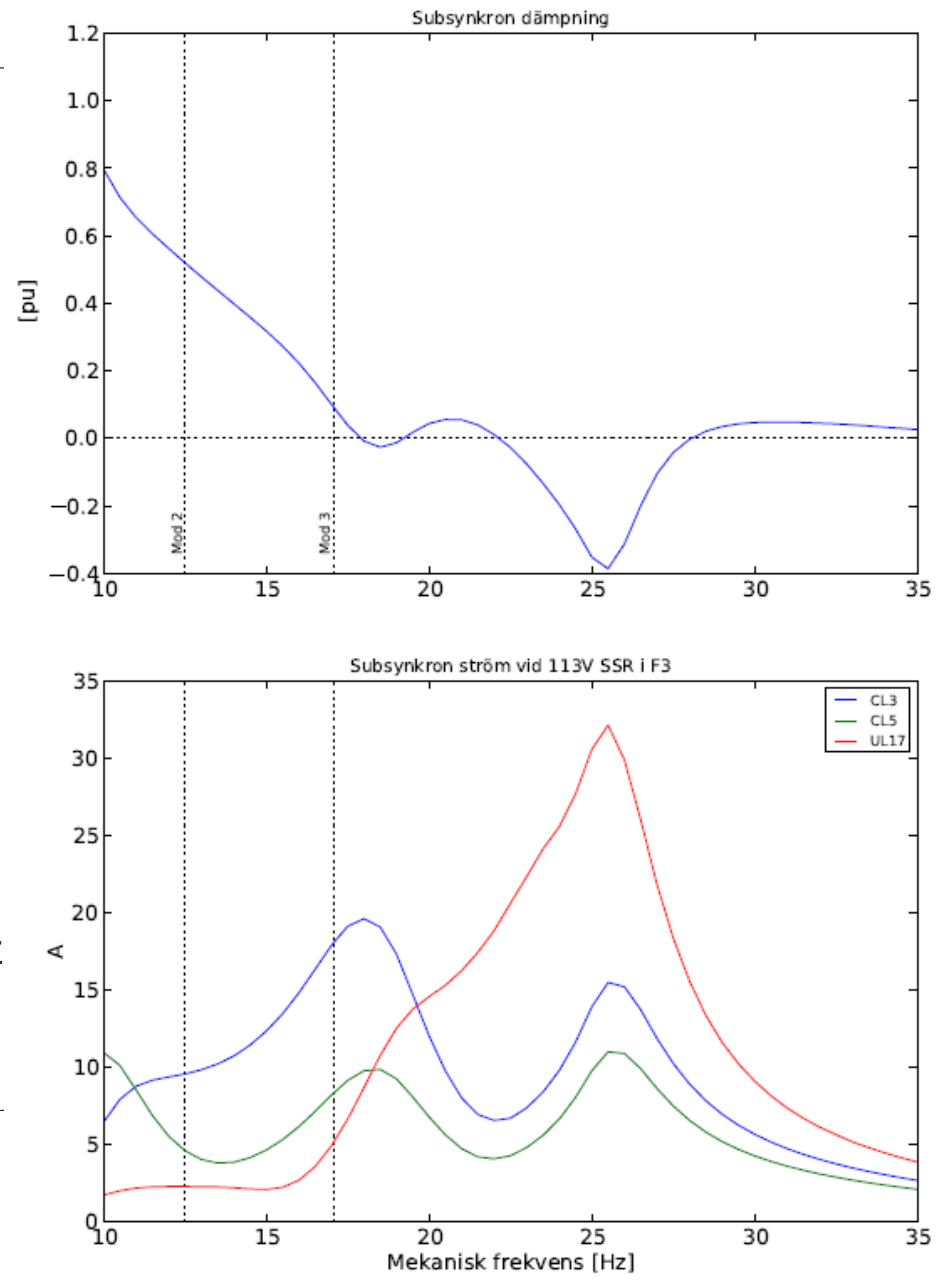
Results

Normal operation

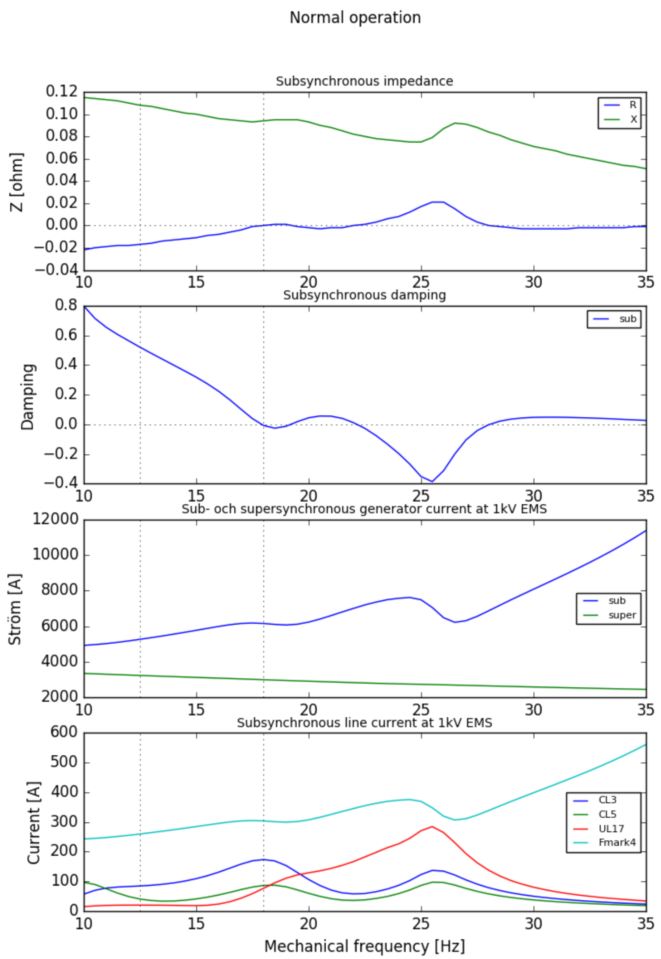
Scanning 10-35 Hz mechanical frequency (40-15 Hz electrical frequency)

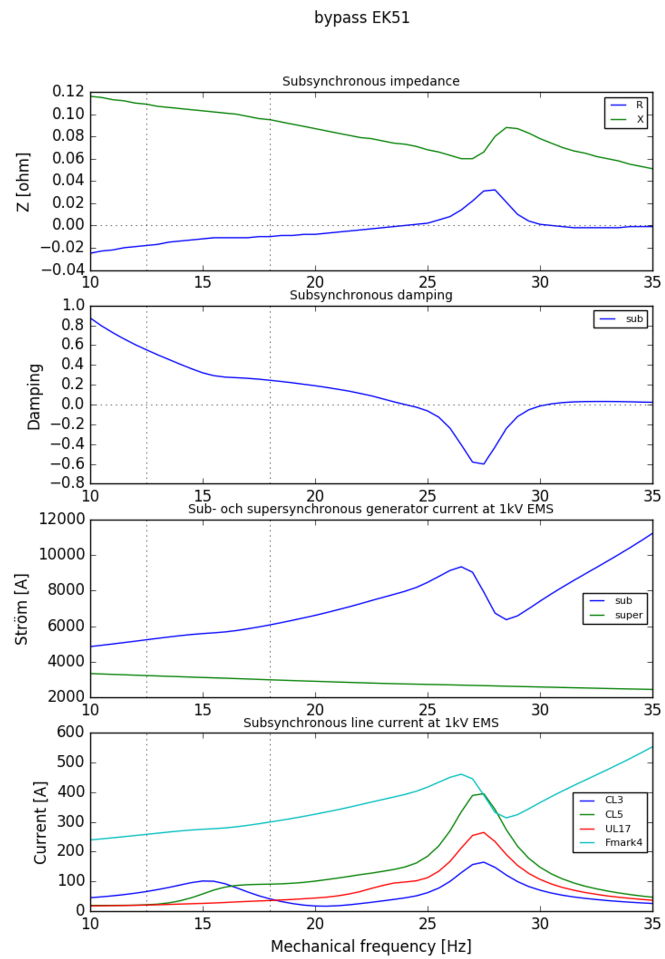
Critical torsional frequencies at 12.5 and 17.1 Hz (indicated with dotted lines)

Resonance peak seen at 25.5 Hz

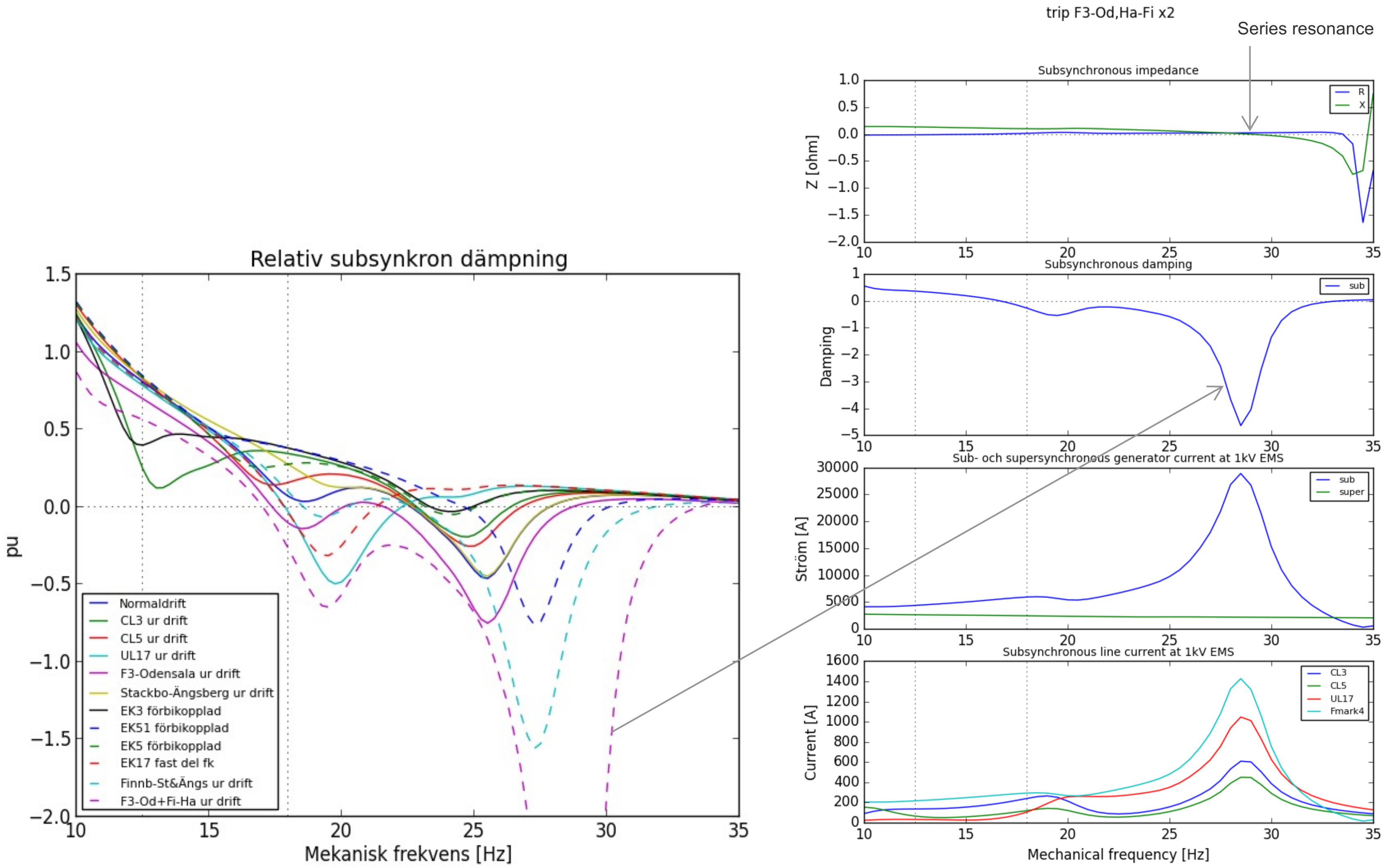


Network Switching Changes the Resonance

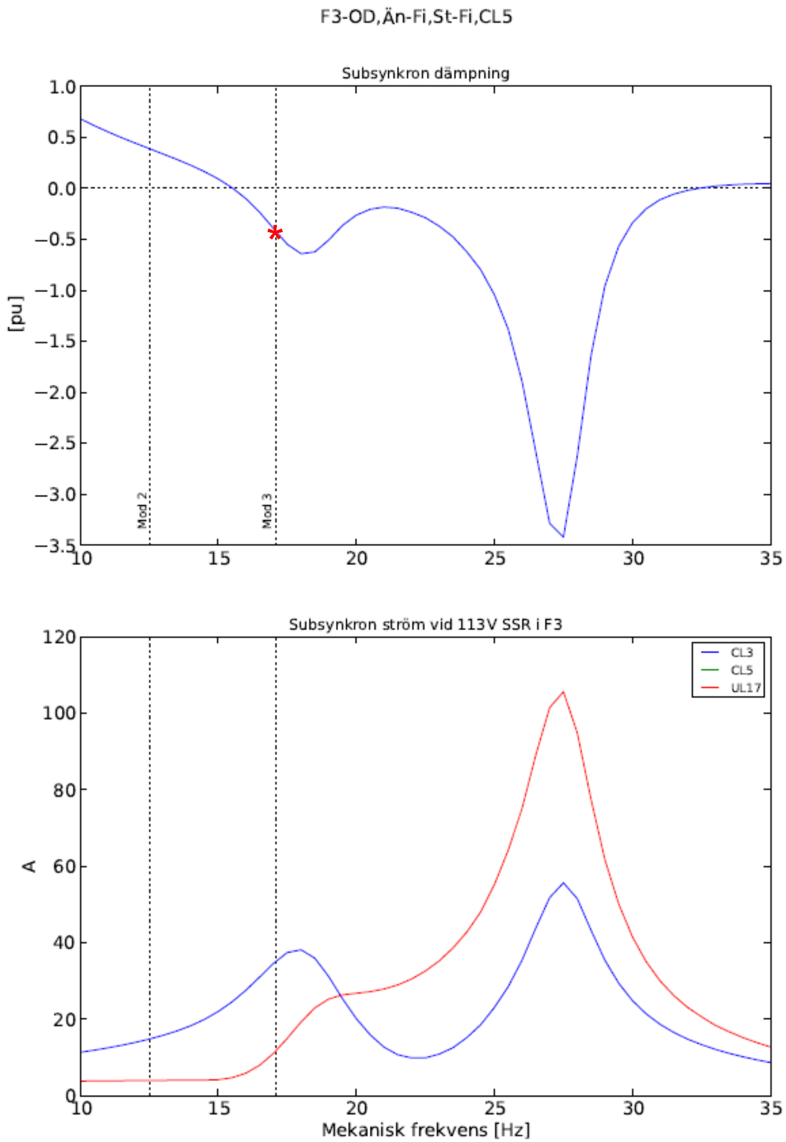


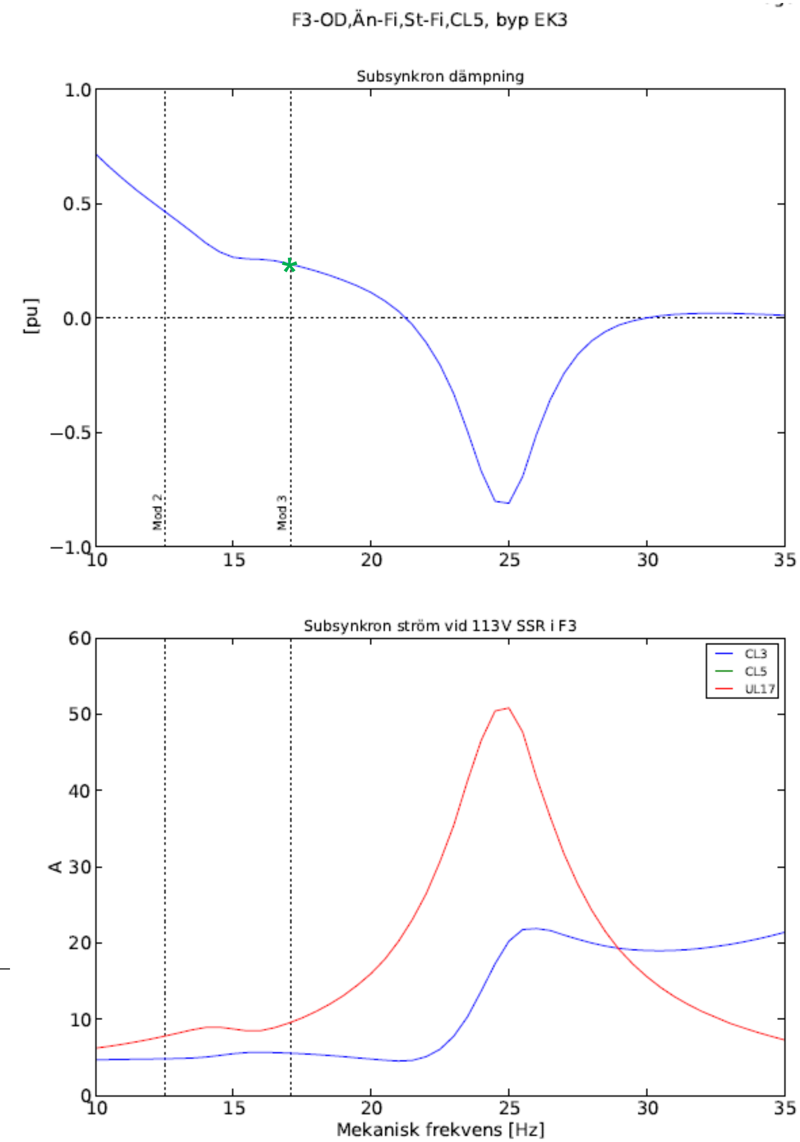


Example of Contingency Analysis

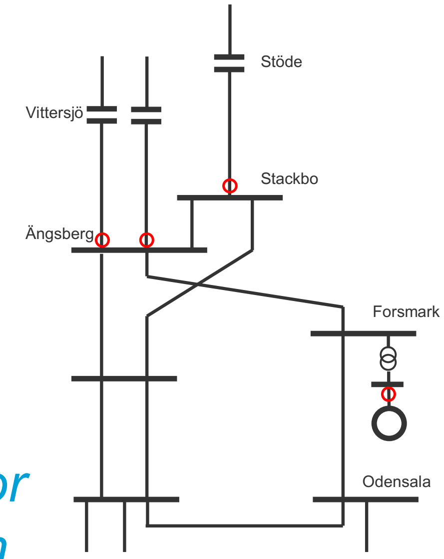


Critical Contingency, Before and After Bypass of EK3





Philosophy of Protection



New SSR-protection developed by ABB based on REG670. Described in paper: *Design Challenges for Numerical Sub-Synchronous Resonance Protection*

Backup-protection installed at F3. Measuring **super-synchronous voltage**.

Primary protection installed on critical lines in Stackbo/Ängsberg s/s. Measuring **sub-synchronous current**.

There is no communication between primary and secondary protection.

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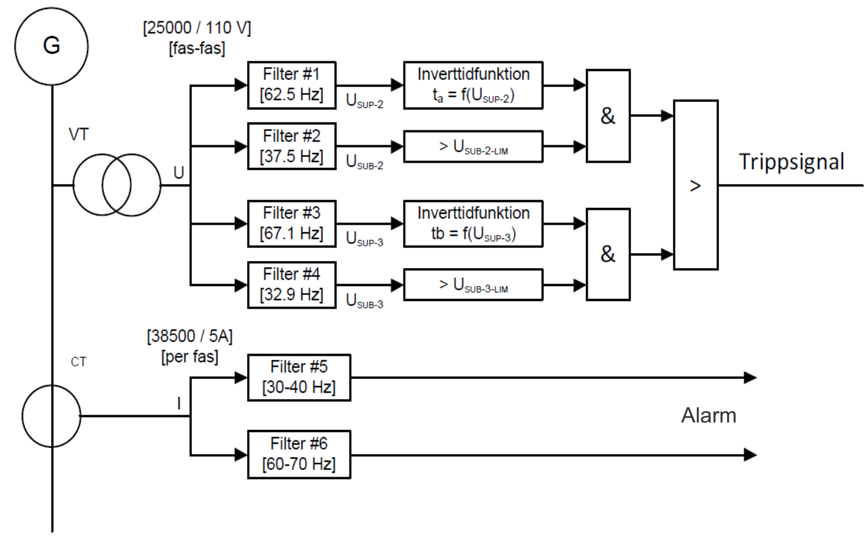
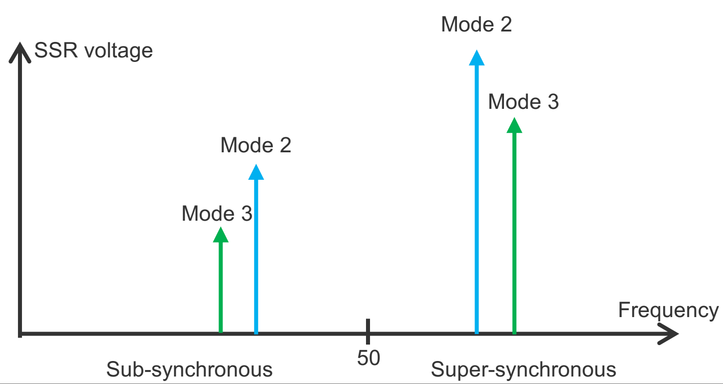
Secondary Protection in Forsmark 3

Measures **super-synchronous voltage** with two narrow band-pass filters.
The old protection measured sub-synchronous current.

Protection setting depends on allowed torsional torques for most critical axis.

Inverse time characteristic with high exponent.





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

Primary Protection for Lines

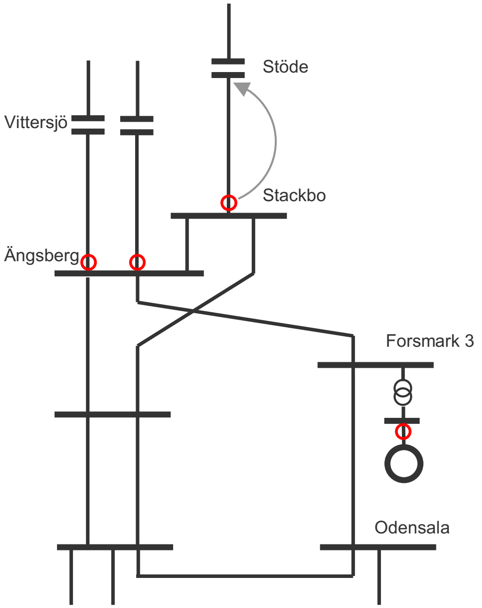
Installed at Stackbo/Ängsberg s/s on lines CL3, CL5 and UL17

Measures sub-synchronous current with narrow band-pass filters for mode 2 and 3.

Setting based on SSR studies and actual setting of back-up protection in Forsmark 3.

Selective setting: Primary protection shall act before back-up protection.

Primary protection sends bypass order to series capacitor station.



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Setting for Line Protection

Study summer 2015 for calculation of setting values.

Inverse time characteristic:

$$\left(\frac{A}{\left(\frac{i}{in}\right)^{p}}\right) \cdot k$$

Start values, i_n , in the region of 10-20 A

Summary

- Torsional interactions may occur for large synchronous turbo-generators connected close to series compensated lines.
- An SSR event may damage a shaft in the generator.
- Mode shape and endurance data will give input to accepted torsional oscillations.
- Network study can be made separate, and D_1 compared with D_r.
- SSR currents and voltages are small compared to synchronous I and U.
- Protection available for generators and lines.
- The new protection is very reliable.
- Tuning of protection is complex!