“Investigation of Possible Network Interactions between Turbine-generator Trains and Converters in the Power Grid at the Oil Platform Visund”

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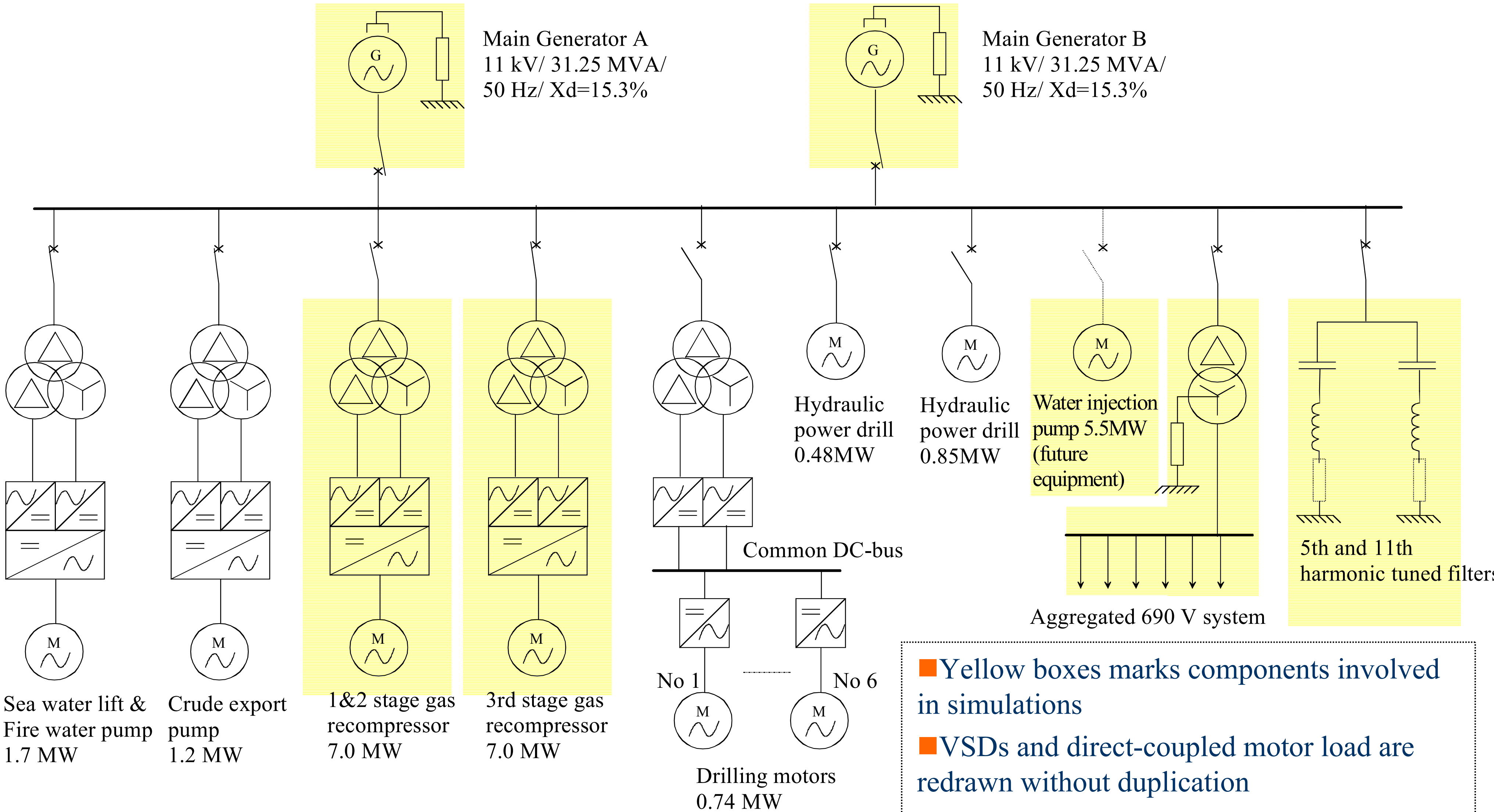
The Oil Platform VISUND in the North Sea

Power Generator Vibration Problems

- Norsk Hydro has periodically experienced severe vibration problems within the power generators at some of their oil platforms in the North Sea
- Initially these problems were believed to have a pure mechanical nature, and actions like modifications of a gear shaft (quill shaft), thereby increasing the inherent mechanical damping of the turbine generator trains (TG trains), was carried out
- Because these modifications did only partly solve the problems, focus was eventually directed to possible sources for the problems within the electric grid, especially to two large current source variable speed drives (VSDs)
- Then it was decided to clarify possible interaction from the power grid by help of numerical simulations. For this purpose the simulation program PSCAD/ EMTDC was used

Aggregated Power System of the Platform

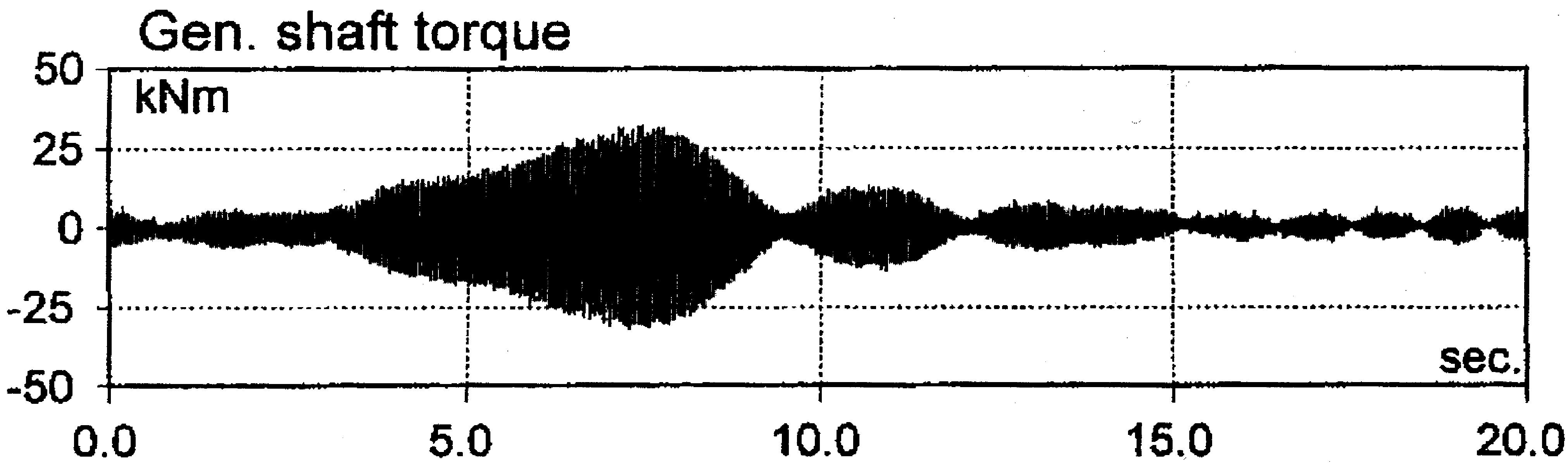


- Yellow boxes marks components involved in simulations
- VSDs and direct-coupled motor load are redrawn without duplication
- The underlying 690V system is aggregated to one exit

Two types of Problems experienced

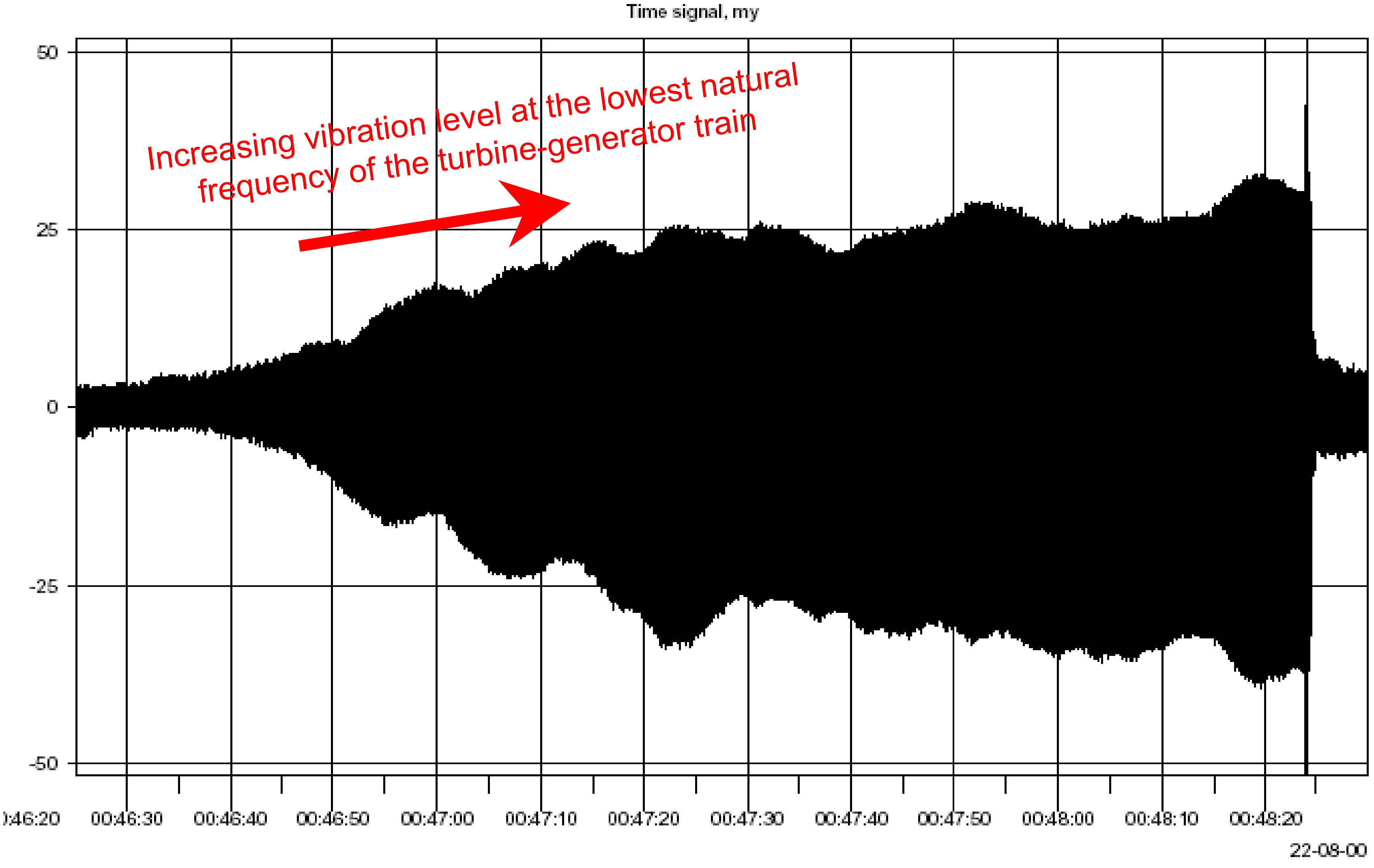
- Two different types of vibration problems within the TG trains have been experienced
- One has a transient character, and has been found to coincide with certain operating speeds of two 7 MW VSD driven compressor drives
- The other phenomenon has only occurred a few times, but is more serious since it leads to power shutdown of the platform. It is experienced as a slowly increasing vibration, which develops over some time (a couple of minutes) to inadmissible levels, finally tripping the generator

Measurement of Transient Excitation

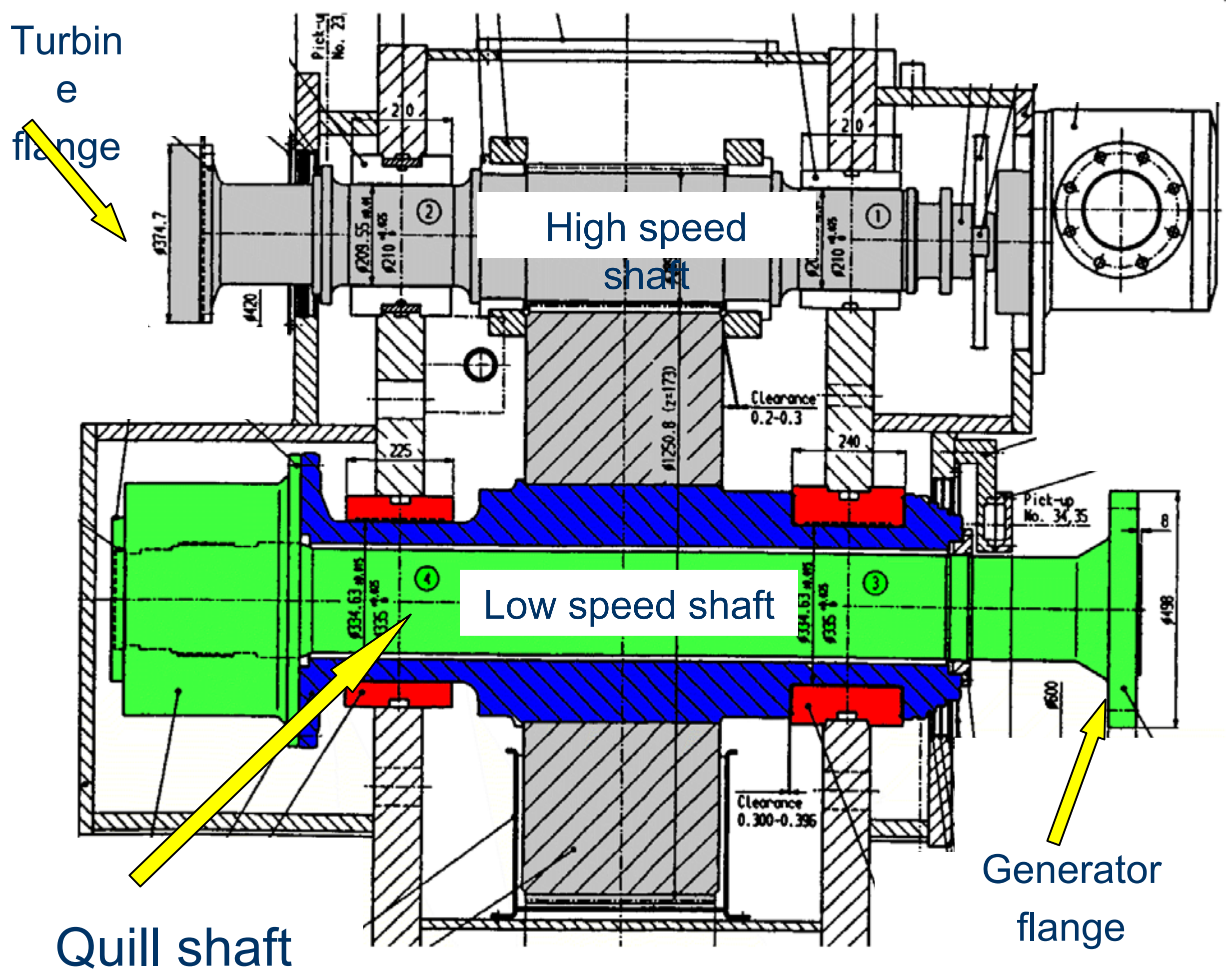


- Shaft torque excitation on generator B when 3rd stage compressor is passing 1428 rpm - Generator A is disconnected
- n_{motor} = 1428 rpm ➔ f_{motor} = 47.6 Hz (4-pole machine) f_{grid} = 50 Hz ➔ 6*|50Hz-47.6Hz| = 14.4Hz ➔ Which coincides with the lowest natural frequency of the rotating system (240 mm quill shaft)

Measurement of Instability leading to Shutdown

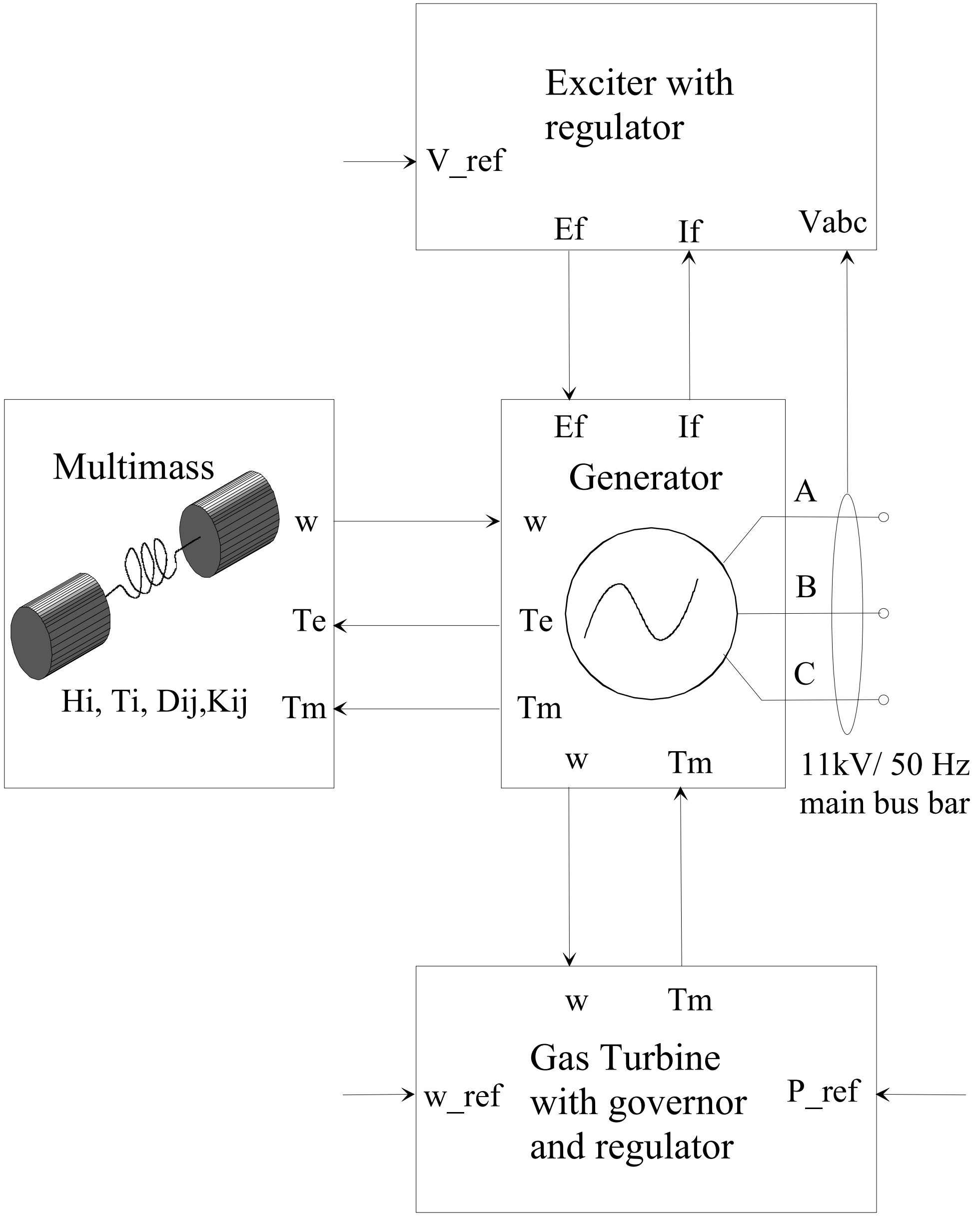


Gear with Quill Shaft



- Torsional and lateral vibrations occur at the lowest natural frequency of the rotating system
- The node of that vibration is localised to the quill shaft
- Rotor dynamic analysis has shown that the torsional damping at the lowest natural frequency is extremely low
- Damping is mainly determined by lateral mode damping within the gear transmission, which is transferred to torsional mode damping via torsional-lateral coupling
- A complicating factor is also that the damping is extremely load dependent, and about 60 times higher at 10% load compared to100% load

PSCAD/ EMTDC model of TG-trains



Data input for Generator:

- Rated data
- Reactances and time constants in d- and q-axes
- Winding and core losses
- Inertia constant and mechanical friction

Data input for Exciter with Governor and Regulator:

- Dynamics all the way from measuring points to applied field voltage.
- Transfer functions, parameters, nonlinearities etc.

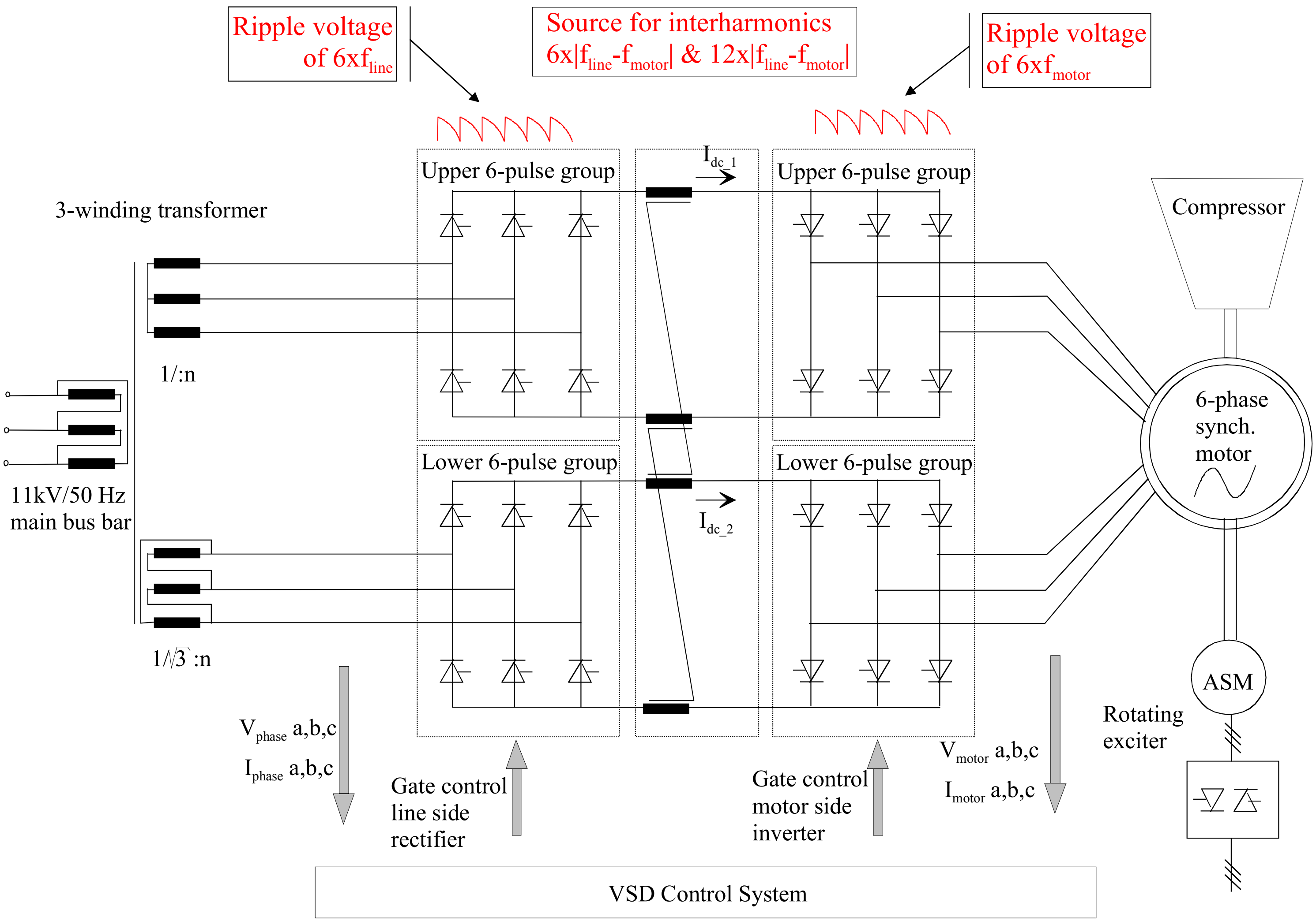
Data input for Turbine with Governor and Regulator:

- A simplified model from the manufacturer applied

Data input for shaft model of complete TG train:

- A two-mass model applied, giving fairly good representation of the dynamics around the lowest natural frequency of the shaft
- Damping parameters converted from lateral mode damping to torsional mode damping

PSCAD/ EMTDC model of VSDs



Data for Power Circuit:

- Converter transformer
- Line side rectifier
- Motor side inverter
- Synchronous motor and load

Data for Rectifier Control:

- Current transducer
- Current error amplifier
- Linearization of firing angle
- Current set point sampler
- Speed error amplifier, ramp-up limiter and filtering of actual value

Data for Inverter Control:

- Modelling of firing angle control
- Modelling of motor excitation

Summary of Simulations carried out

Resistive load tests with 218, 240, 290 and 340 mm quill shafts (Mechanical damping increasing with increasing diameter):

- Sudden load change on and off between 0% and 100% load

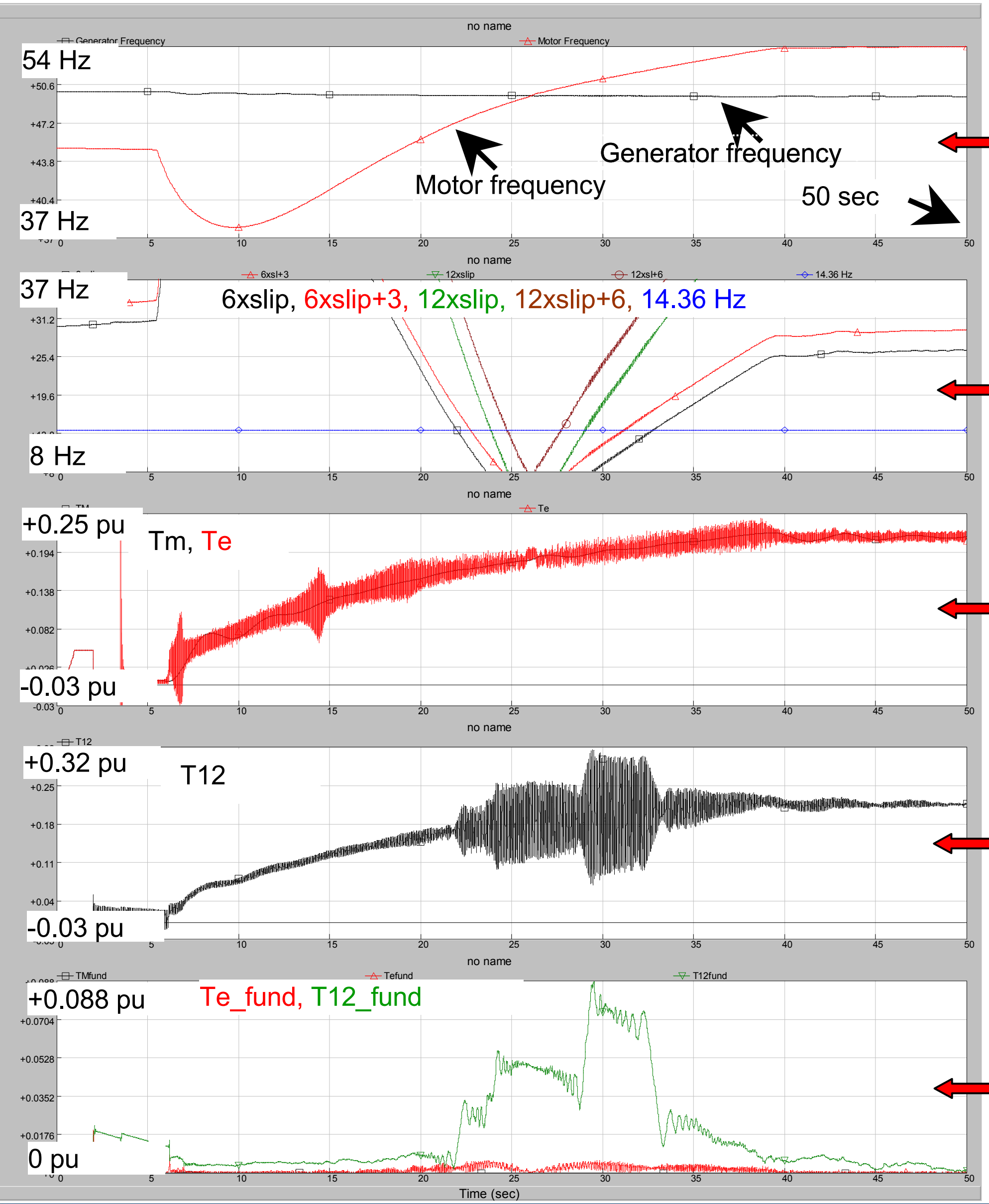
Interharmonics - (All with 240 mm quill shaft):

- One VSD running through critical operation points - No additional loads
- One VSD in stationary operation at points of interharmonic interaction
- Effect of additional loads
- Effect of two-generators in operation

Negative damping:

- One VSD fed from one generator with original quill-shaft (218mm) - No additional load
- Two VSDs fed from one generator with original quill-shaft (218mm) - No additional load
- Two VSDs fed from one generator with modified quill-shafts (240 and 290mm) - No additional load
- Simulations with additional loads - E.g. a 5.5 MW water injection pump

Simulation of Interharmonics



The generator frequency and the motor frequency
The motor is initiated with a speed corresponding to 45 Hz in order to avoid the long simulation time involved with starting from standstill. When connecting the VSD at (t=5 sec), the motor frequency initially drops because of the lag within the VSD speed control loop.

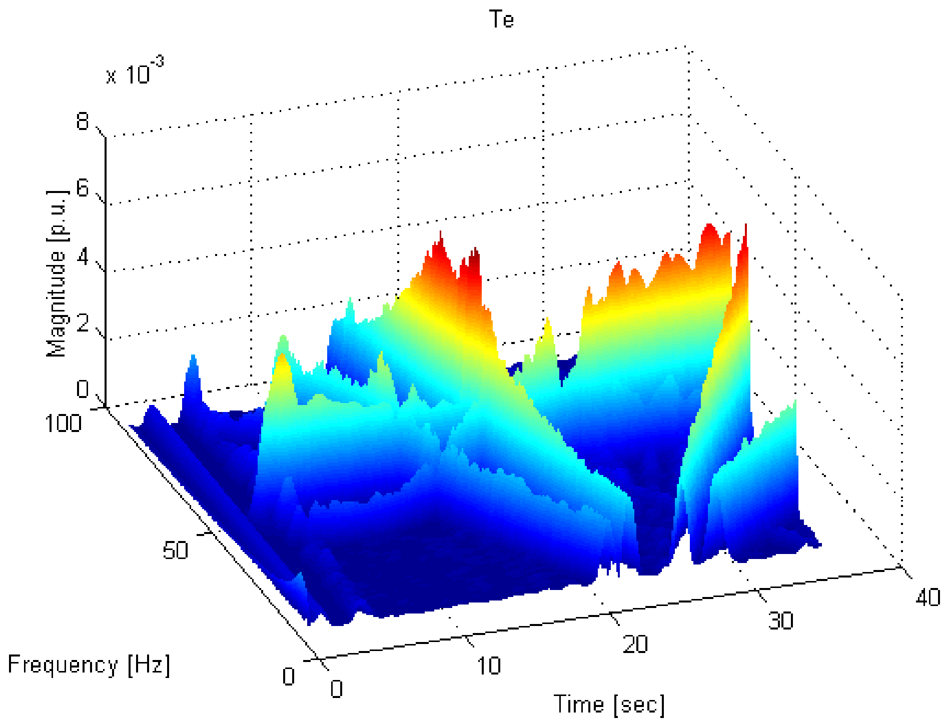
The calculated values for 6*fslip and 12*fslip
Torque oscillations are expected to appear when these quantities become equal to the natural shaft frequency (14.36 Hz for the 240 mm shaft). Also is shown calculated values for 6*fslip+3 and 12*fslip+6, because torque oscillations have been measured at these frequencies. These oscillations could not be explained theoretically, or be reproduced by simulations.

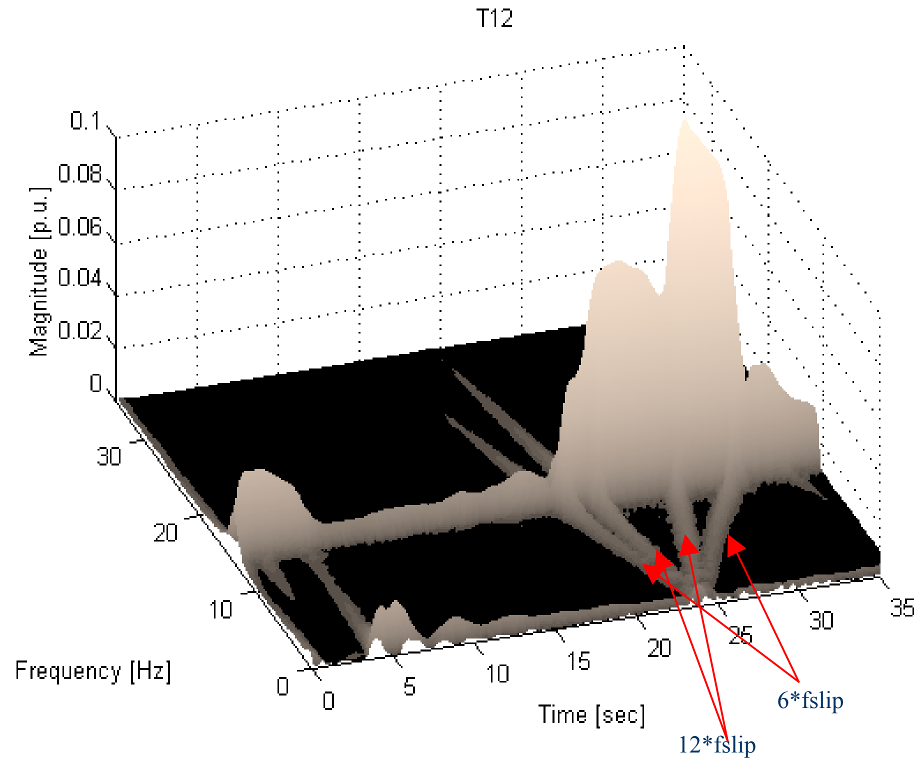
The generator mechanical torque Tm and electrical torque Te
The AC-component in Te is mainly ripple torque from the VSD rectifier.

Torque (T12) at the critical node of the TG train
T12 is the torque between the two masses in the two-mass model. It is seen that large oscillations are excited when 6*fslip and 12*fslip intersect 14.36 Hz. The peak value of the oscillation is 0.125 p.u. of the nominal generator torque.

The rms-value of the 14.36 Hz oscillation in Te and T12
It is clearly seen that the torque oscillation is strongly present in T12, and weakly present in Te.

Frequency Analysis of Interharmonics

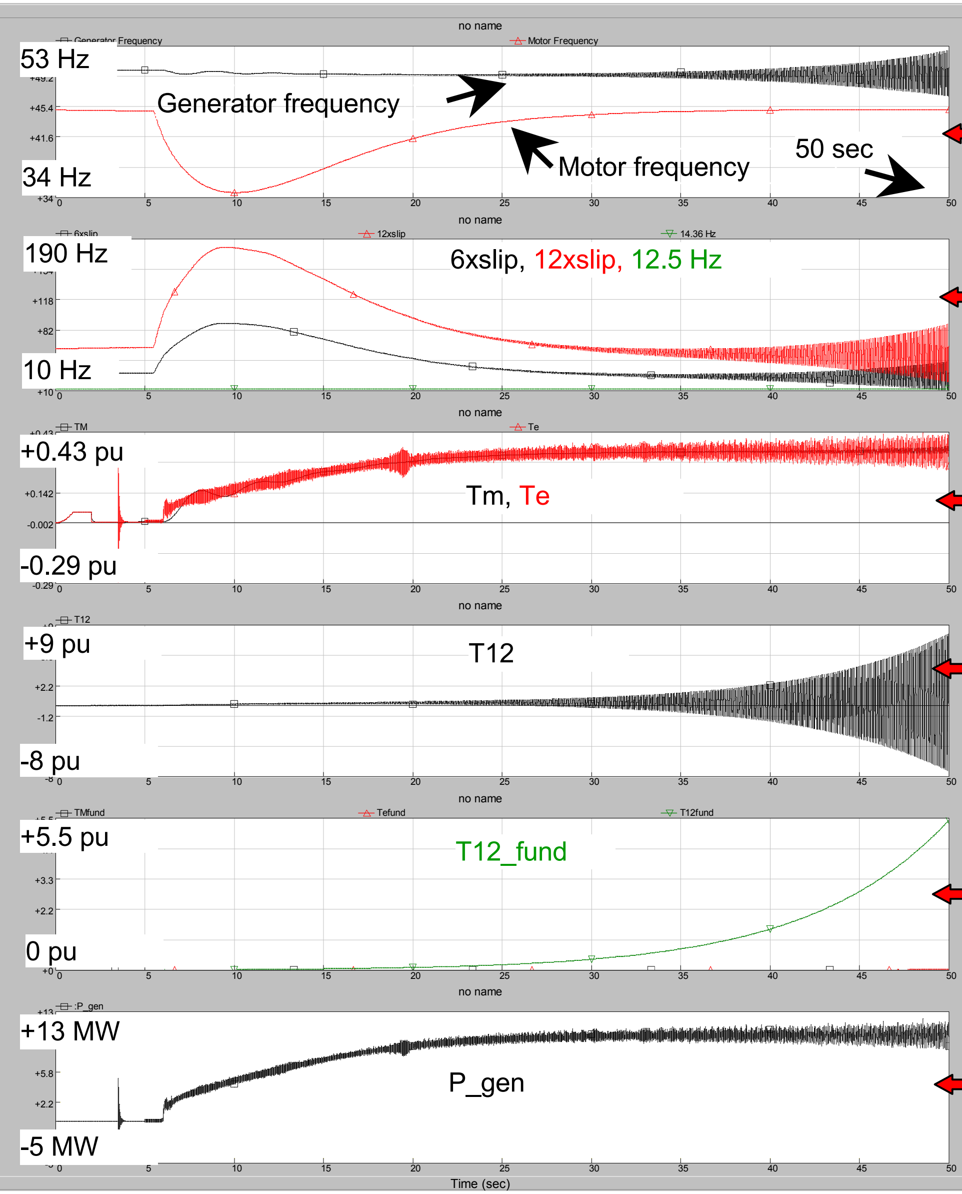




- ”Water fall” plots of the generator air gap torque Te

- ”Water fall” plots of the torque T12 at the critical shaft node
- As can be seen large oscillations are excited in T12 when 6*fslip and 12*fslip intersect 14.36 Hz

Simulation of Negative Damping



The generator frequency and the motor frequency.
A single generator with the original 218 mm shaft feeds two compressor drives. The two compressor motors are running at 40 Hz and 45 Hz respectively, which is outside the operating points for the interharmonics - No additional loads.

The calculated values for 6*fslip and 12*fslip.
These plots show that the operating area for this test does not mingle with the operating area where interharmonic frequencies occur (12.5 Hz for the 218 mm shaft)

The generator mechanical torque Tm, and electrical torque Te

Torque (T12) at the critical node of the TG train
The level of the 12.5 Hz oscillation, “measured” at the critical node (T12) is seen to increase in an exponential way, demonstrating an unstable situation.

The rms-value of the 12.5 Hz oscillation in T12

The generator electric power

Conclusions

- Both the interaction mechanisms described initially in the presentation have been identified and demonstrated by simulations with PSCAD/EMTDC. The source for the interharmonic interaction was found to be frequency components in the DC-link currents of the compressor VSDs, generated by the difference between line side and motor side fundamental frequency
- The torsional oscillation level may reach 0.24 p.u. peak-peak with modified 240mm quill shaft, when the compressor VSDs are allowed to run through critical operation points with their maximum slew rate
- If the VSDs are allowed to stay at critical speeds, torsional oscillations of 2.5 peak-peak of nominal generator torque have been simulated. It should be noted that this is theoretical values applicable for a linear system
- Experience after installation of the 240 mm modified shaft confirms that the vibration level is still to high
- The control system for the compressor VSDs seems to be passive to the interharmonic oscillations
- Neither the turbine governor, nor the exciter control system seem to interfere with the oscillations introduced by interharmonics

Conclusions (cont.)

- Exponential increasing generator shaft oscillations as result of negative damping have been demonstrated, when simulating a situation where one generator powers both compressor drives. The original 218 mm shaft was definitively unstable, while the modified 240 mm shaft could become unstable during worst case conditions
- The positive effect of further additional mechanical damping by increasing the diameter of the quill shaft to 290 mm, was clearly demonstrated
- The stabilizing effect of additional resistive load in the power grid was demonstrated for both original and modified shafts
- Positive damping effect from the direct line driven 5.5 MW water injection pump was demonstrated for modified shafts, while the original shaft shows to be unstable
- Time domain simulations applying tools like PSCAD/EMTDC have proved to be a very valuable tool to clarify possible interaction problems in power grids where power electronic converters are involved, provided sufficient detailed modelling, and provided that sufficient data is obtainable from the vendors
- As result from this simulation study a new quill shaft with 290 mm diameter has been installed

Further Work planned for Evaluation and Selection of Countermeasures

- Investigate the possibility for introducing active damping at the lowest natural frequency of the TG train by modifications of the generator exciter controller
- Investigate possible modifications of the control system of the compressor drive VSDs
- Evaluate a dedicated active DC-type filter or attenuator in the DC-link of the VSDs, tuned to the critical generator shaft frequency
- Evaluate an active AC-type filter or attenuator in the 11kV network, directly, or preferably via transformer. Such device could also be configured to take care of other possible interaction sources in the platform power grid

Approximations and Uncertainties

The approximations of most concern as regards influence on simulation results are:

- Uncertain data for TG train shaft dynamics. Especially data for mechanical damping
- Lack of data for dynamics for the synchronization of control angles for the VSD rectifier and inverter
- Lack of data for dynamics of the compressor load-torque characteristics
- Lack of data for dynamics of the compressor motor excitation controller