DNV·GL

Frequency Control in Power Systems

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Agenda

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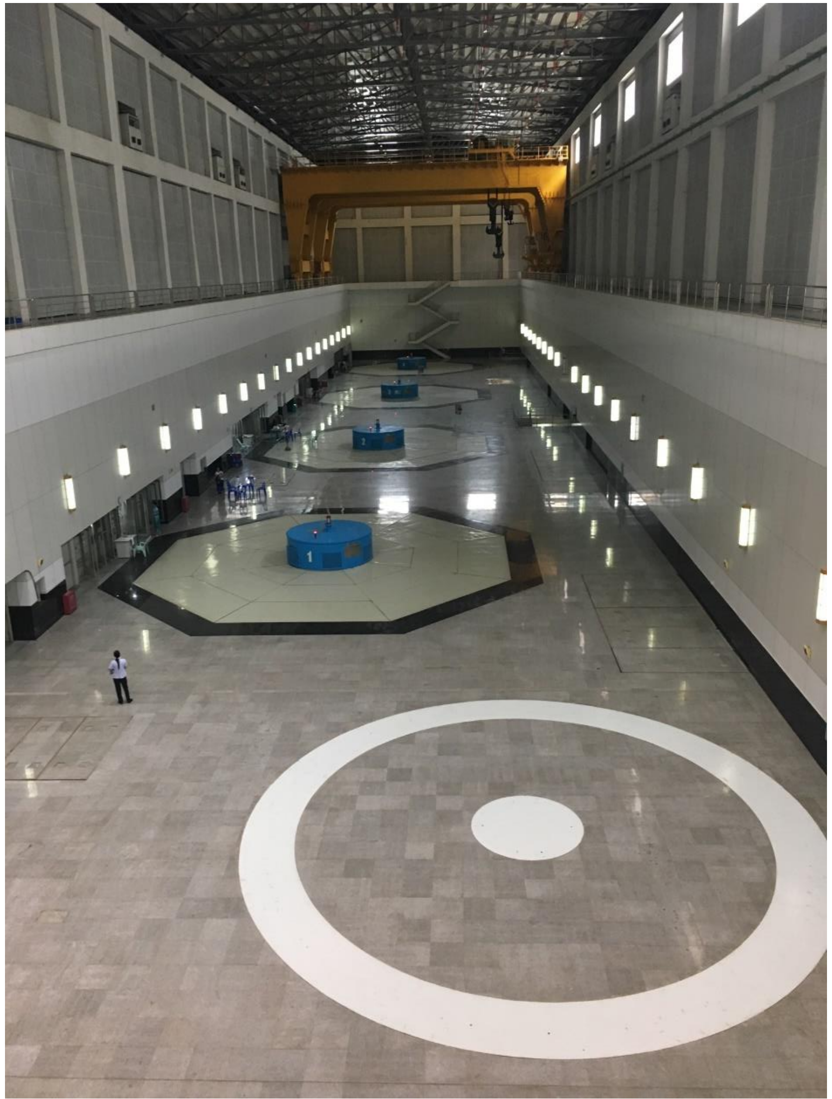
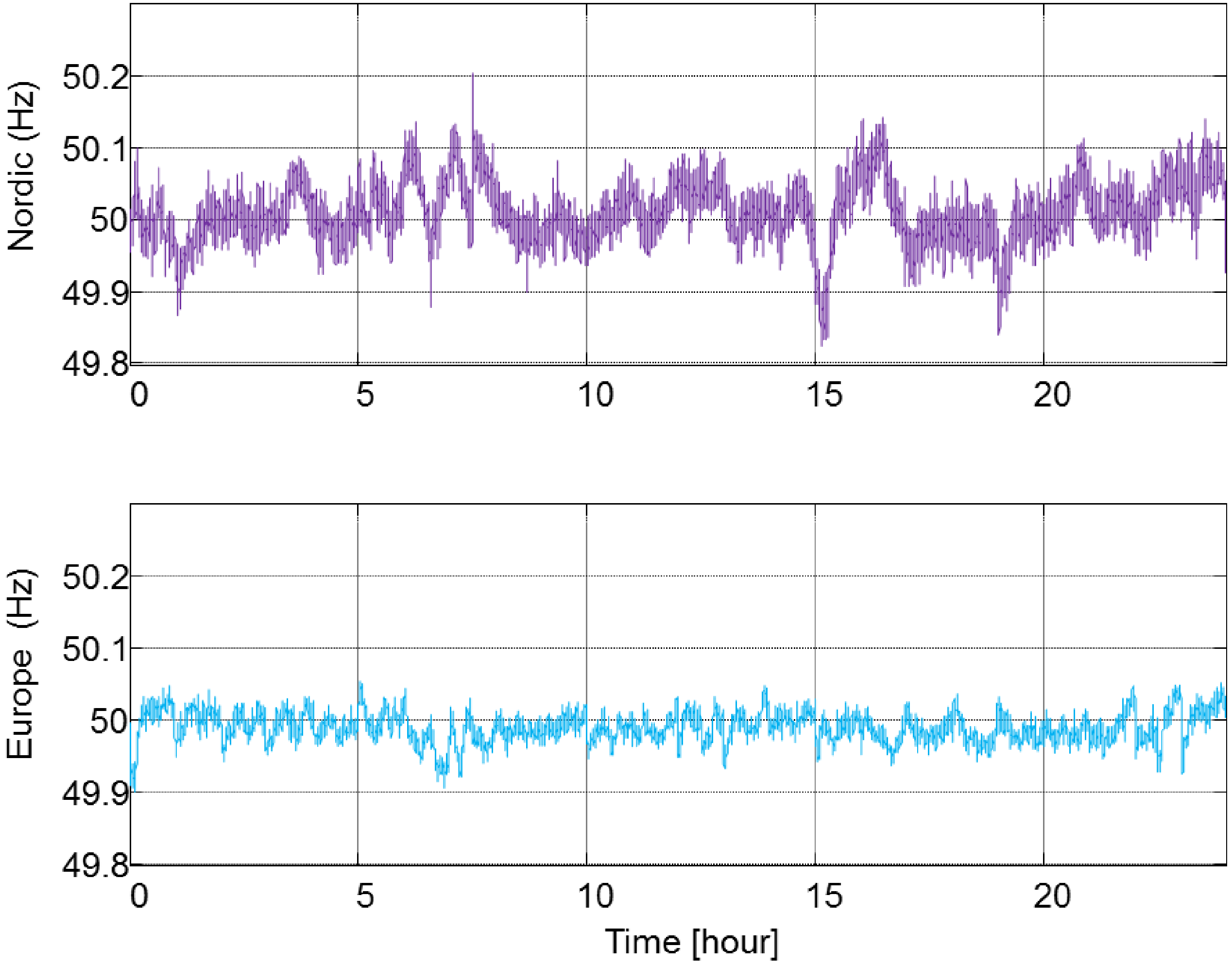


Personal Introduction

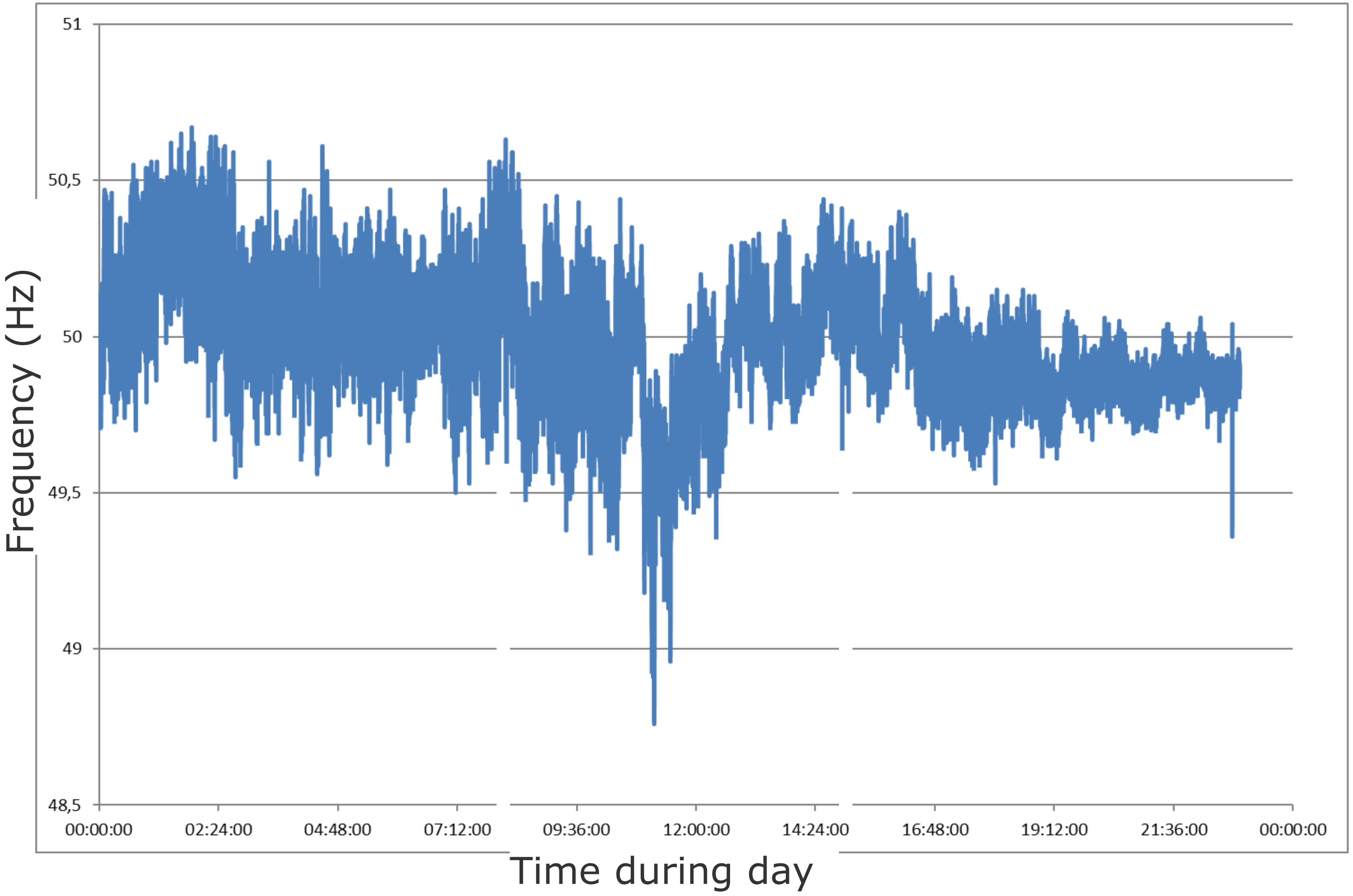
- Evert Agneholm
- PhD, Power Systems, Chalmers
- Senior Principal Engineer, DNV GL Energy
- Adjunct Professor at University West

- Major experiences
  - Power system analysis
  - Frequency control
  - Voltage control
  - Power system restoration
  - Island operation
  - Combining theoretical studies using simulations with field tests

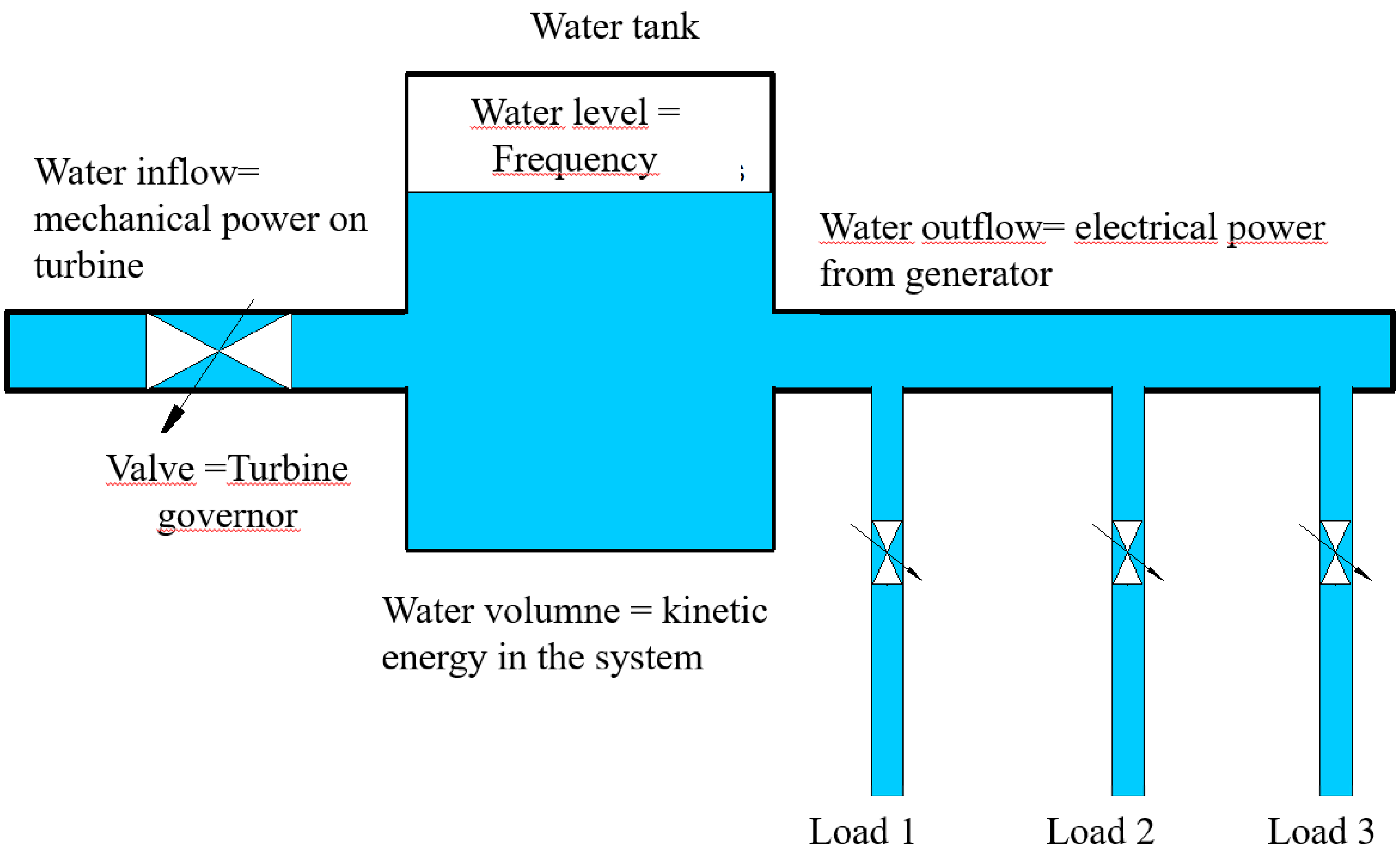
Frequency in the European and Nordic system



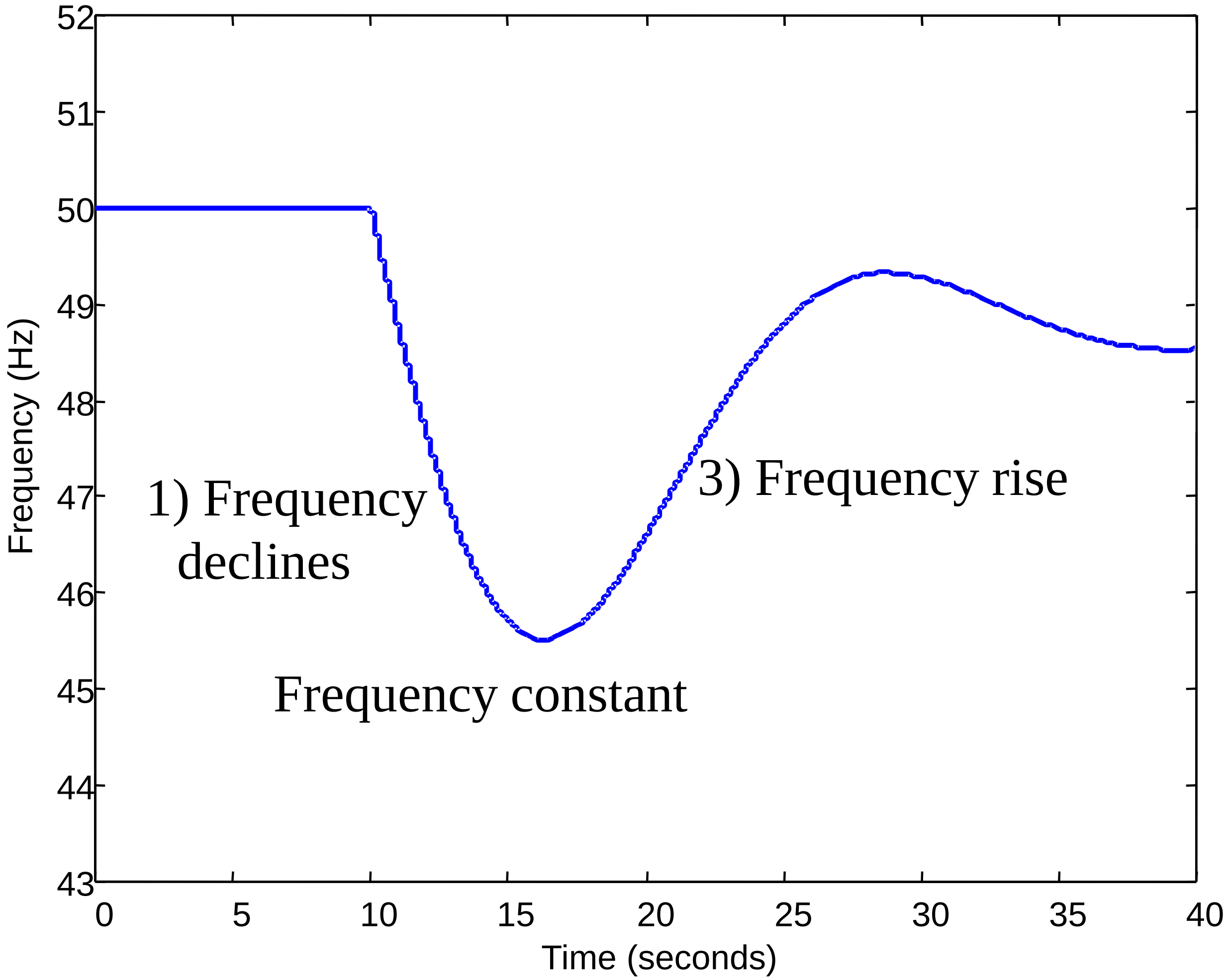
Frequency in the Faroe system – very small system



The frequency in a small island grid consisting of a turbine and a generator



Frequency control – connection of a load in an island grid



Kinetic energy in the system

Available kinetic energy in the system can be written as:

$$W_k = \frac{1}{2} \times J \times \omega^2$$

Initially after a change in the load in an island system the mechanical power on the turbine is not changed. The power increase must therefore be taken from the kinetic energy stored in the system, available in rotating machines, i.e. turbines, generator and motors. The time derivative of the kinetic energy gives the mismatch in power, ΔP

$$\frac{dW_k}{dt} = \Delta P = \frac{d}{dt}\left(\frac{1}{2} \times J \times \omega^2\right) = J \times \omega \times \frac{d\omega}{dt}$$

Change of frequency in the system

This can be rewritten as:

$$\frac{d\omega}{dt} = \frac{\Delta P}{\omega \times J} = \frac{\Delta P \times \omega_0}{2W_k}$$

As the frequency, f, is proportional to the angular frequency, ω, it is possible to replace ω with f or Δf

$$\frac{df}{dt} = \frac{d\Delta f}{dt} = \frac{\Delta P}{f \times J} = \frac{\Delta P \times f_0}{2W_k}$$

Kinetic energy and inertia constant

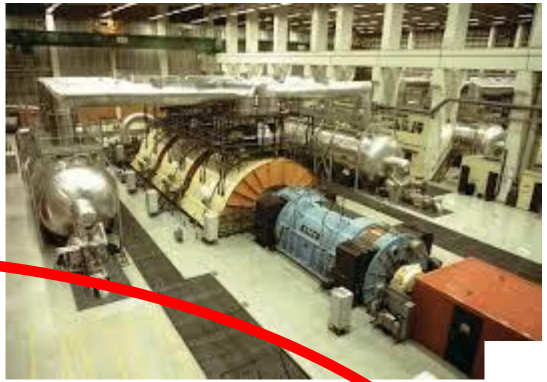
- To compare different production plants the inertia constant, H, is used

$$H = \frac{W_k}{S} \text{ [MWs/MVA]}$$

where S is the rated power of the generator and W_k the kinetic energy of the turbine and generator

- Gas turbines and thermal power plants typically H=1.5-2.5 MWs/MVA
- Hydro power plants typically H=3-4 MWs/MVA
- Nuclear power plants typically H=5-7 MWs/MVA
- Solar and wind power H=0 MWs/MVA (wind can have virtual inertia)

The Issue of kinetic Energy / Inertia / Flywheels / Synthetic Inertia



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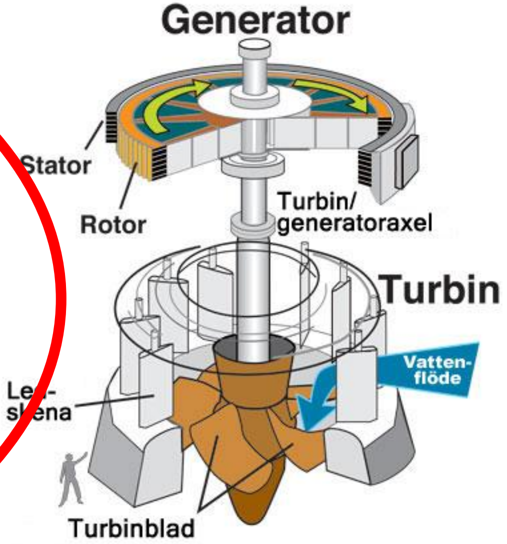
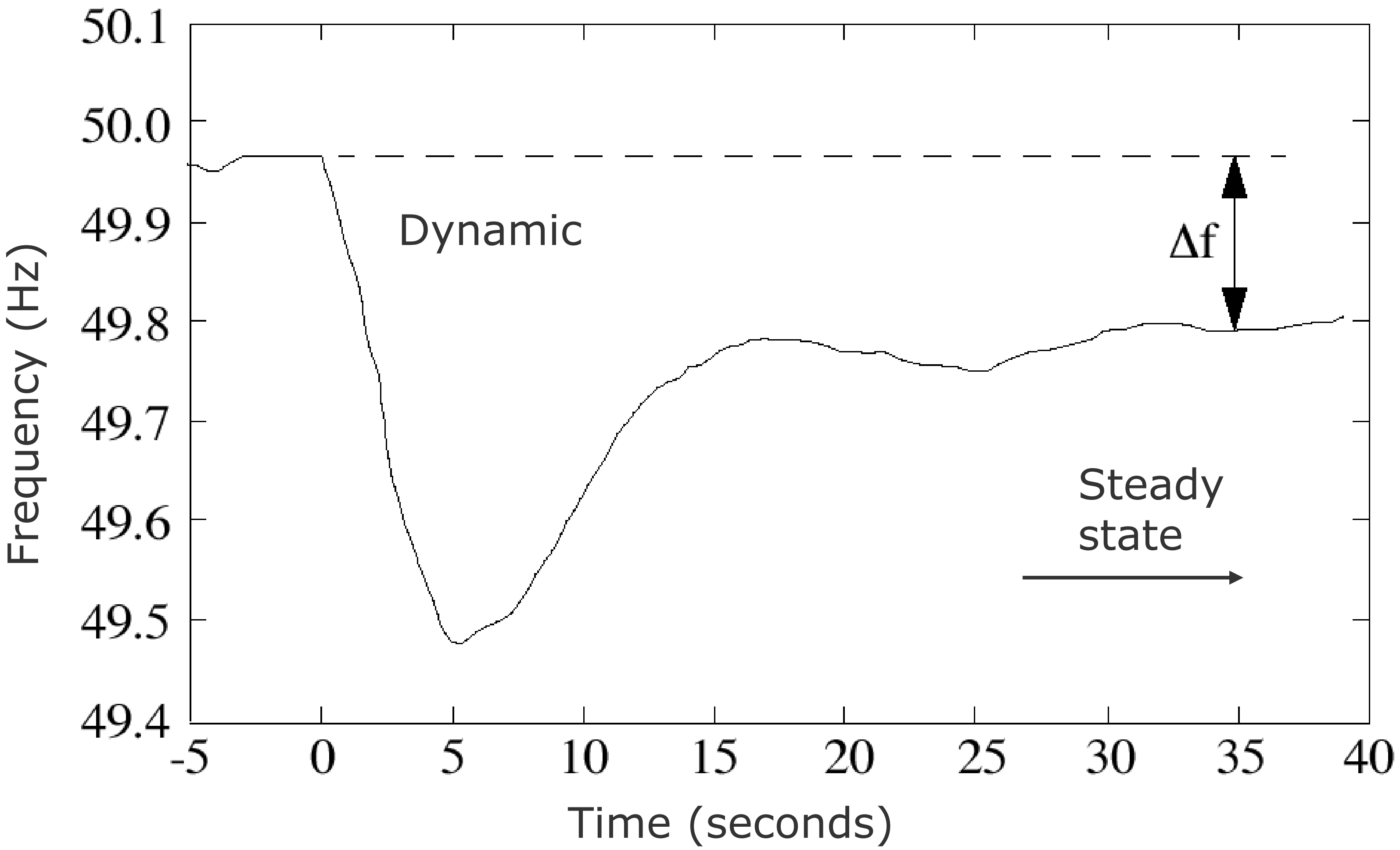
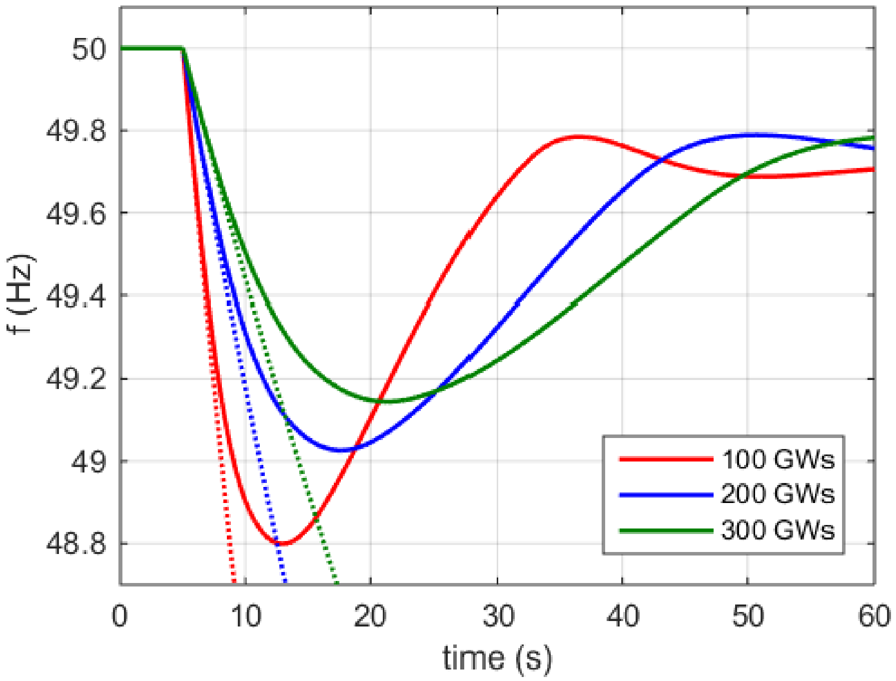


Frequency Control – disconnection of a production plant in the Nordic system



Future System:



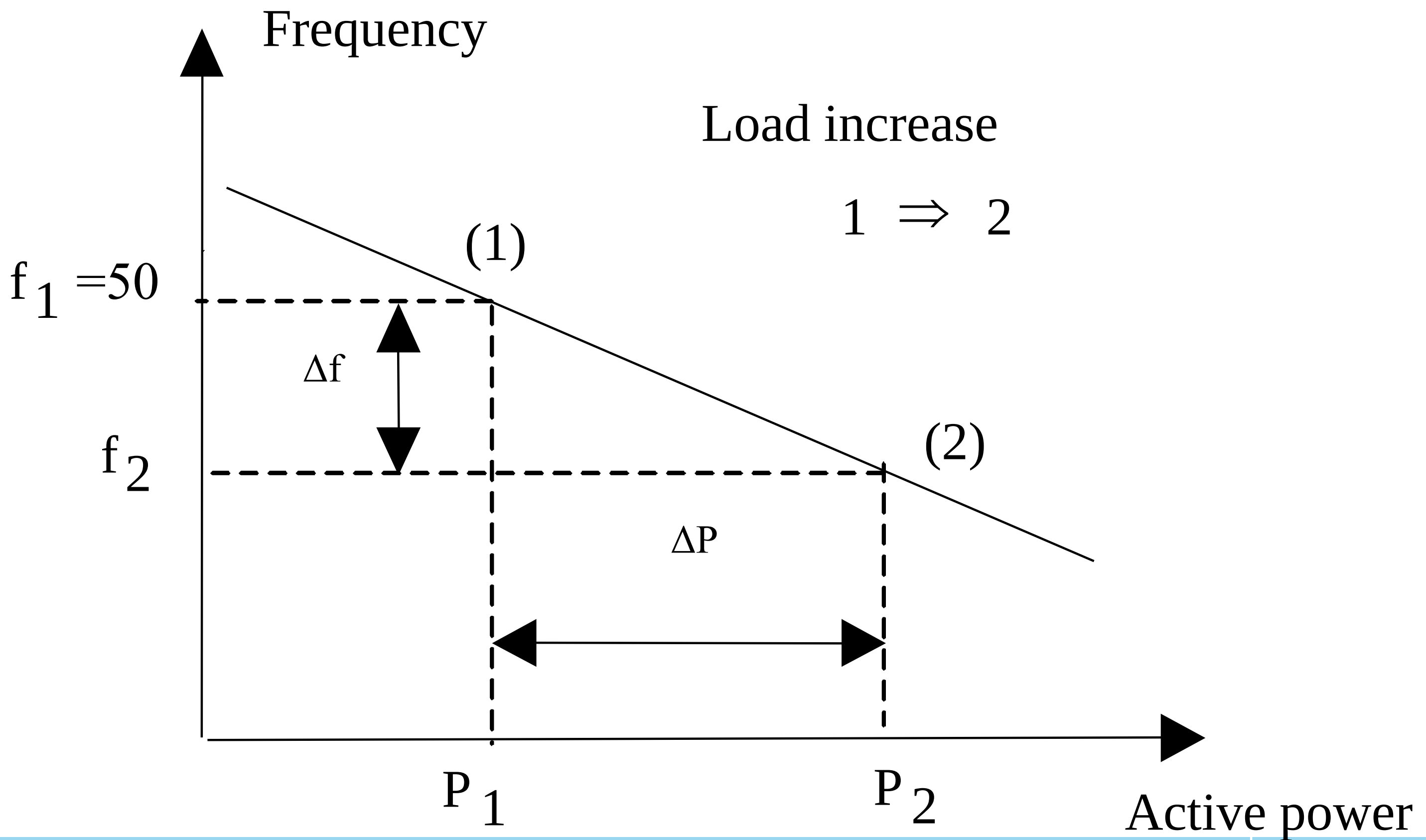
Different times after disconnection of a production plant

1. Initially the power production is taken care of in the generators that are closest (impedance) to the production plant
2. Secondly the production is shared according to the kinetic energy/inertia of the production plants
3. Steady state the production is shared according to the droop of the production plants
4. Active power set-point values are increased manually or automatically or new production sources are started up, i.e. secondary frequency control, aFRR/mFRR

Frequency control – steady state

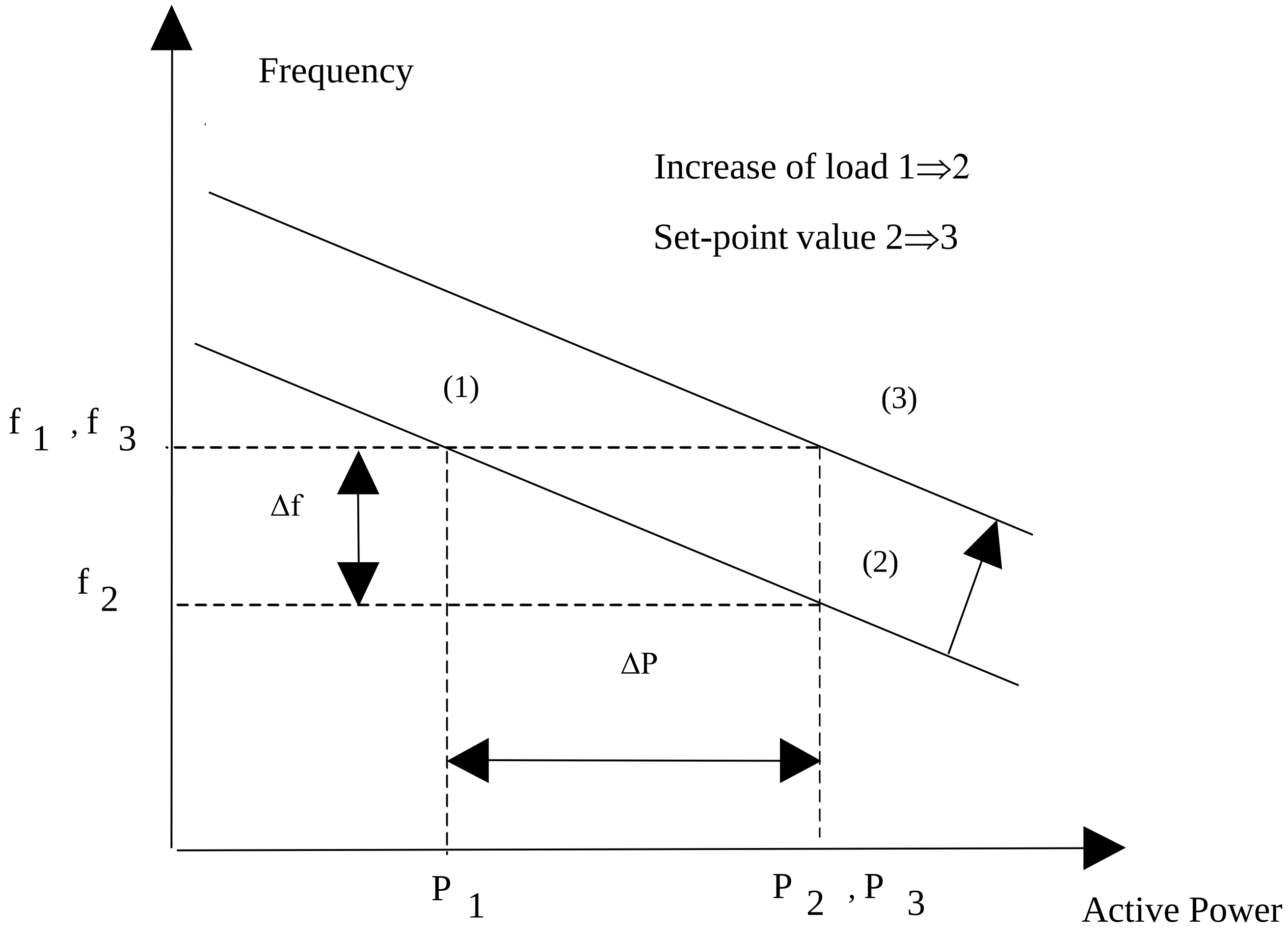
- The dynamic power frequency characteristic, “Reglerstyrkan”, R, defines the strength of the system

$$R = \frac{\Delta P}{\Delta f}[MW / Hz]$$



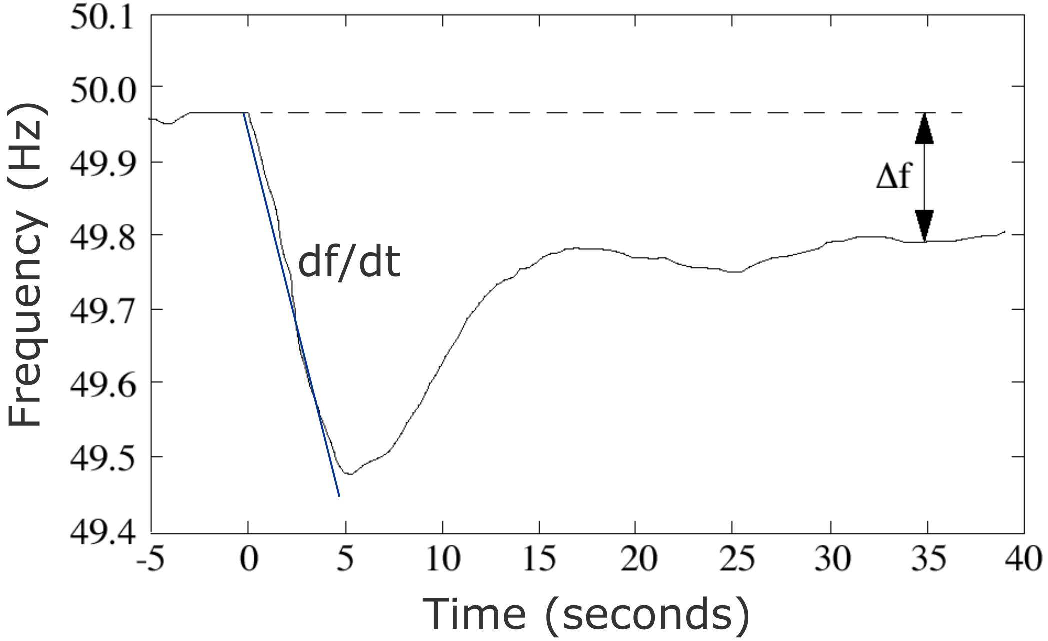
Frequency control – steady state

- After a load change the turbine set-point values must be changed or new production started to eliminate the frequency error Δf



Estimation of kinetic energy in the system – previous example

- The speed of the frequency decrease, df/dt, after a generator disconnection of $\Delta P = 800$ MW is dependent on the kinetic energy in the system, W_k.
- Calculate the kinetic energy?



Example

$$\frac{df}{dt} = \frac{\Delta P \times f_0}{2 \times S \times H}$$

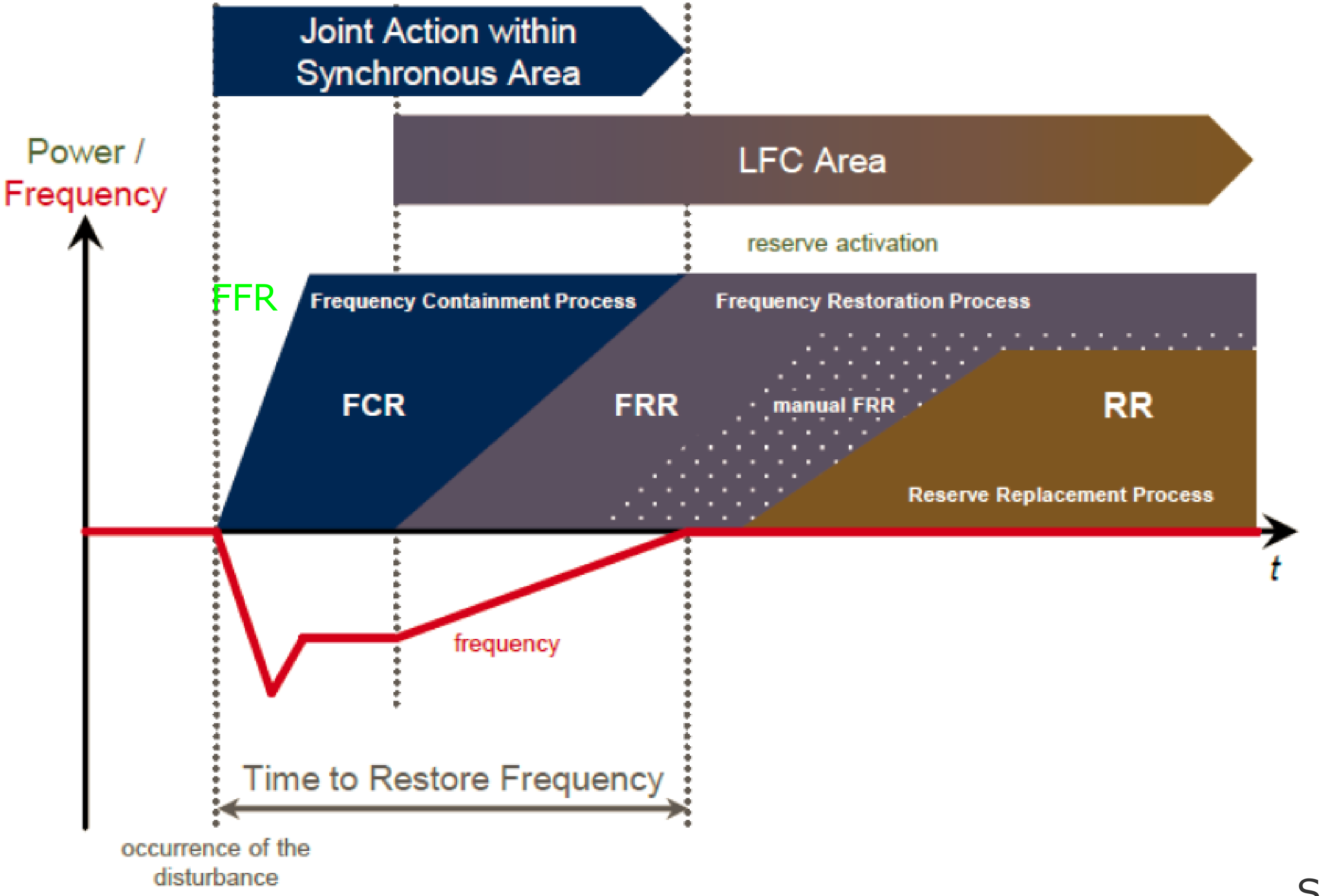
- According to the previous example

$$\Delta P = 800MW, f_0 = 50Hz, df/dt = 0.11Hz/s$$

$$W_k = \frac{\omega^2 \times J}{2} = S * H = \frac{\Delta P \times f_0}{2 \times df/dt} = 182GWs = 51MWh$$

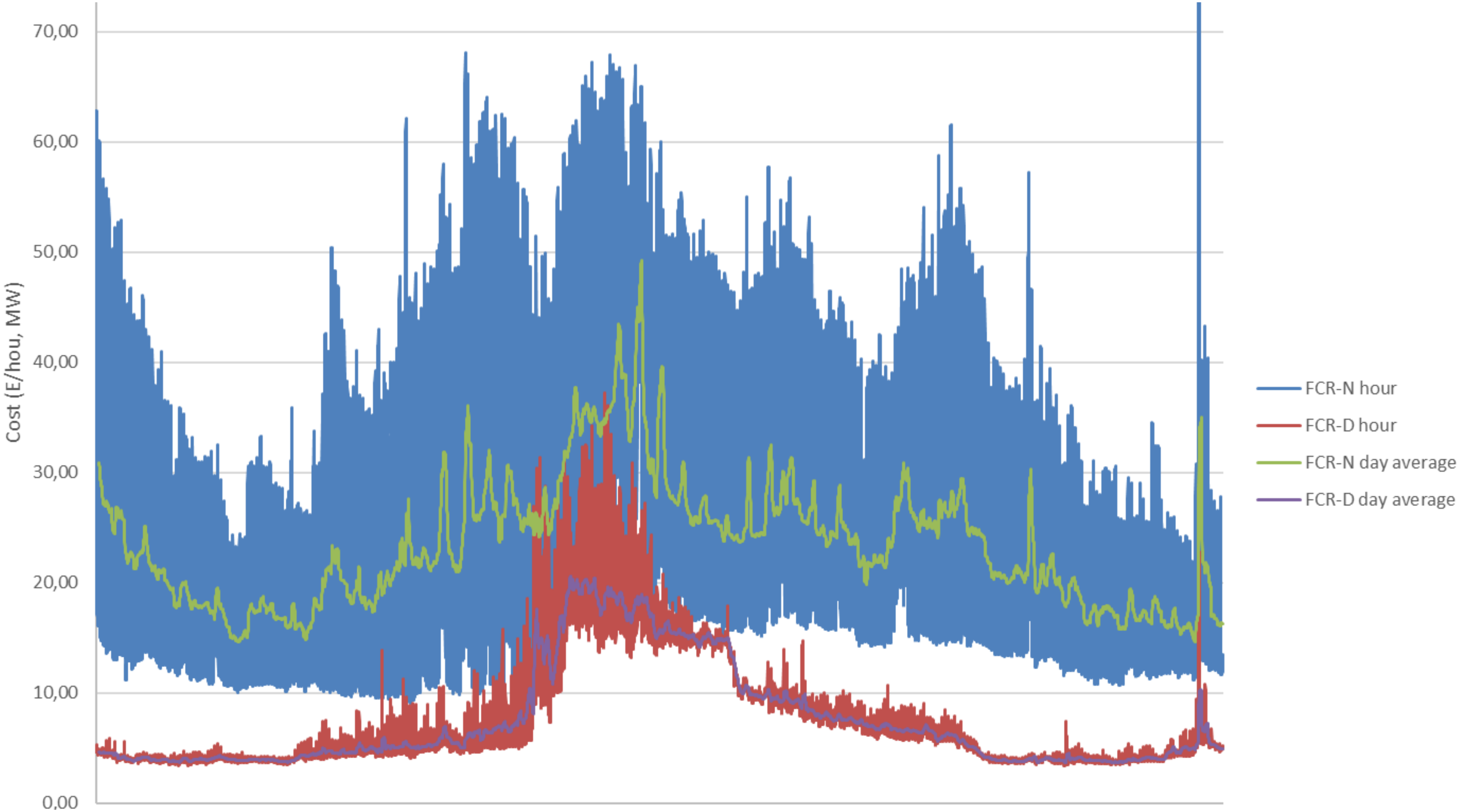
- This corresponds to the electricity consumption of 10 households without electricity heating (5000 kWh/year) during a year.

Frequency control in the Nordics – different products



Source: Svenska kraftnät

Costs for FCR during 2017



Changes in the Nordic power system affecting frequency control

- More renewables like wind and solar
  - Varying production, both in long and short term
  - No kinetic energy (wind can have virtual inertia)
- Less nuclear power
  - Predictable production
  - Much kinetic energy
- More loads fed by power electronics
  - Less system load frequency dependence
  - Less system kinetic energy

Tests of individual production units

- Why testing?
- How to test?
- Typical tests?

- “Att mäta är att veta”
- “To measure is to know”

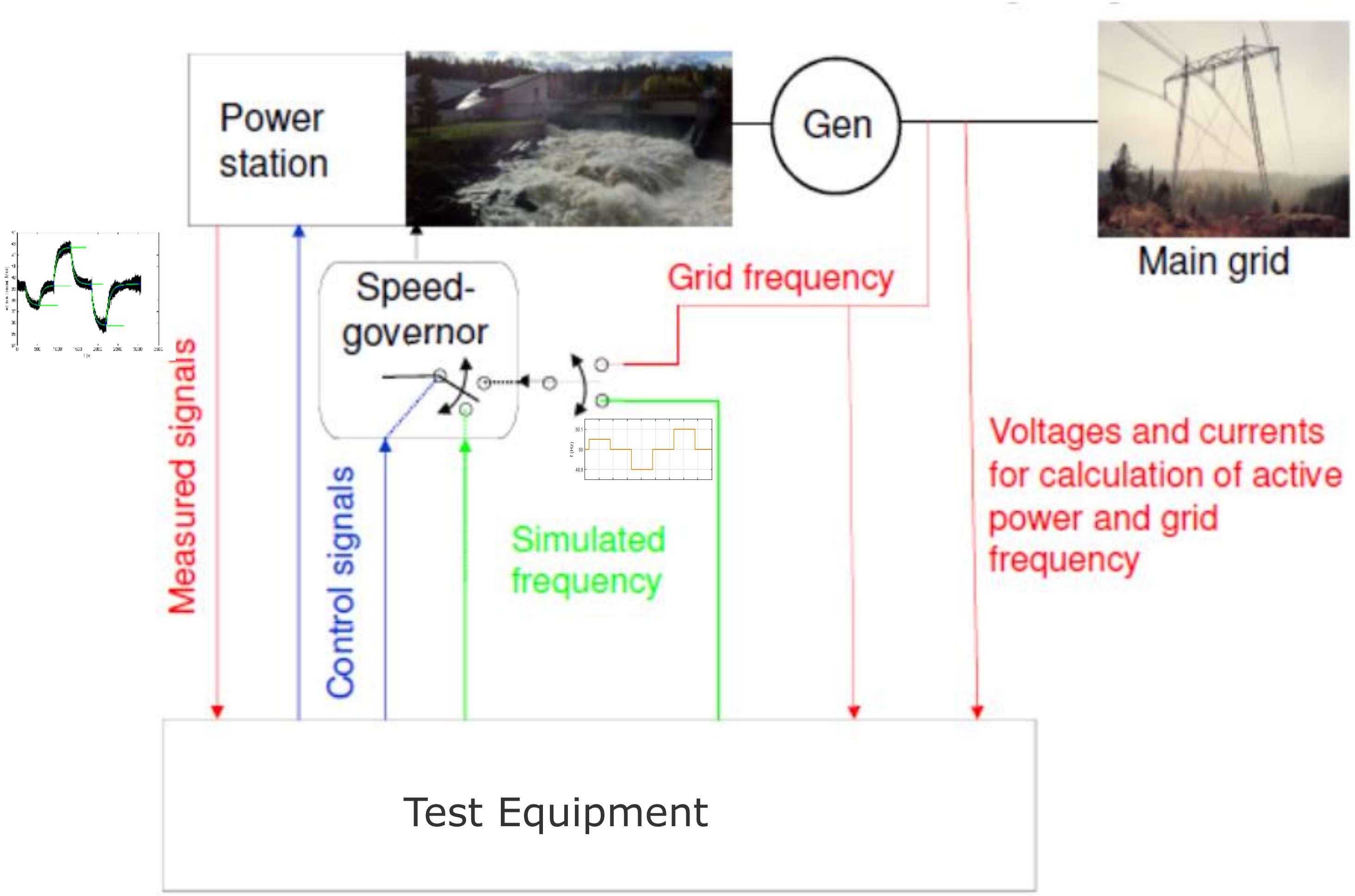
Why testing?

- Tests to verify frequency control capability, fulfilling grid codes (RfG)
- Tests to validate dynamic simulation models (RfG)
- Tests to verify fulfilment of FCR products
- Tests to verify island operation capability

How to test

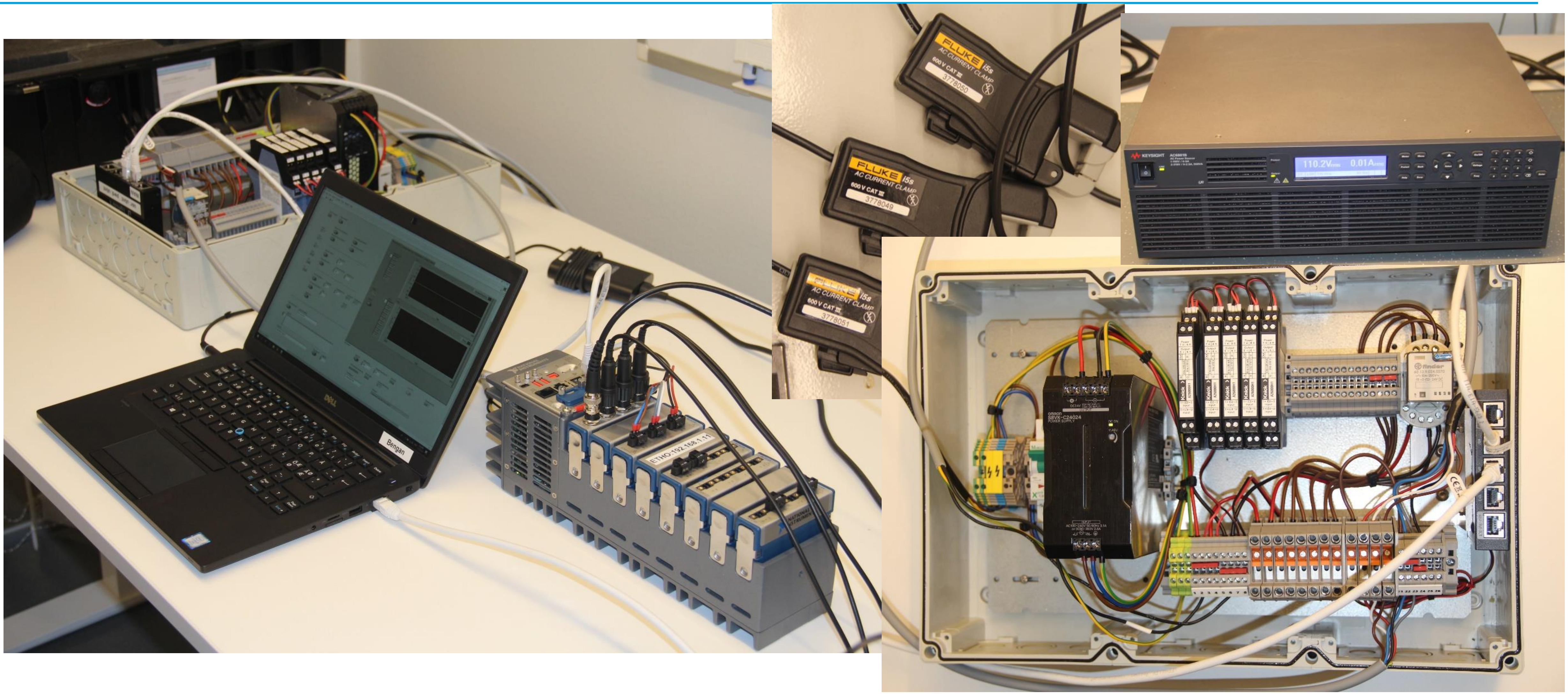
- Use dynamic simulation tools to simulate the behaviour
  - Requires validated simulation models
  - Rather easy and low cost
- Use normal frequency variations in the system to make sure that frequency control works properly
  - Rather small variations including “noise” that can be hard to use
- Use data from disturbances that occur some times per year
  - Can be useful
  - Hard to find dimensioning situations
- Perform tests using a simulated frequency signal

Connection of test equipment

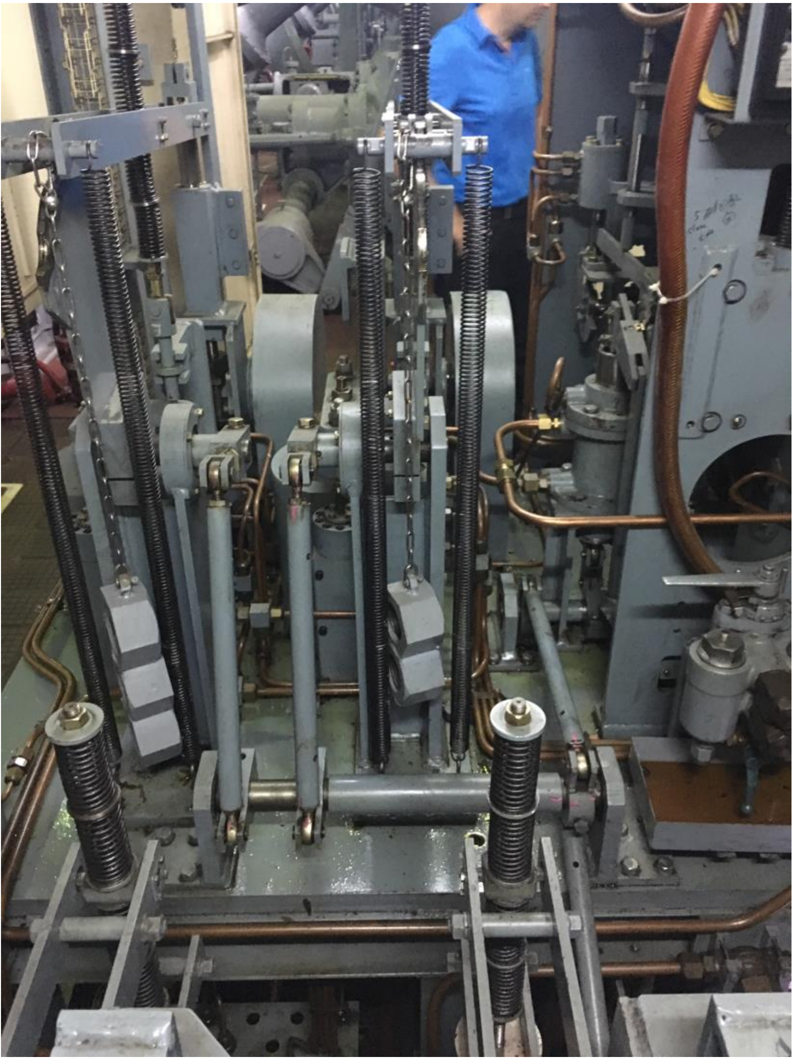


- Preferable to connect the frequency signal from “normal” way as it involves all relevant parts in the measurement and governing system
- Recommendable to measure as many signals as possible to be used for model validation

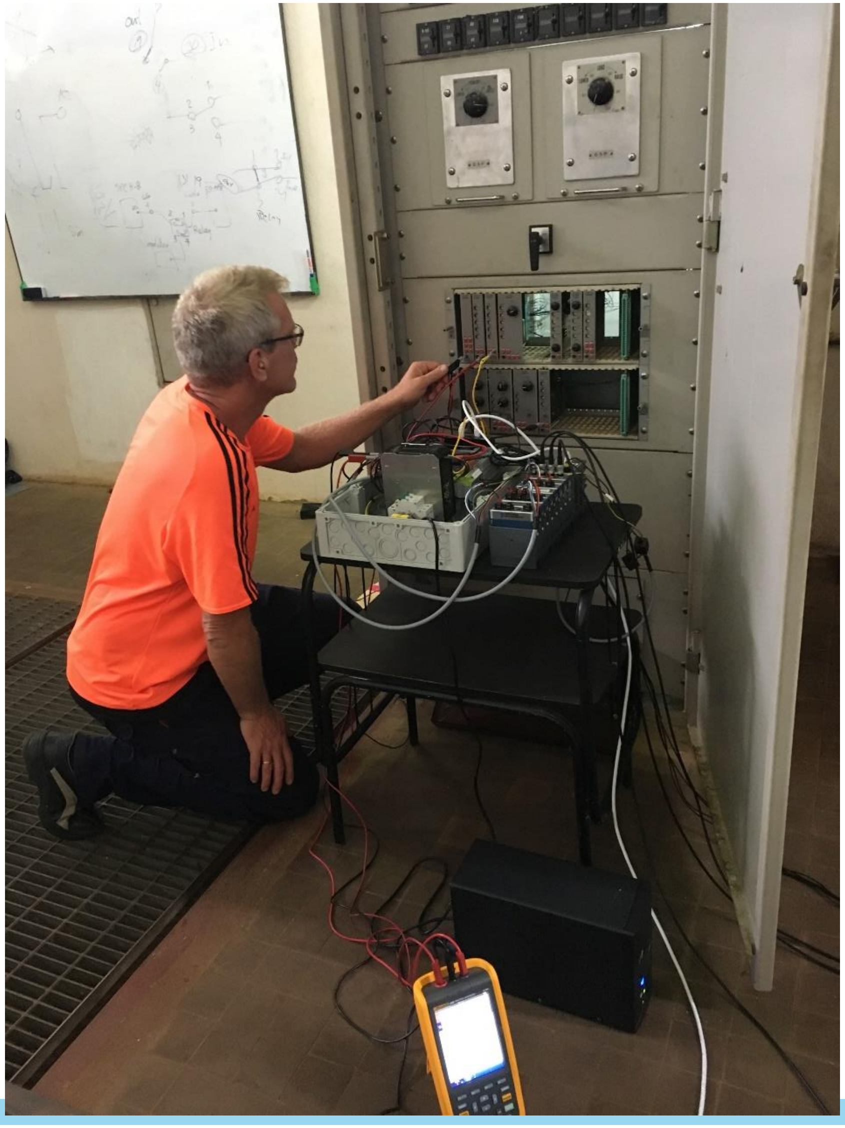
Hardware – test equipment



Testing different governor types



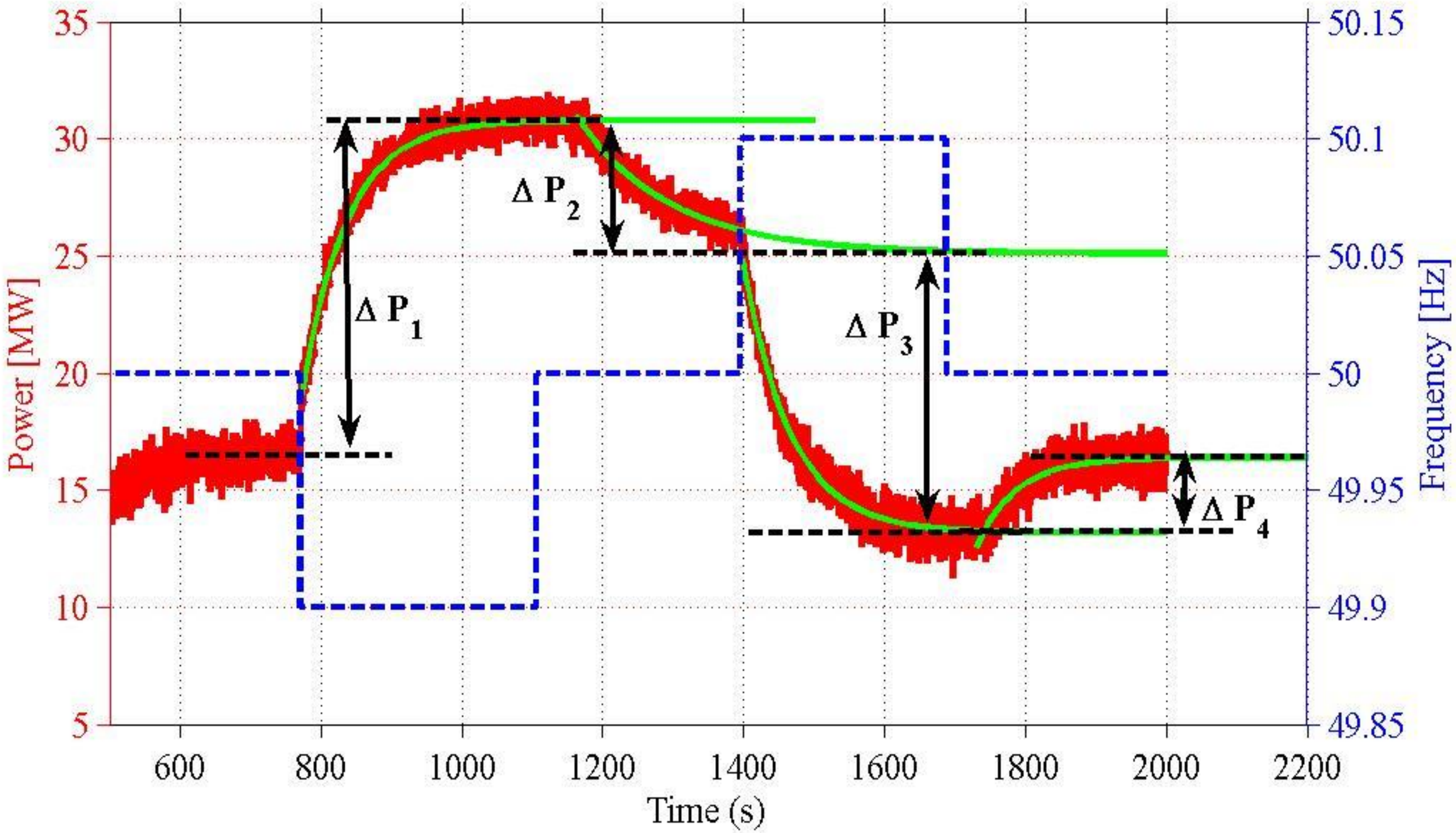
Connection in an old hydro unit



Typical tests

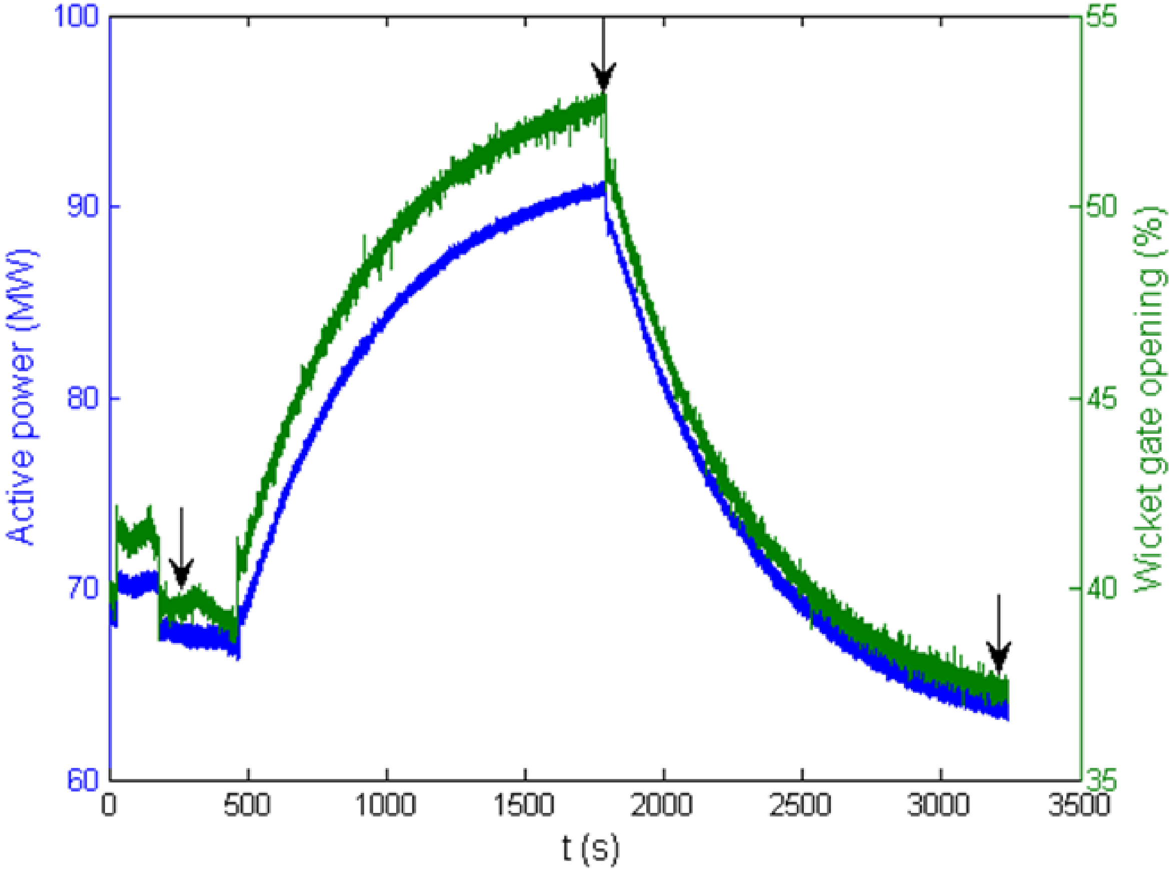
- Frequency step response tests
- Frequency ramp tests
- Superimposed sinusoidal frequency signal
- Simulated island operation

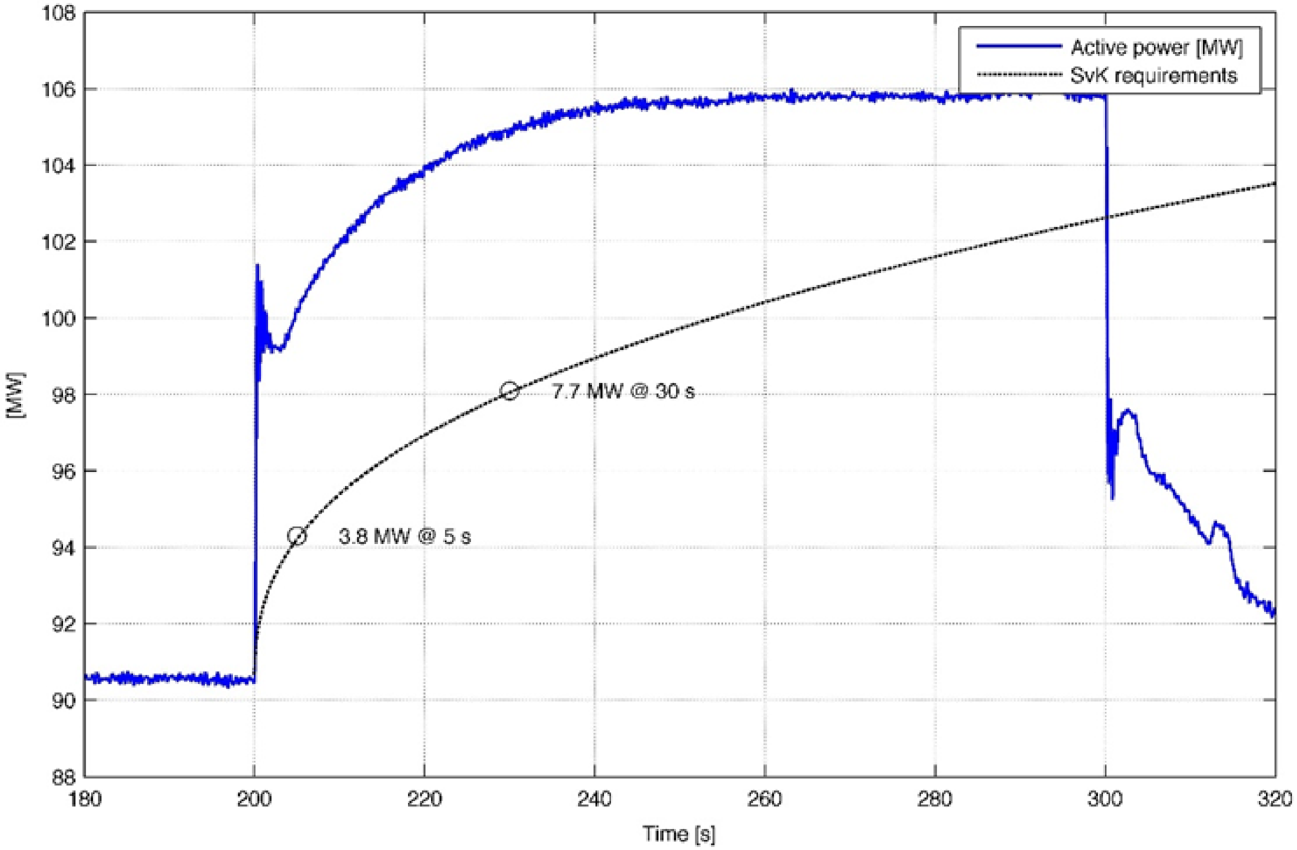
Frequency step response test – to verify steady state activation and backlash



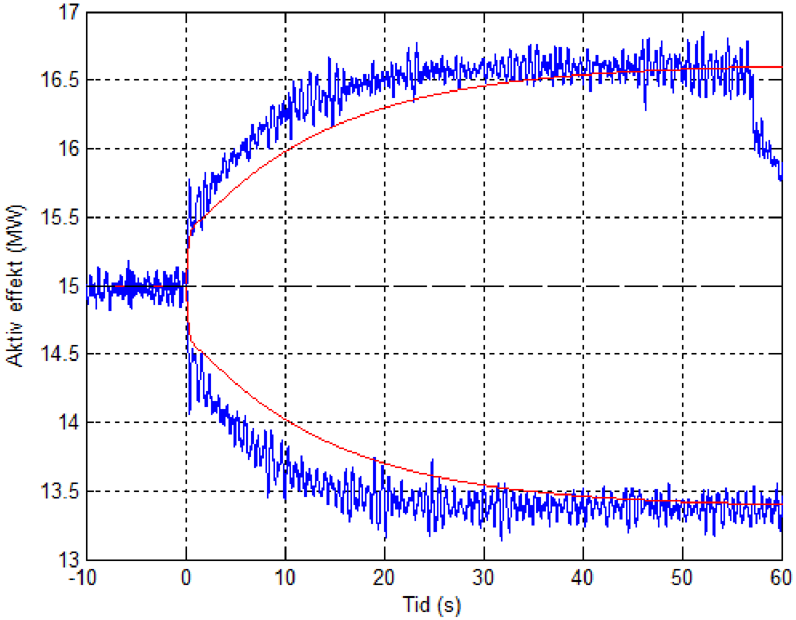
- Example from a Francis turbine
- Due to backlash $\Delta P_1 \neq \Delta P_2$ and $\Delta P_3 \neq \Delta P_4$

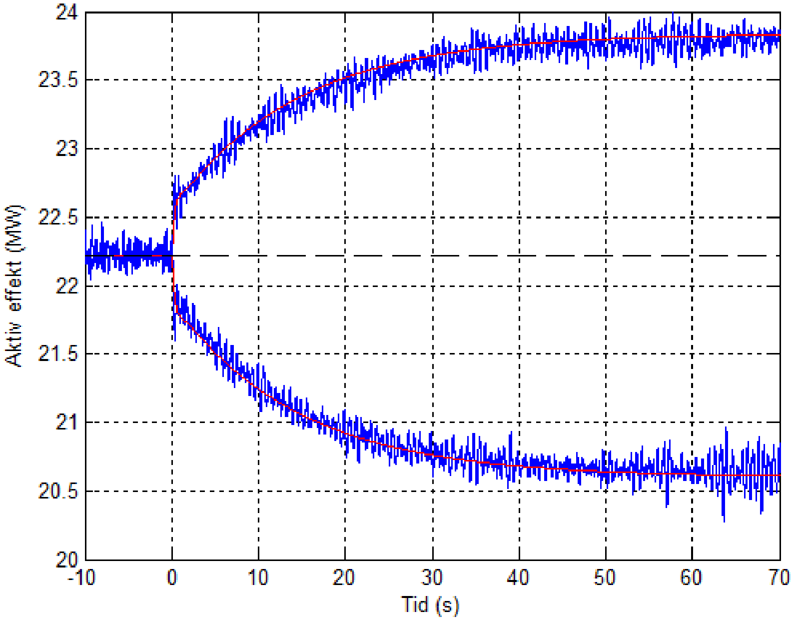
Frequency step response test – slow and fast response

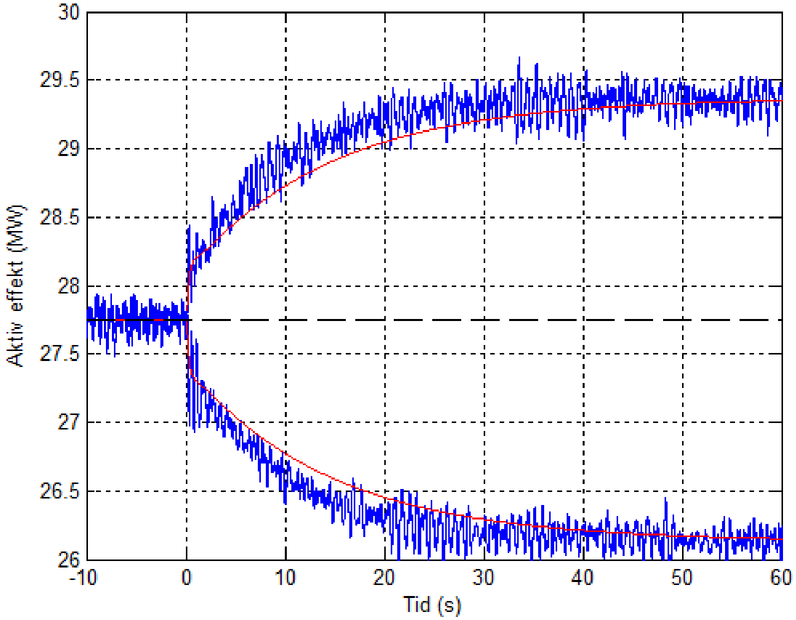




Frequency step response test – comparison with simulation at different load levels



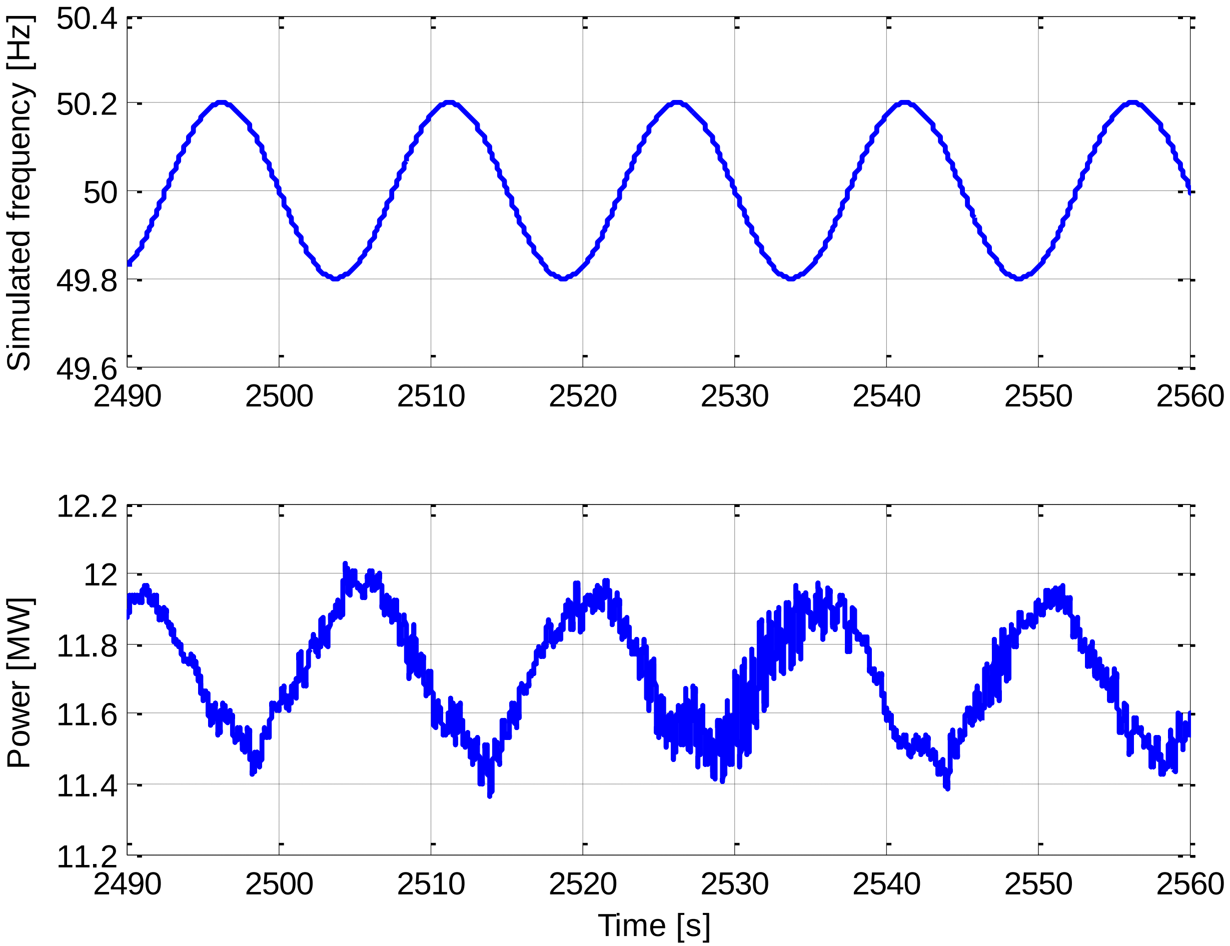




- The system is not linear, i.e. the response varies with the loading

Superimposed sinusoidal tests

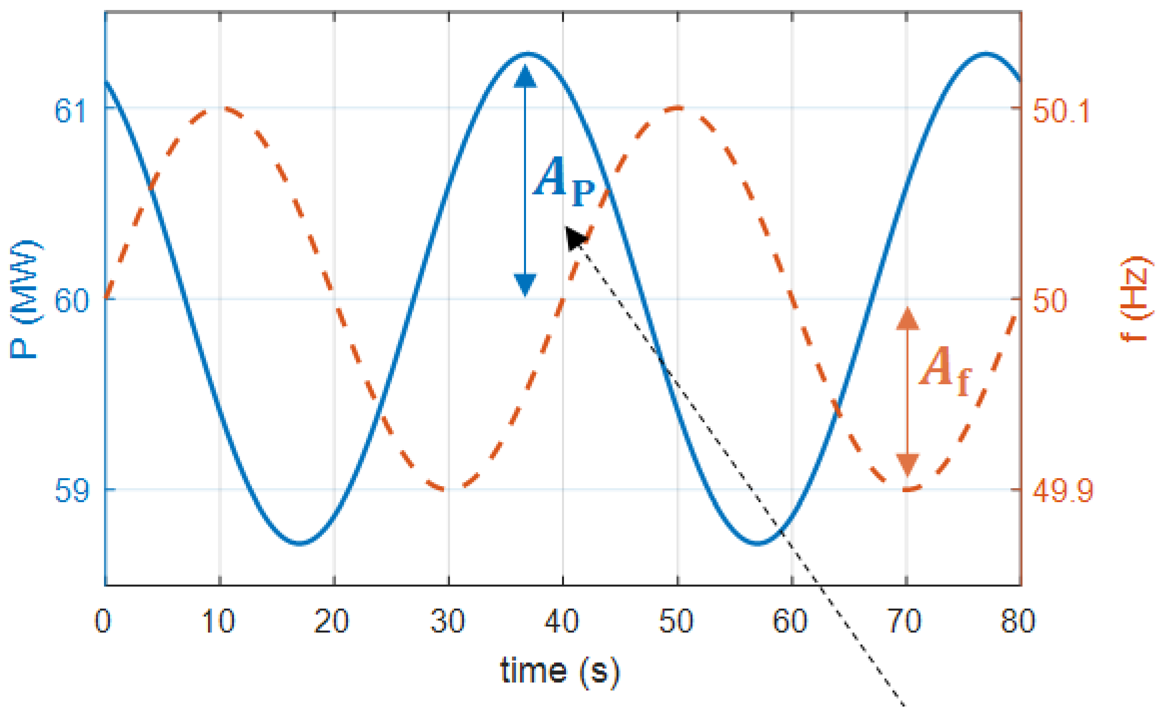
- $f = f_n + A_f \cdot \sin\left(\frac{2\pi}{T} t\right)$
- $P = P_n + A_p \cdot \sin\left(\frac{2\pi}{T} t + \varphi\right)$
- Stability margins
- Requirements FCR
- Simulation model validation (governor models used in simulation
  of power system)
- Cycle times typically from 3 s to 400 s



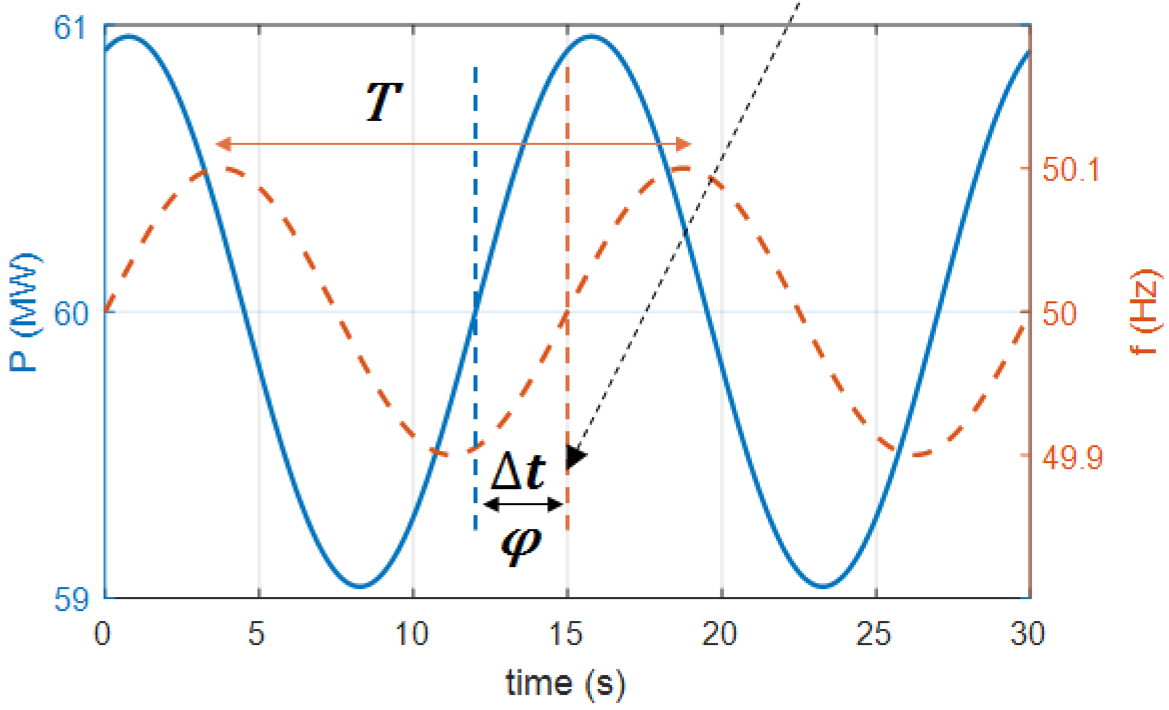
Sinusoidal test evaluation

$$\varphi = \mathrm{Arg}(F(j\omega)) = \Delta t \frac{360°}{T}$$

Time period $T = 40\mathrm{s}$

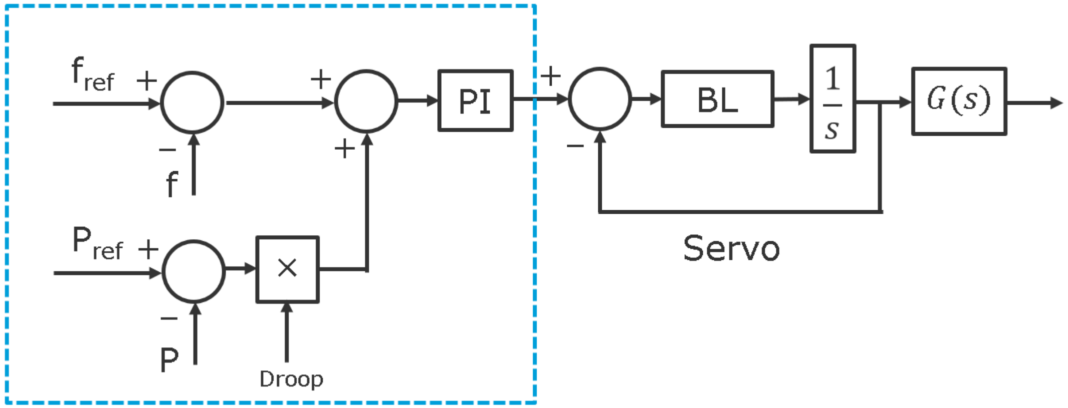


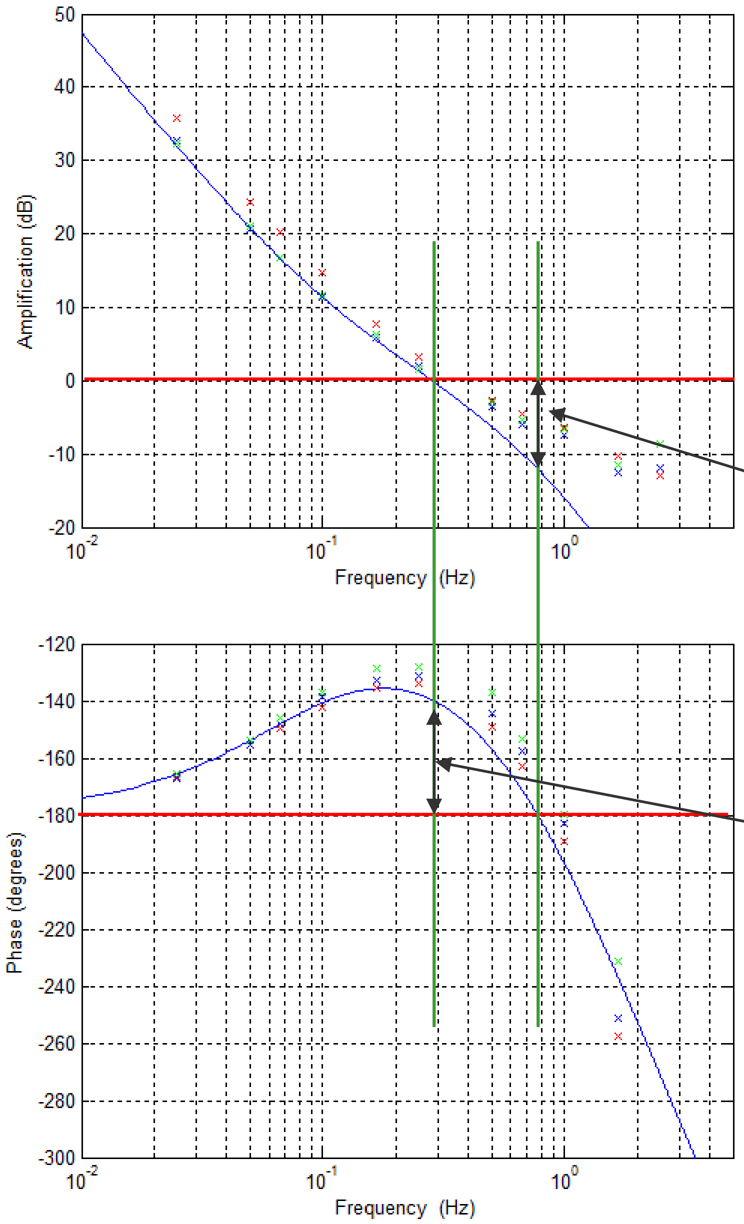
Time period $T = 15\mathrm{s}$



Sinusoidal test evaluation

- Bode plot
- Stability margins in the open loop systen (amplitude and phase)
- Simulation model validation (governor models used in simulation of power system)



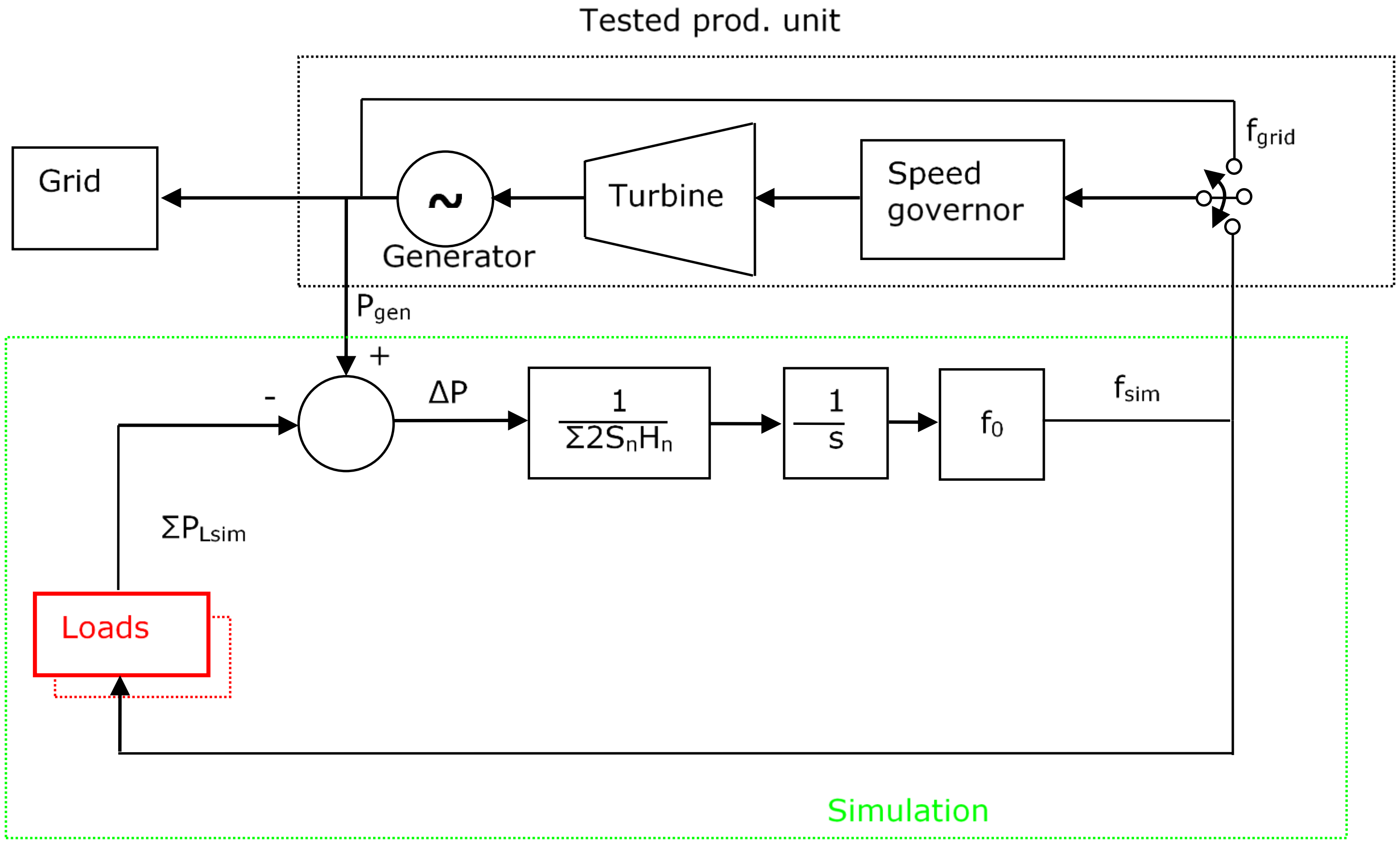


red stars 46% loading
blue stars 71% loading
green stars 86% loading

Amplitude margin
Need > 3 – 5 dB

Phase margin
Need > 25 – 35°

Principle of HIL (Hardware In the Loop)



$$\Delta P_N = P_{GenN} - \sum P_{LsimN}$$

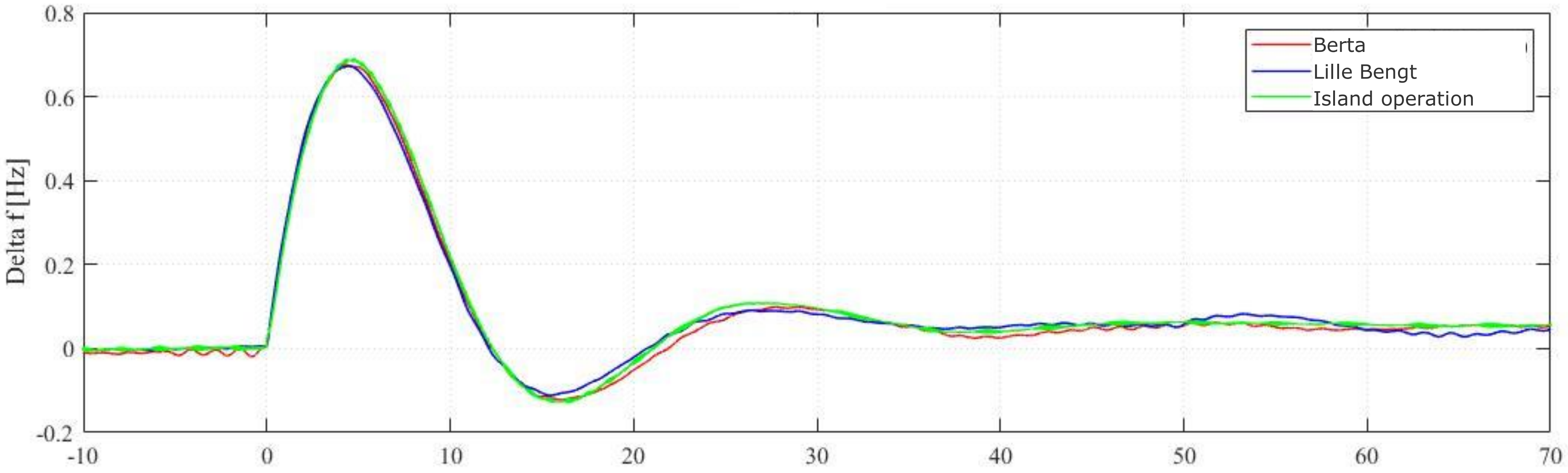
$$\frac{df_N}{dt} = \frac{\Delta P_N \cdot f_N}{2\sum S_n \cdot H_n}$$

$$\Delta f_{N+1} = \frac{df_N}{dt} \cdot \Delta t$$

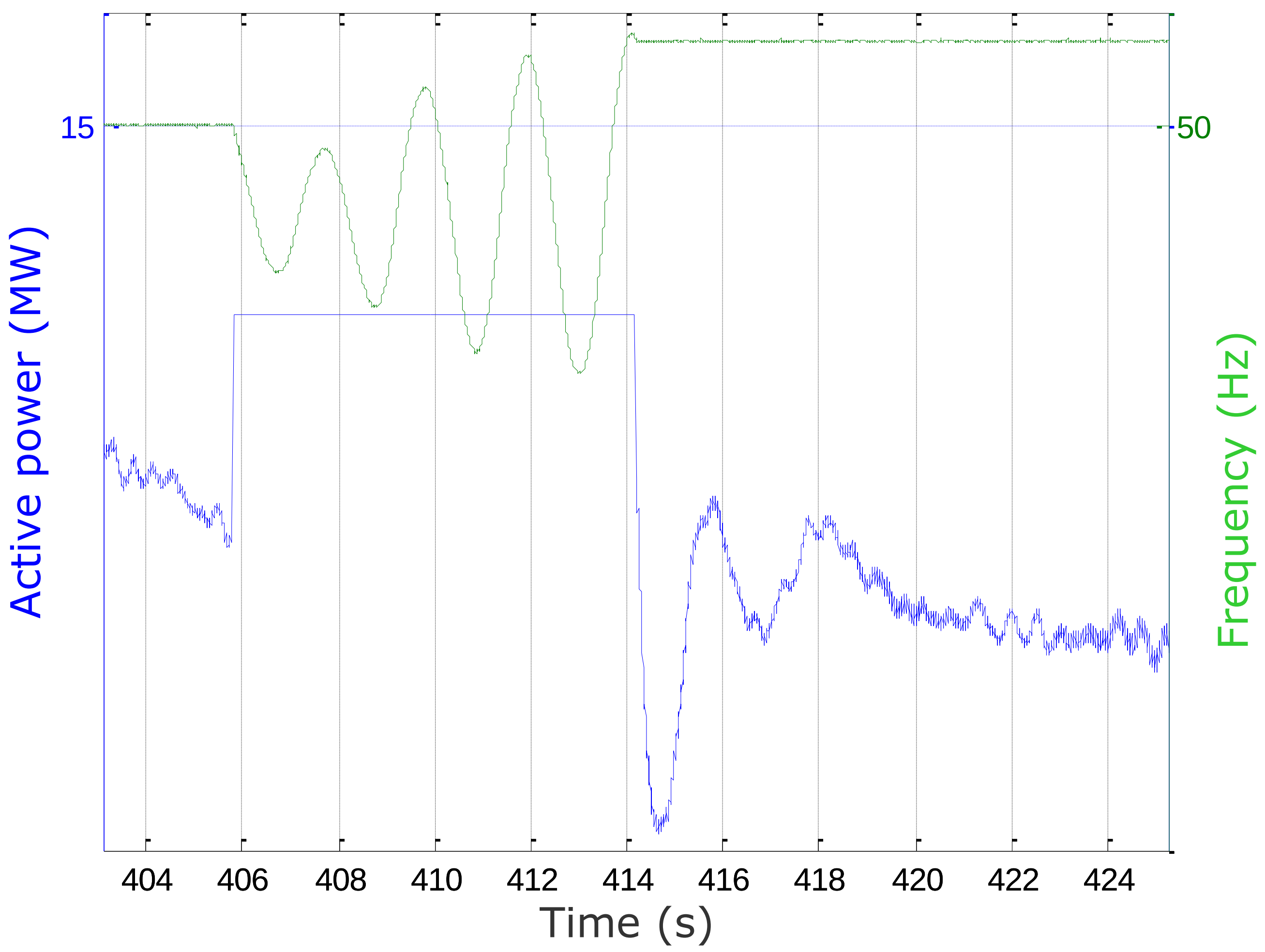
$$f_{N+1} = f_N + \Delta f_{N+1}$$

Validation of HIL

- Tests were made at the laboratory at Chalmers on a 75 kVA generator with turbine governor
- Tests were made with Lille Bengt, Berta (similar test equipment from Opal RT) and real island operation
- Tests below show the frequency change when performing a load rejection of 7 %
- Governor setting is a typical hydro governor setting

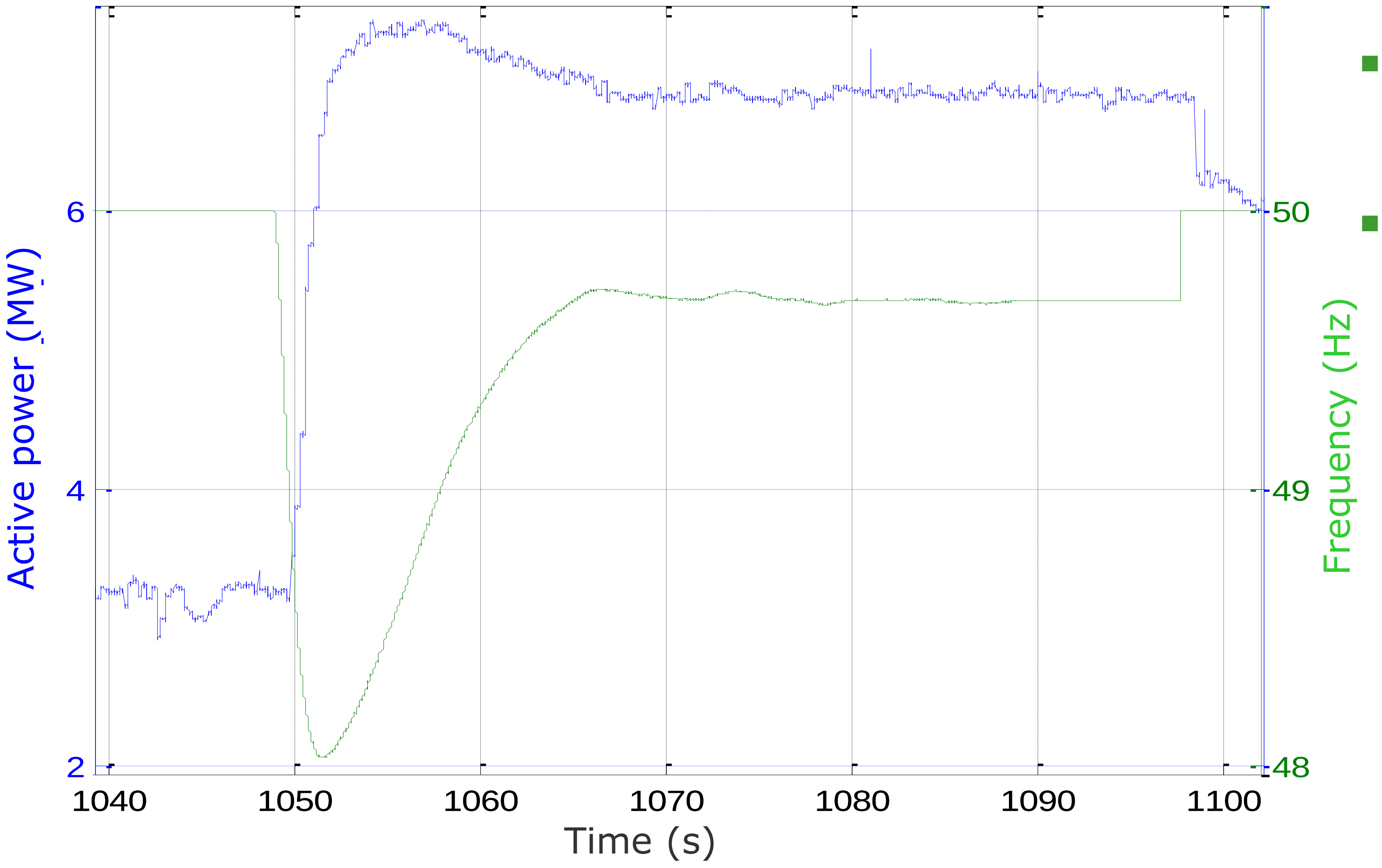


Test of island operation – thermal unit with original governor settings



- The system is not stable – test interrupted

Test of island operation – thermal unit with tuned governor settings

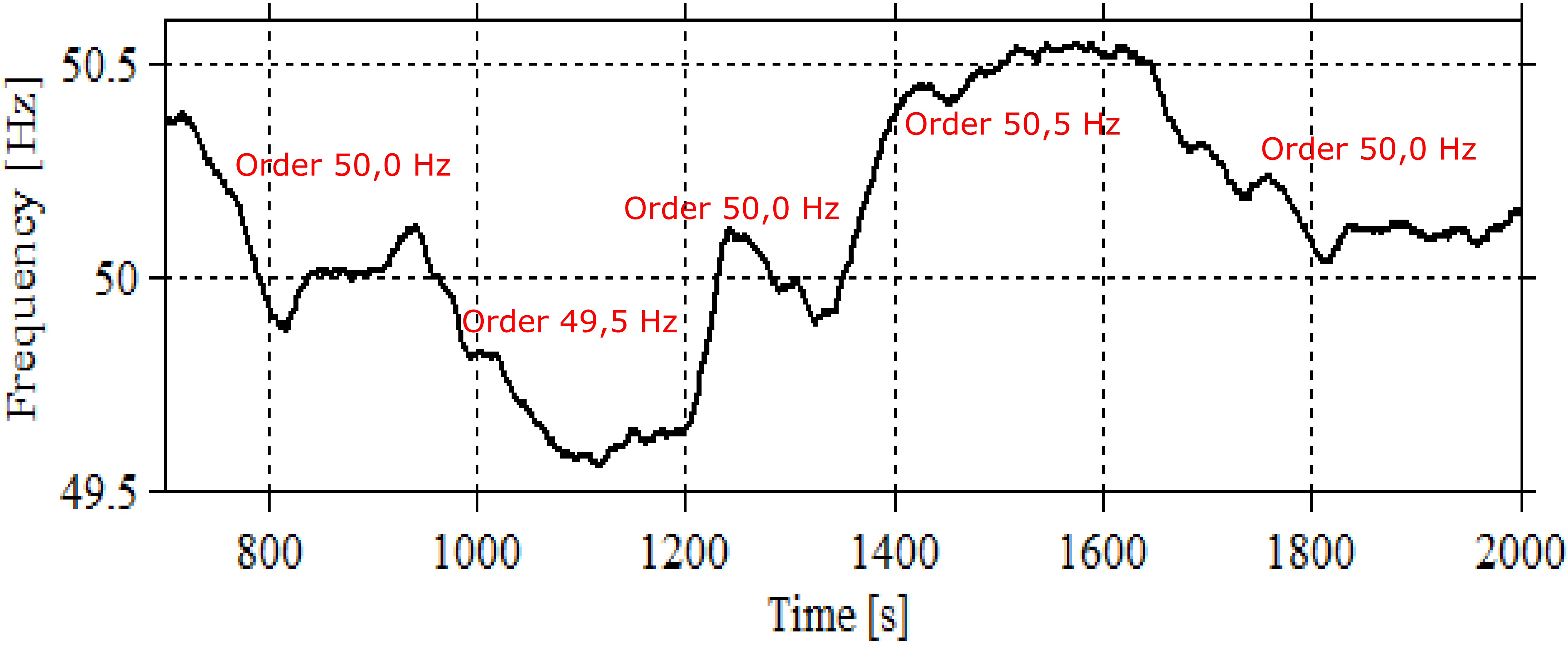


- The system becomes stable
- Manage 10 % load connection with 2 Hz dynamic frequency change

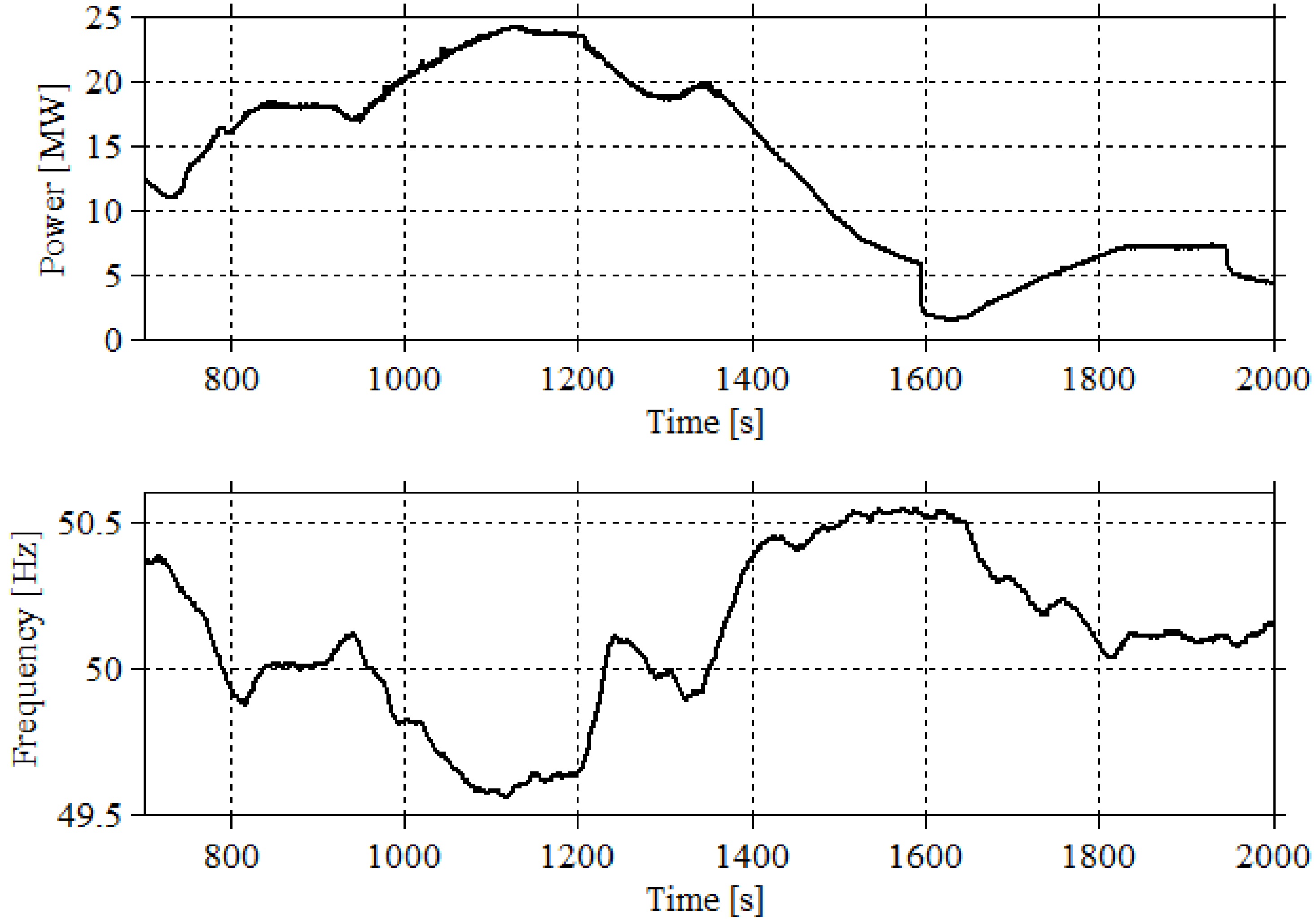
Full scale tests in a small islanded system (2500 MW)

- Frequency control is normally controlled by the national load dispatch centre
  - Gives order to production plants to increase or decrease the production in order to control the system frequency
- Manual frequency control of the power system was taken over by “our” power station during the test
- I asked for changes in the system frequency and 3 operators adjusted production manually to change the system frequency
- System frequency 50.0 Hz; 49.5 Hz, 50.0 Hz; 50.5 Hz and 50.0 Hz

Full scale tests in a small islanded system – system frequency during test

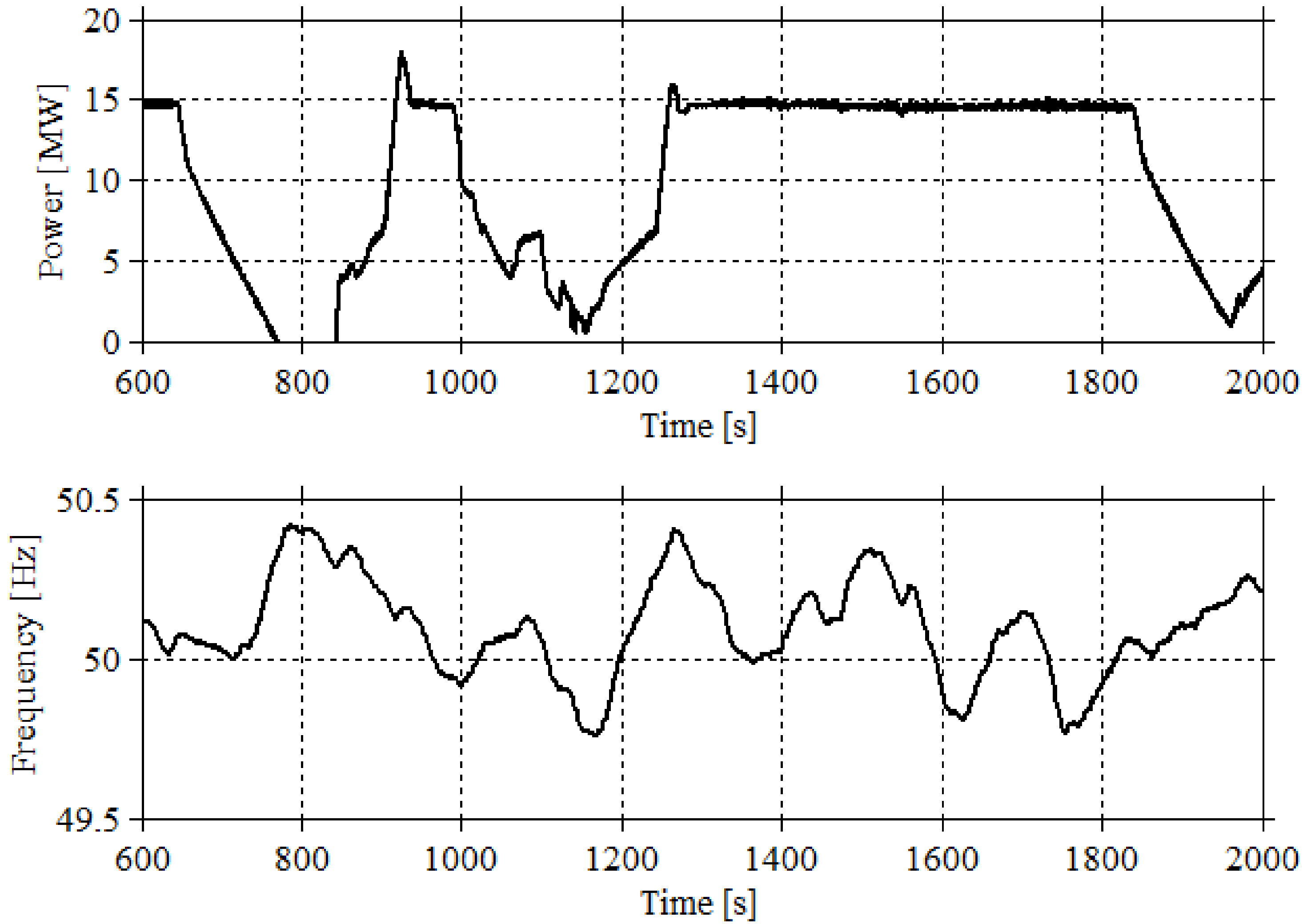


Full scale tests in a small islanded system – system frequency during test



- Frequency control works as expected, i.e. frequency decrease => active power production increase and vice versa

Full scale tests in a small islanded system – system frequency during test

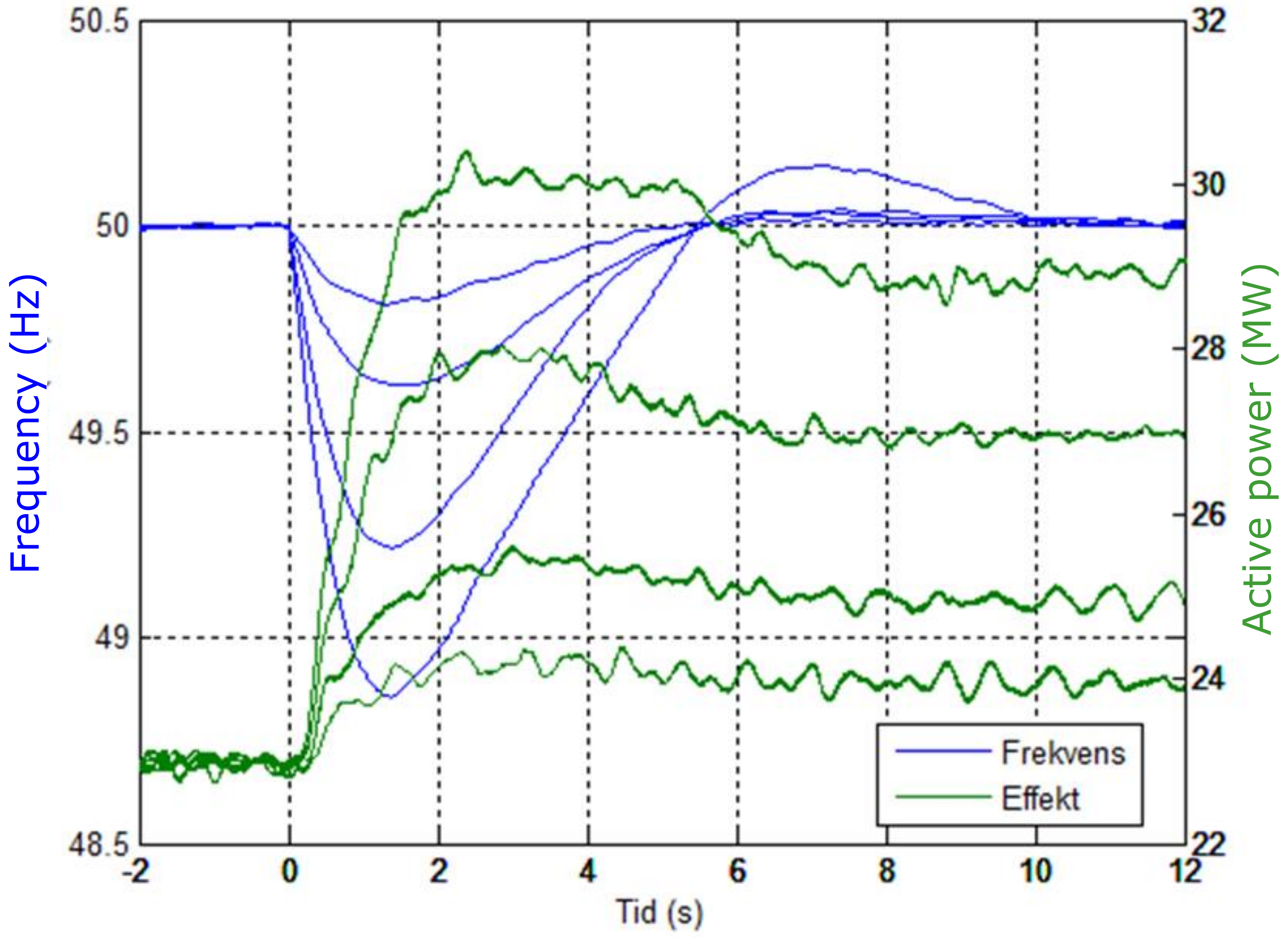


- Frequency control does not work as expected
- Power production goes to 0 when changing over to frequency control

Example island operation of a pulp and paper industry

- First test of a single unit with test equipment
- Frequency step response
- Superimposed sinusoidal signal
- Simulated island operation
- Load rejection test to house load operation with 0 MW load

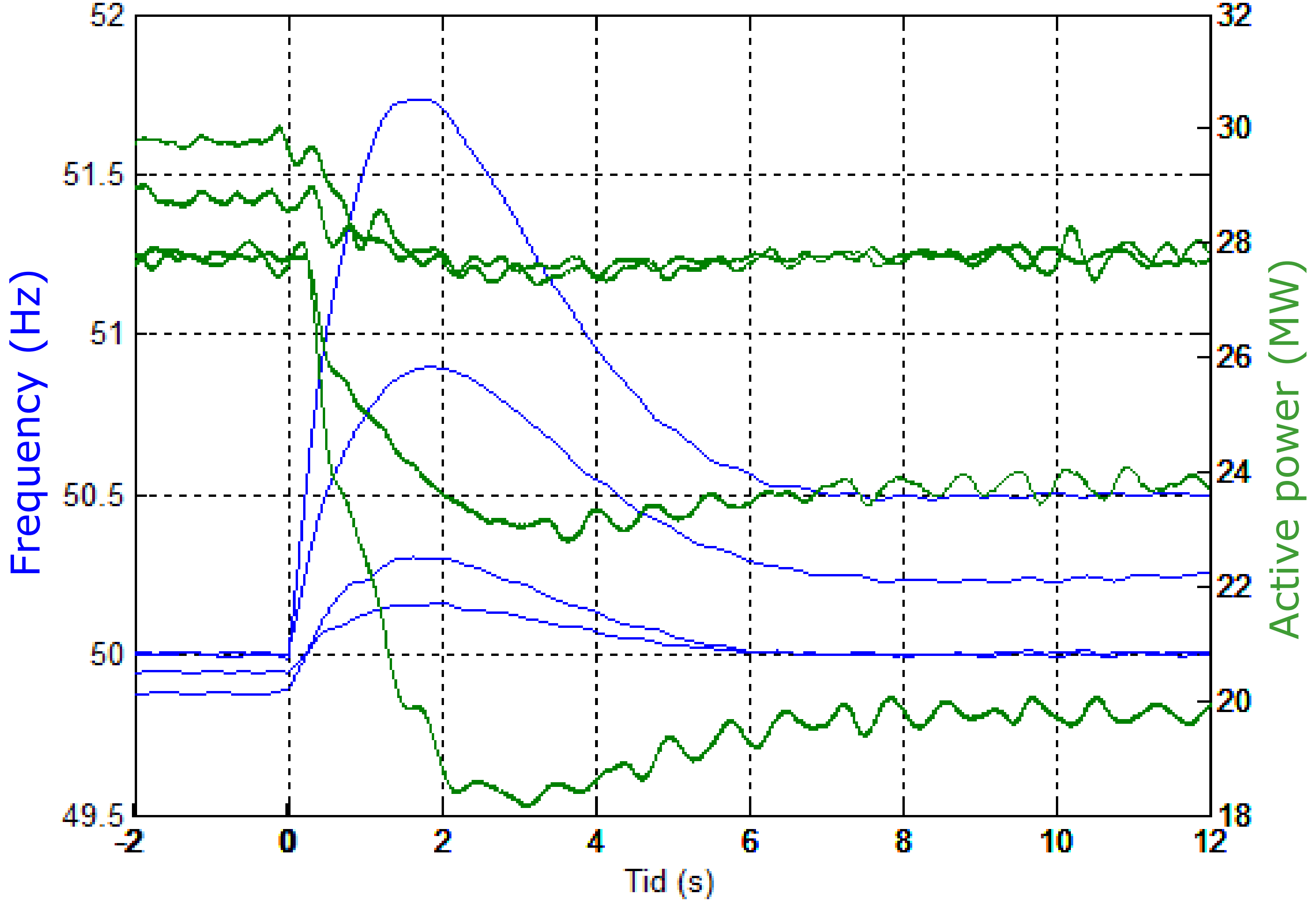
Example island operation of a pulp and paper industry



- Different connections of load in the island – only one 33 MW turbine in the island
  - 1 MW
  - 2 MW
  - 4 MW
  - 6 MW

- Which droop setting is used?

Example island operation of a pulp and paper industry



- Different disconnections of load in the island – only one 33 MW turbine in the island

–1 MW

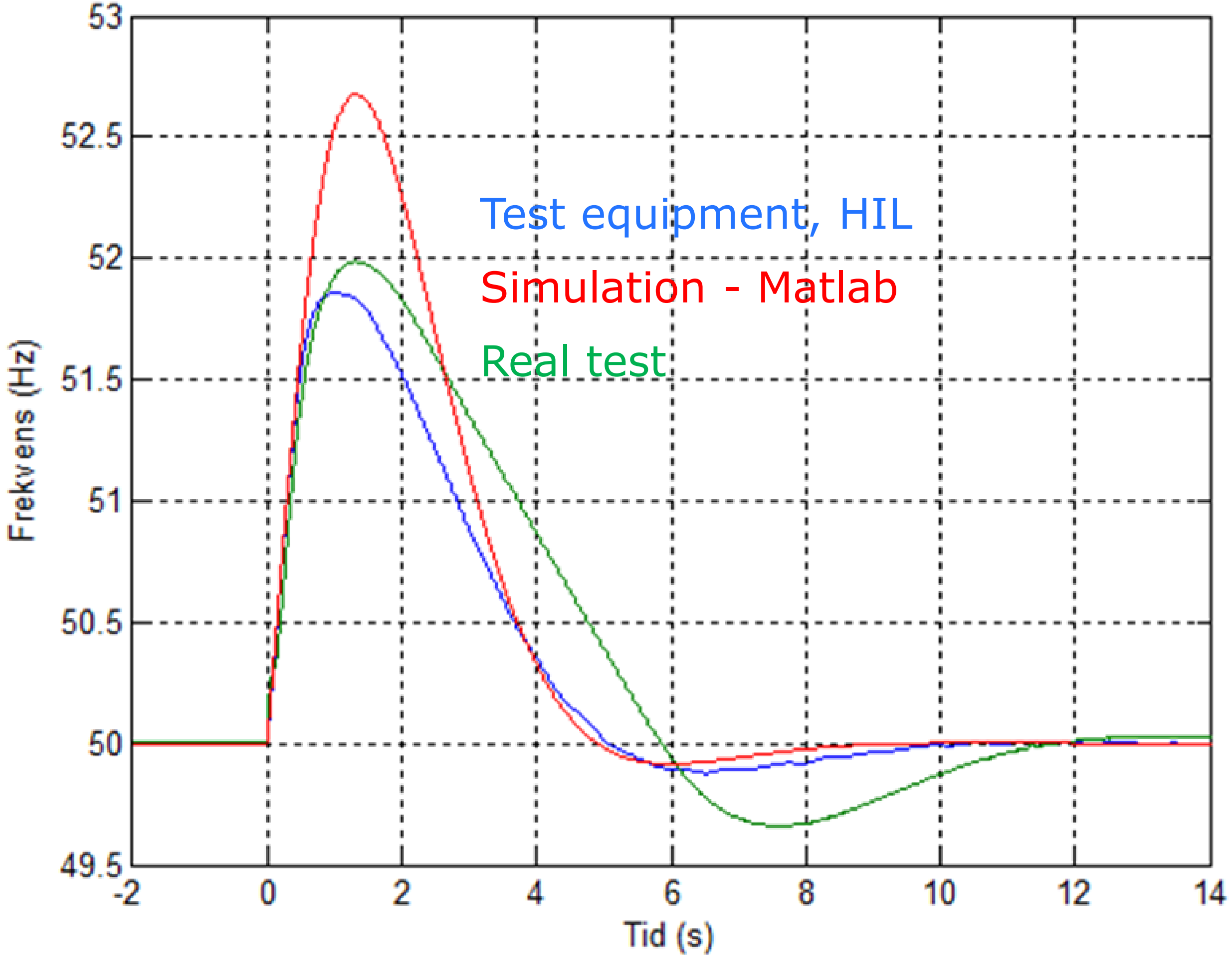
–2 MW

–4 MW

–6 MW

Comparisons of tests and simulations

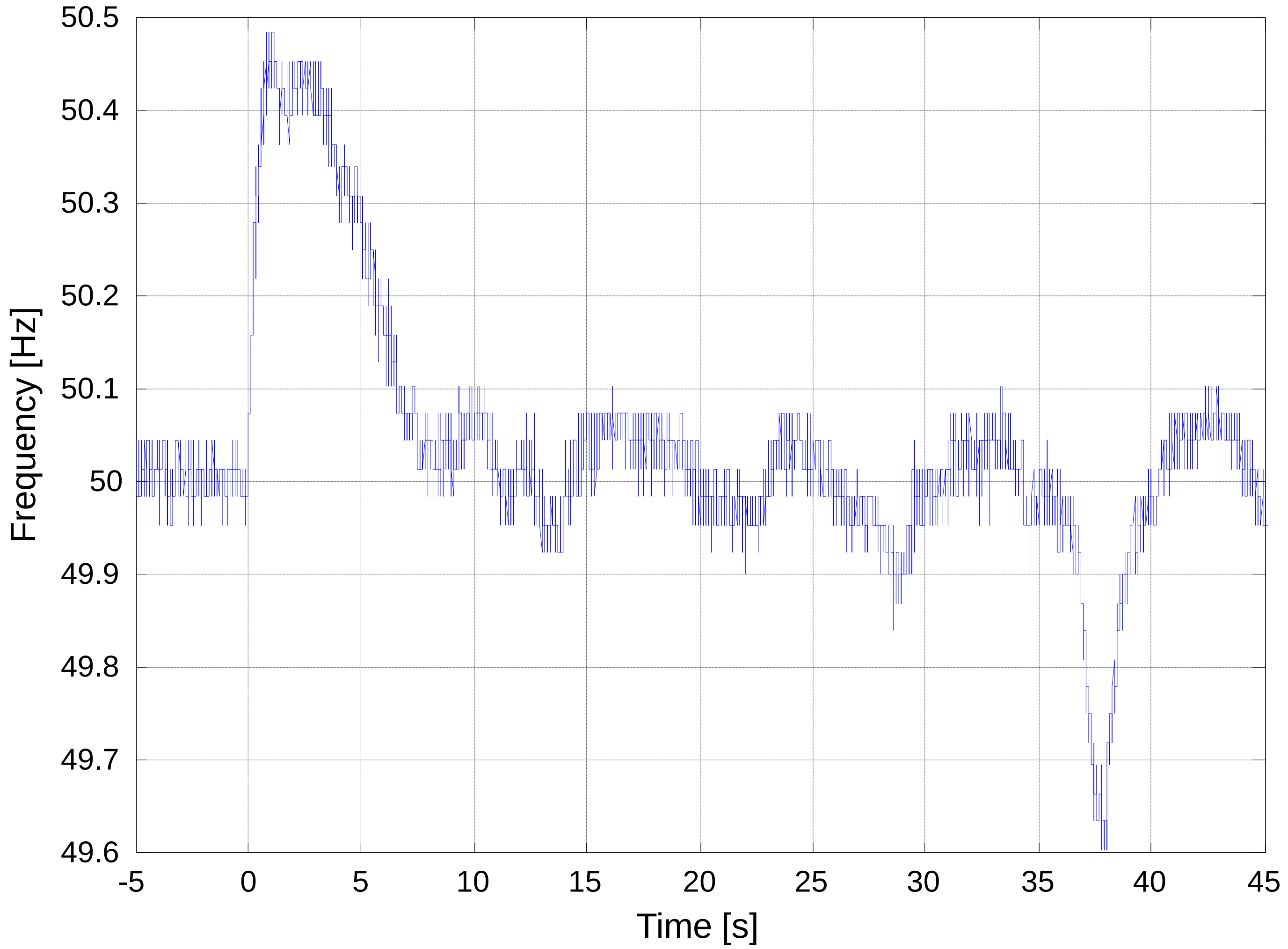
- Tests were made on 33 MW backpressure turbine
- Tests were made with Test equipment and real island operation. Dynamic simulations were made using the model supplied by the manufacturer
- Test of load rejection was made by changing over to inhouse operation without load, 12.4=>0 MW
- Test of load rejection with test equipment was performed by changing load from 15.4=>3.0 MW
- Tests with test equipment therefore give a slightly better behaviour



Example island operation of a pulp and paper industry

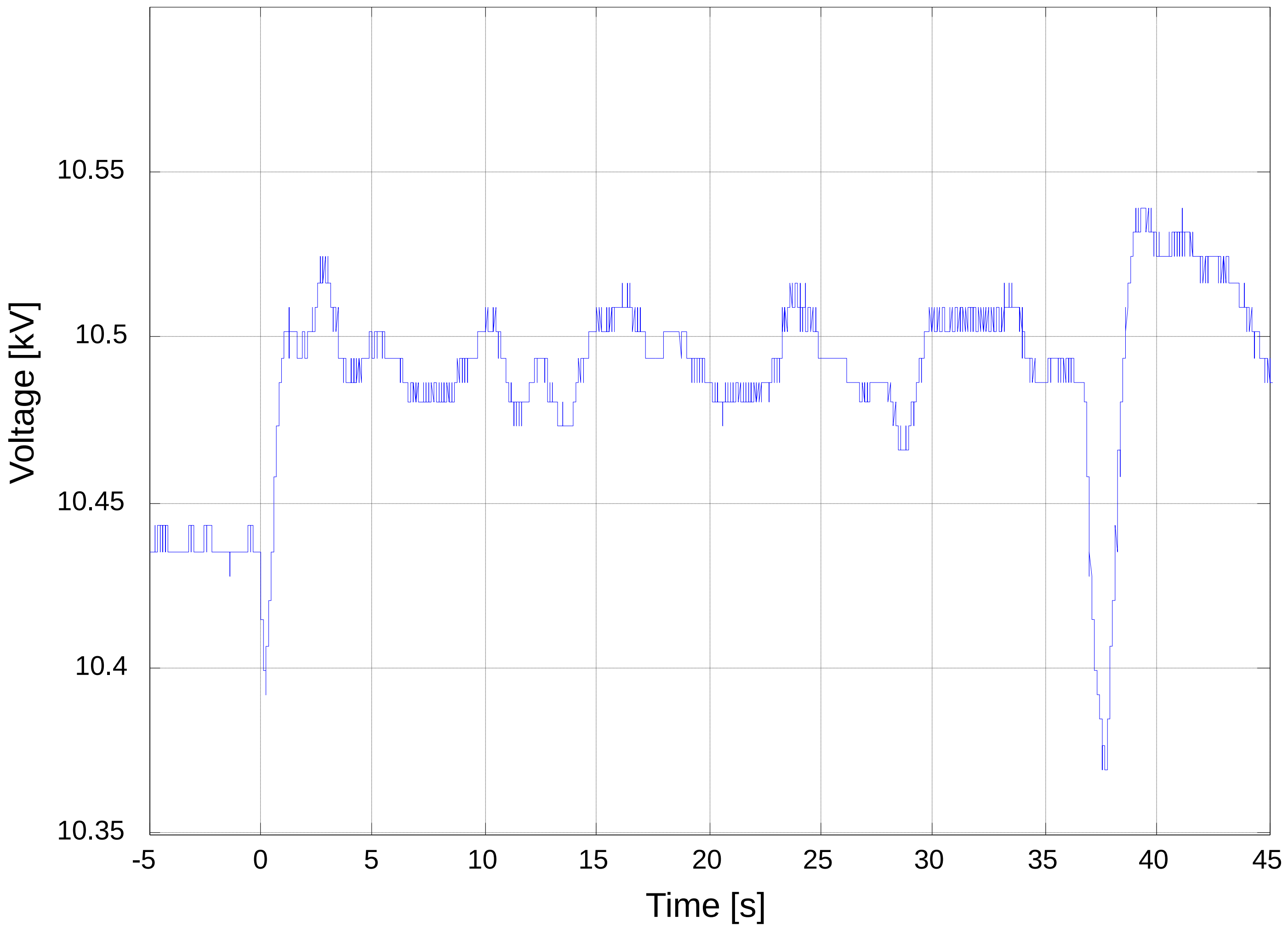
- 3 production units
- Total island load around 70 MW
- Step decrease with 7 MW when entering island operation results in a frequency increase with 0.5 Hz
- Step increase in reactive power production with 2.5 Mvar when entering island mode resulted in a small voltage change of 50 V
- Change over from back-pressure control to frequency control worked properly
- Change over from Mvar control to voltage control worked properly

Example island operation of a pulp and paper industry – load decrease

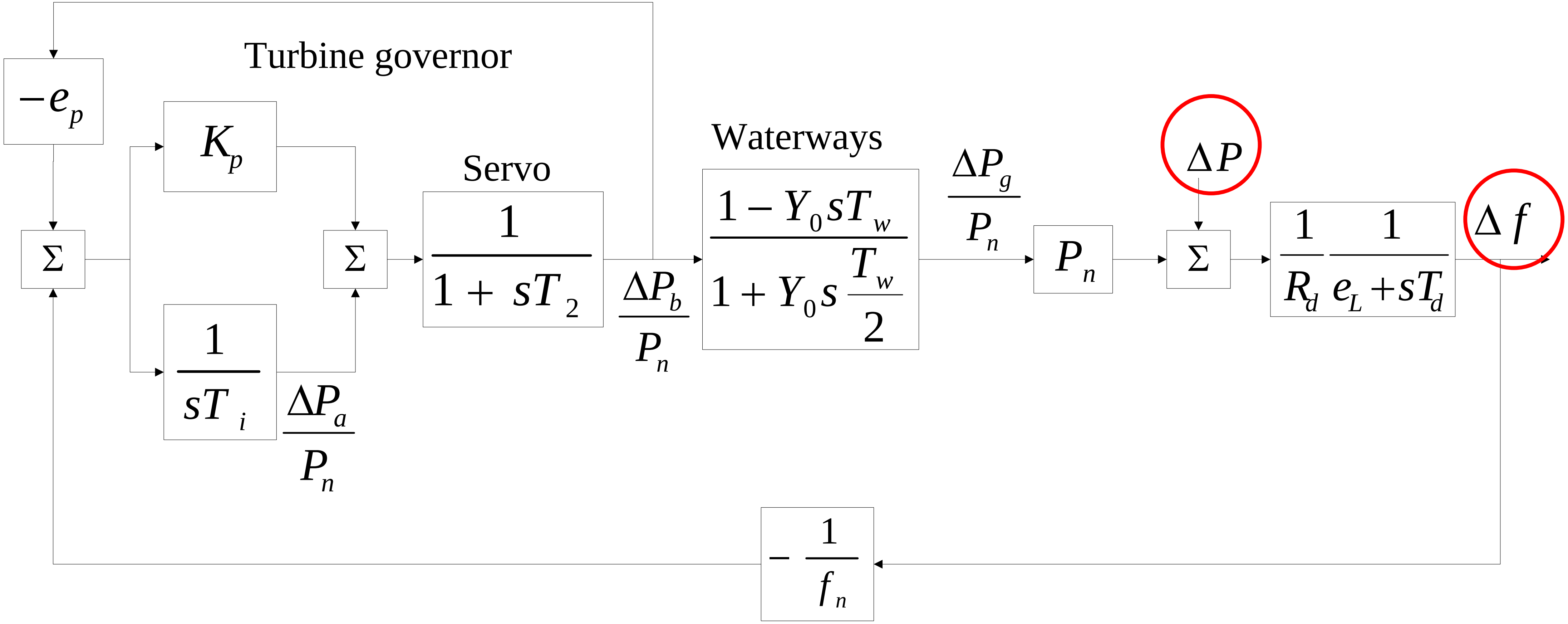


Load rejection of 7 MW corresponding to 10 % of the island load

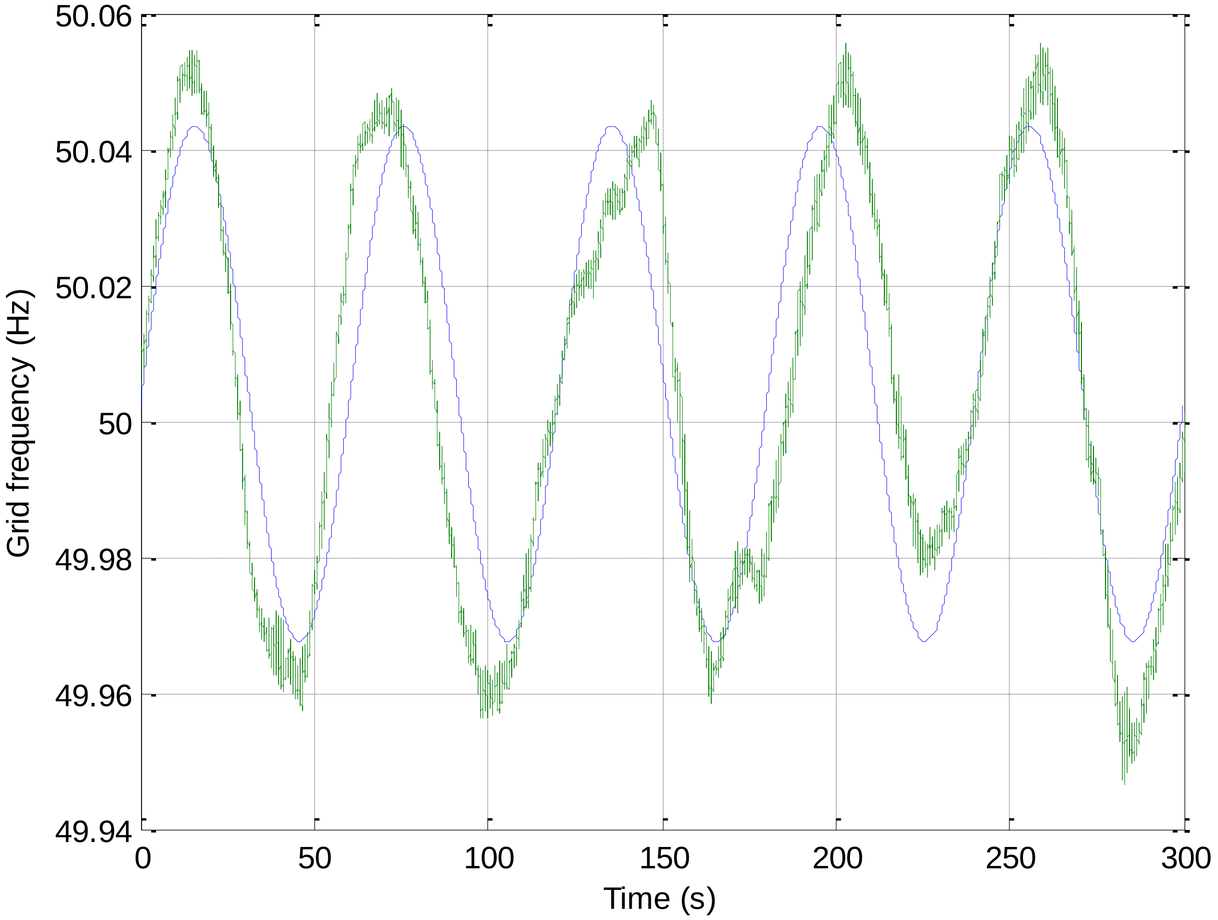
Example island operation of a pulp and paper industry



Full scale tests in the Nordic power system – verify linear lumped model

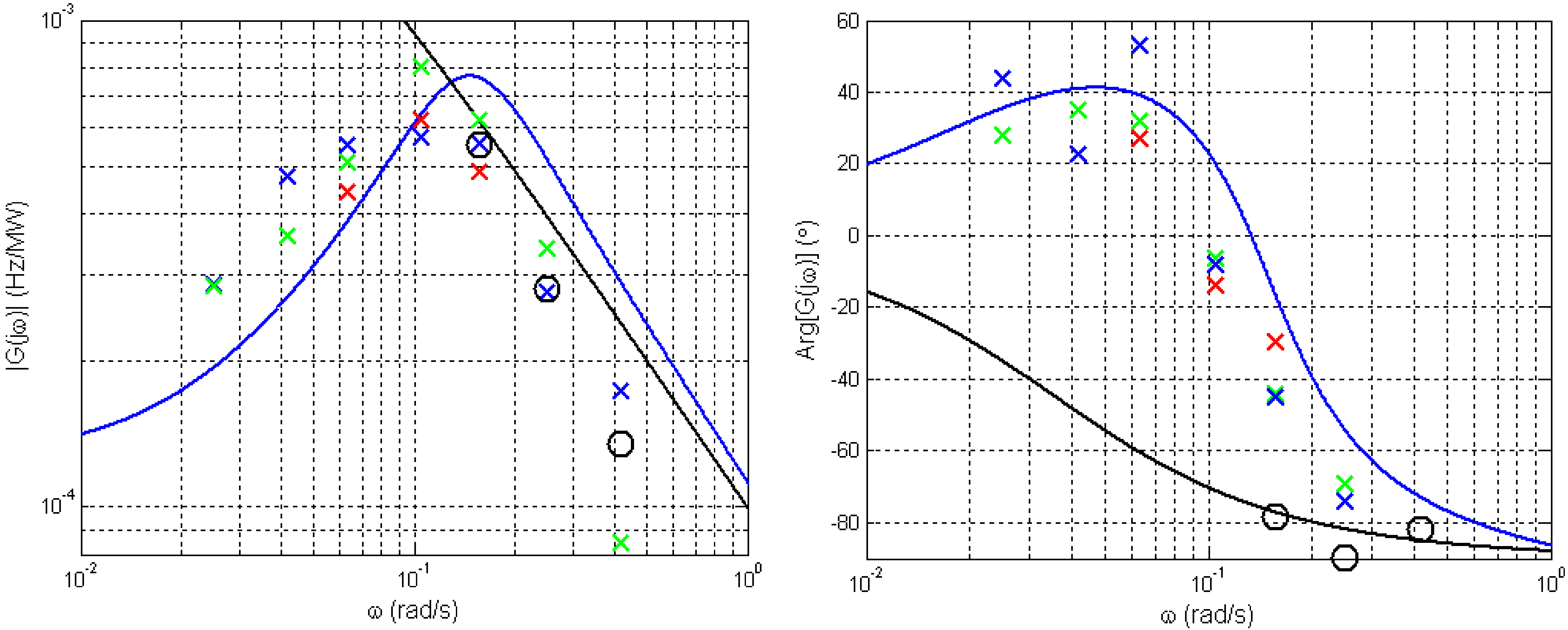


Injecting a sinusoidal power variation of ±72 MW into the Nordic system Messaure

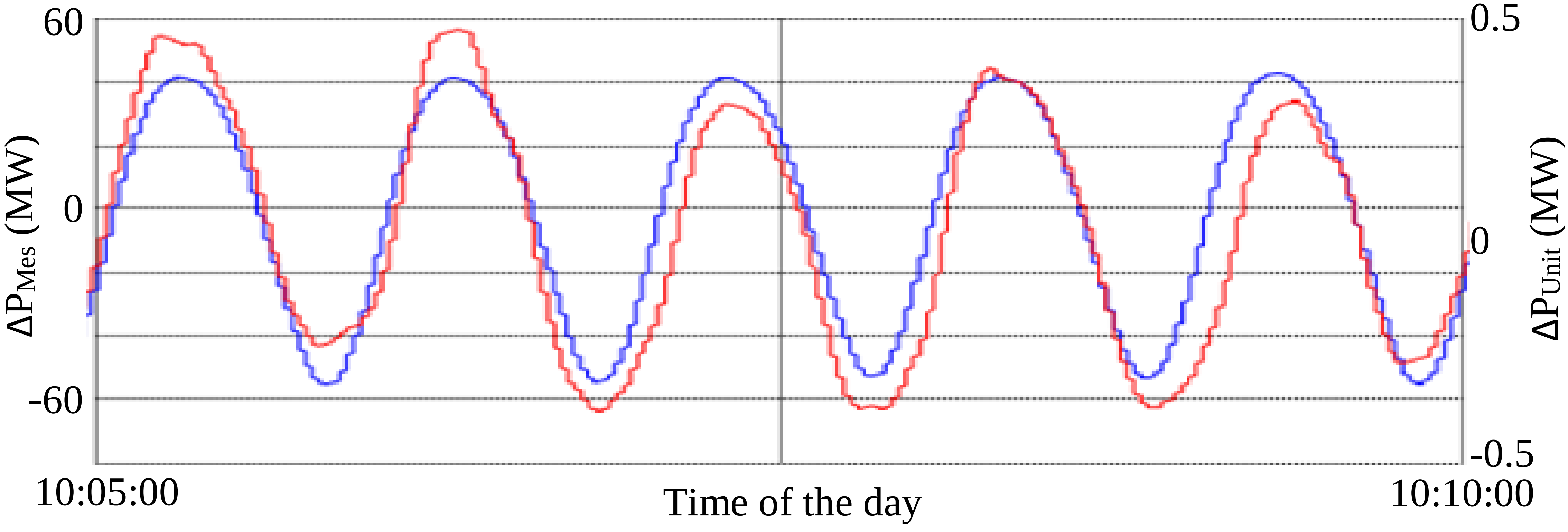


$$G(j\omega) = \frac{\Delta f(j\omega)}{\Delta PMes(j\omega)}$$

Injecting a sinusoidal power variation into the Nordic system



Bad unit response



Summary

- The frequency quality in power systems have been detoriated during a number of years
- Many ongoing changes in the power systems giving further challenges for the frequency control
- New resources taking part in frequency control
- Market based solutions and more products
- Important to test to verify the behavior

- “Att mäta är att veta”
- “To measure is to know”