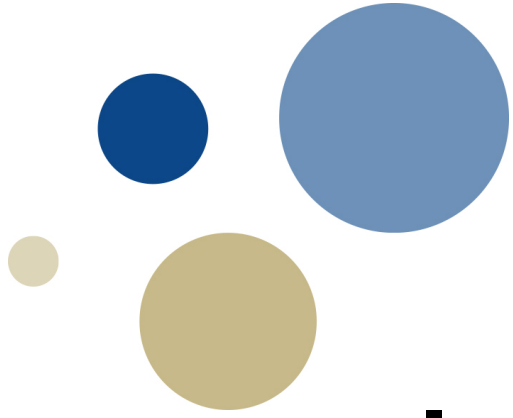
NTNU
Norwegian University of
Science and Technology



Identification of hydro power plant dynamics using PMUs

Sigurd Hofsmo Jakobsen

Norwegian university of technology and science Department of electri engineering

November 13, 2018

Outline

Studies and work

- From Sola

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- Studied and works in Trondheim

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- 10% position at SINTEF Energy Research

Work at SINTEF

- Power system reliability and security

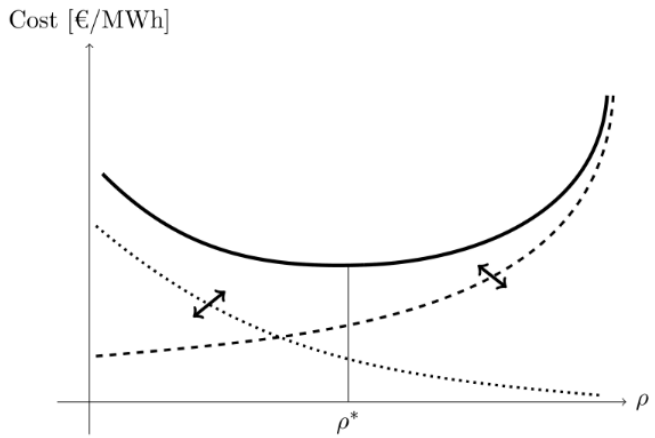


Figure 1.1 Total costs (solid line), interruption costs (dotted line) and all other electricity market costs (dashed line) as a function of the reliability level.

Work at SINTEF

- Power system reliability and security
- Power system simulation

Work at SINTEF

- Power system reliability and security
- Power system simulation
- Coding and code management

git

Work at SINTEF

- Power system reliability and security
- Power system simulation
- Coding and code management
- European research and research coordintaion

Hobbies

- Running

Hobbies

- Running
- Game of go

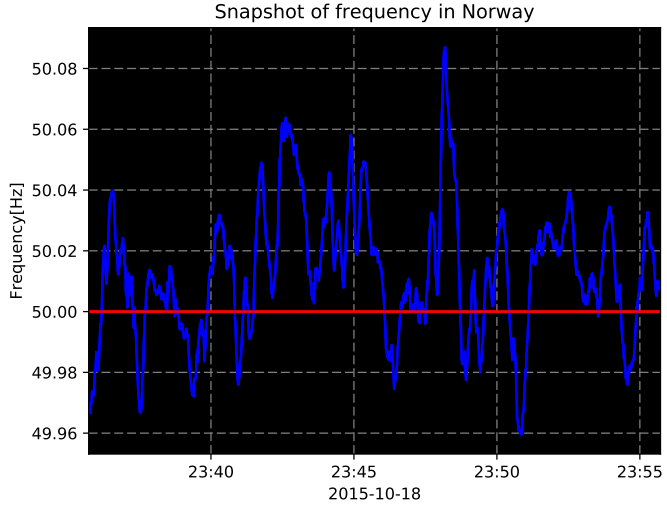
Hobbies

- Running
- Game of go
- Everything mountains(skiing, climbing and hiking)

Outline

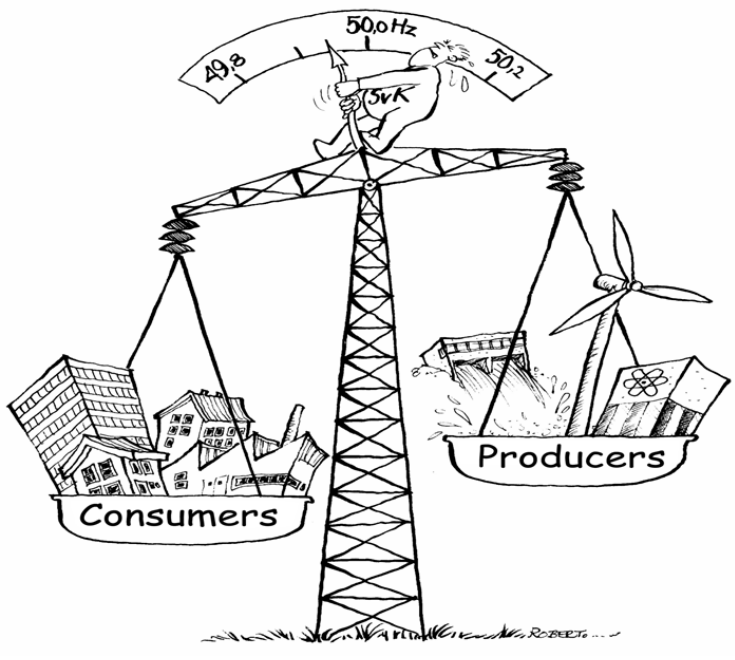
Frequency quality in the Nordics

- From 2008 there has been a growing concern for power system frequency.



Frequency quality in the Nordics

- From 2008 there has been a growing concern for power system frequency.
- It is a question of balancing

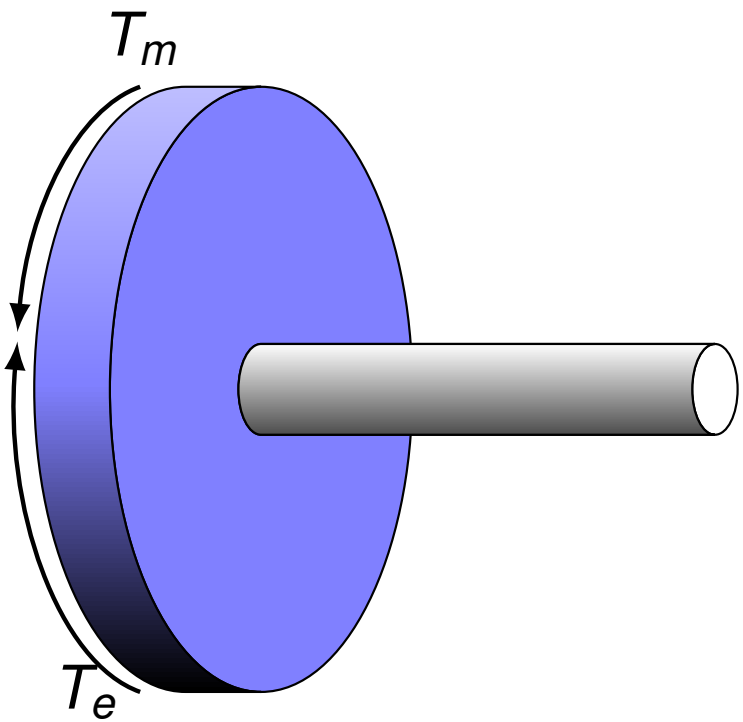


Why frequency is a question of balance

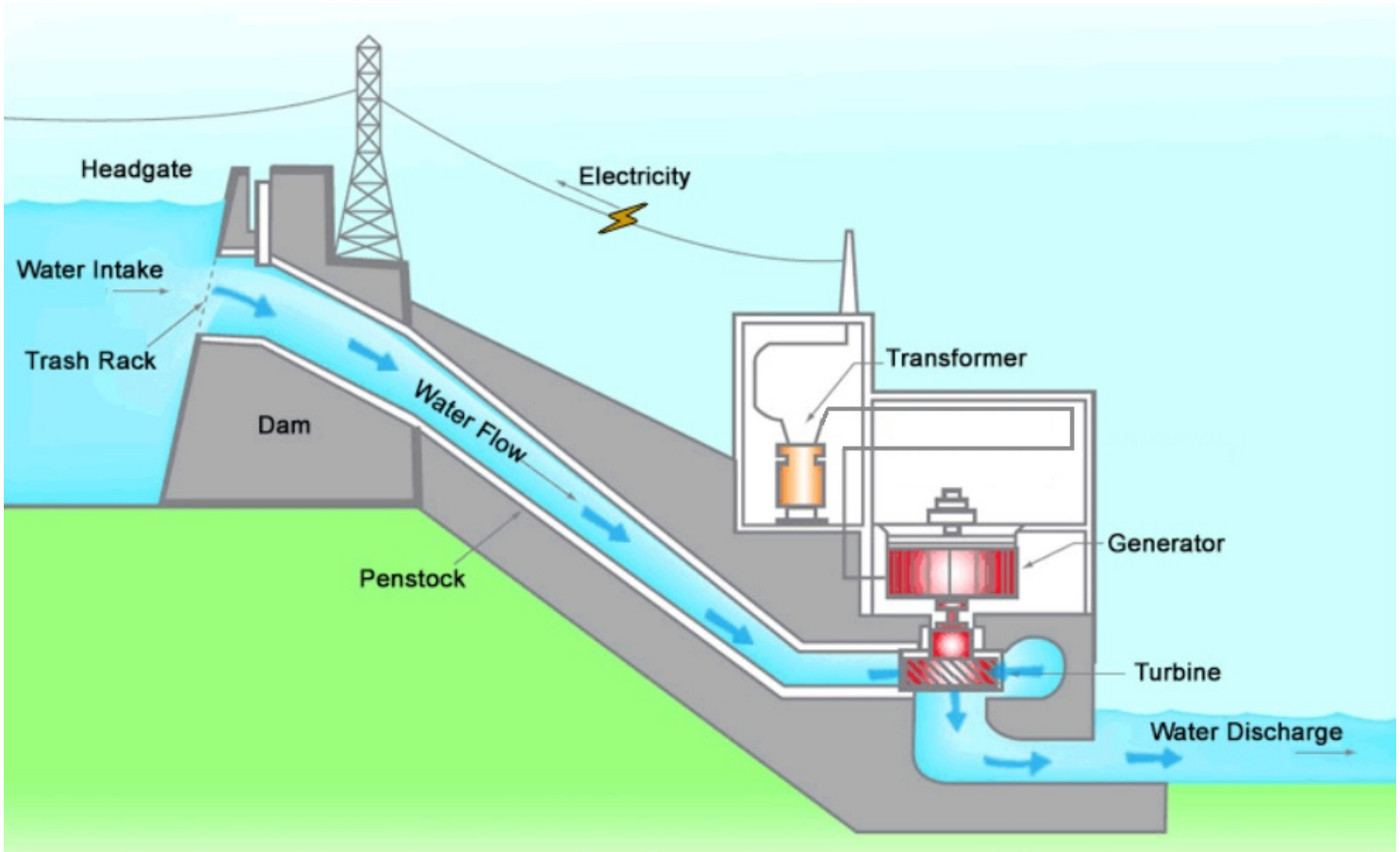
$$J\dot{\omega}_m + D_d\omega_m = T_m - T_e \qquad (1)$$

$$\omega_e = \frac{p}{2}\omega_m \qquad (2)$$

- Most generators are synchronous generators

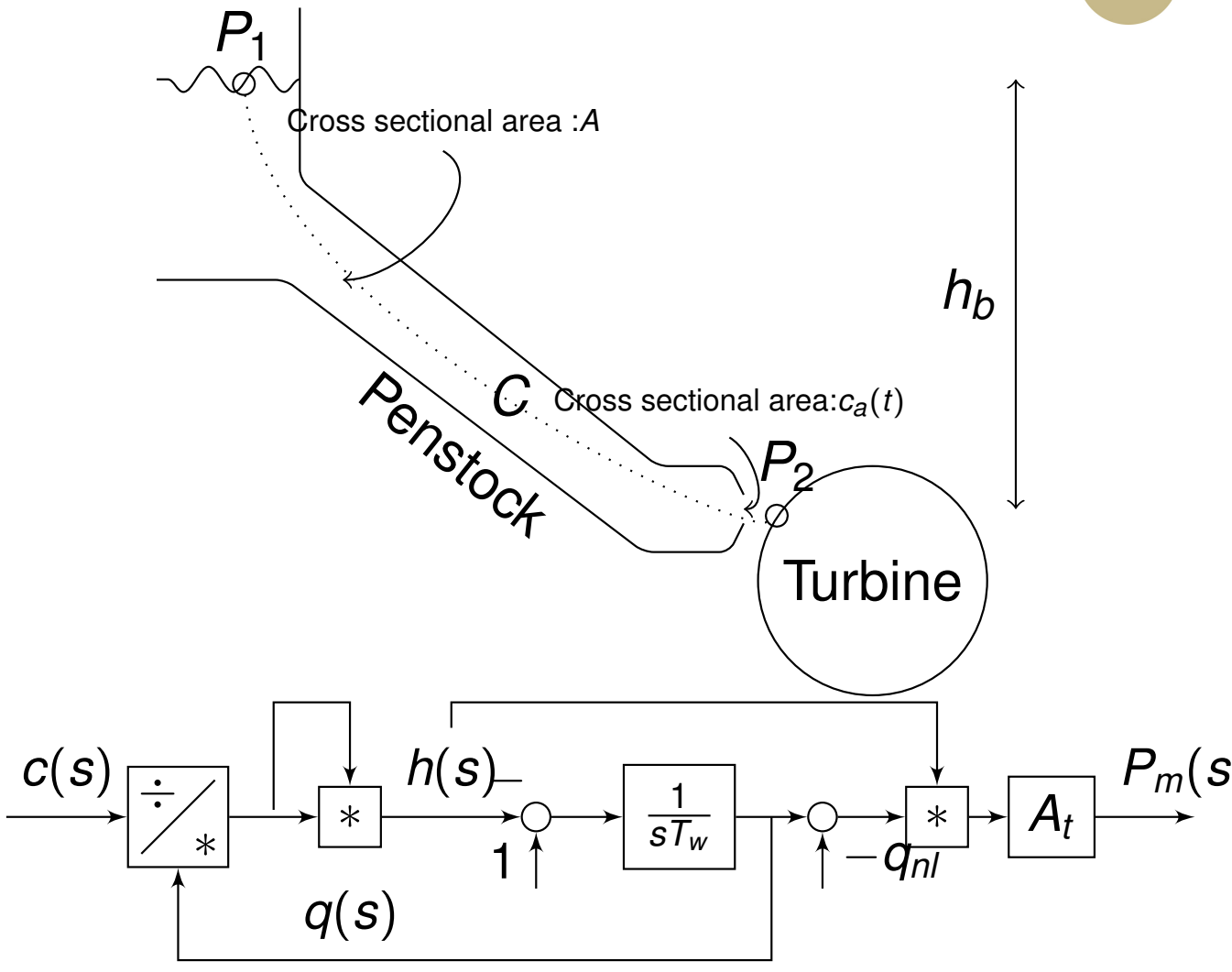


Hydro power, the main producer in the Nordic system

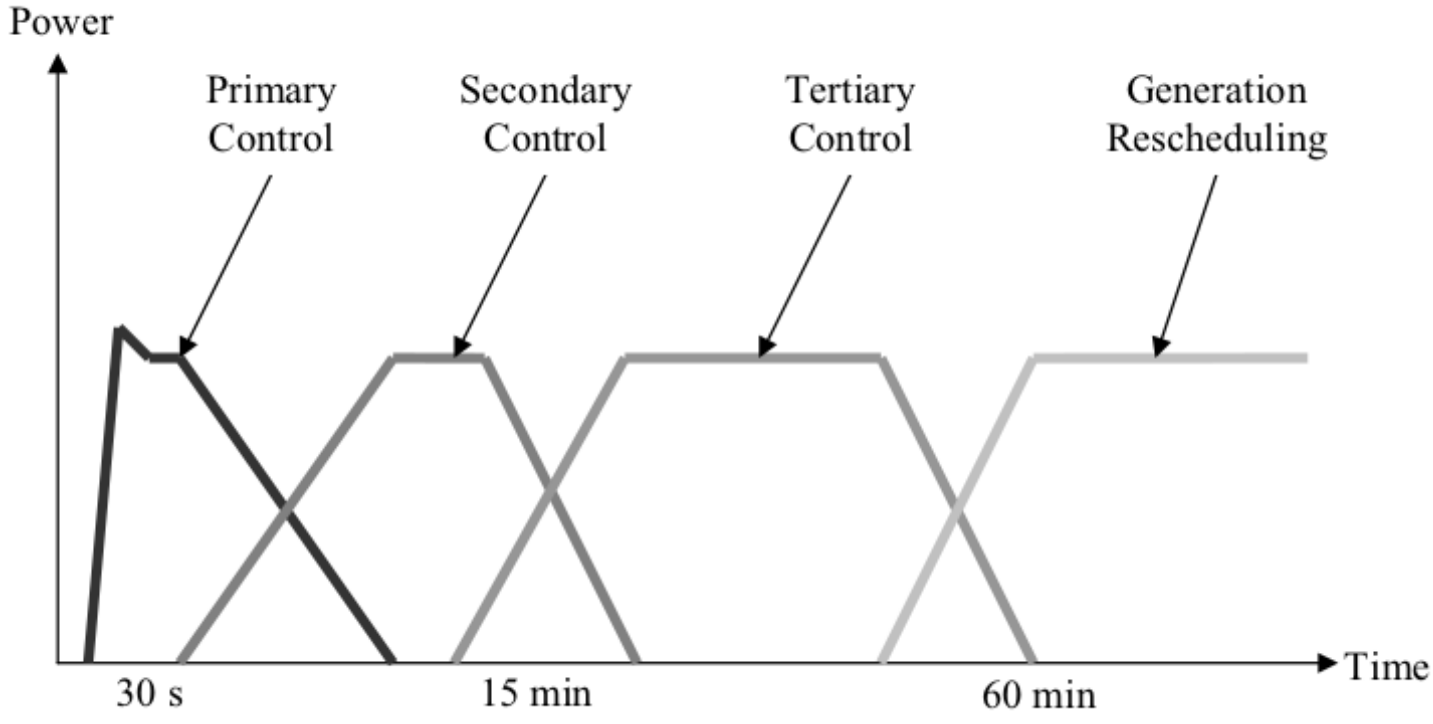


Modelling of a hydro power plant

- Nonlinear
- Bernoulli used for derivation
- Operates normally within a small operating region



Different frequency control mechanisms



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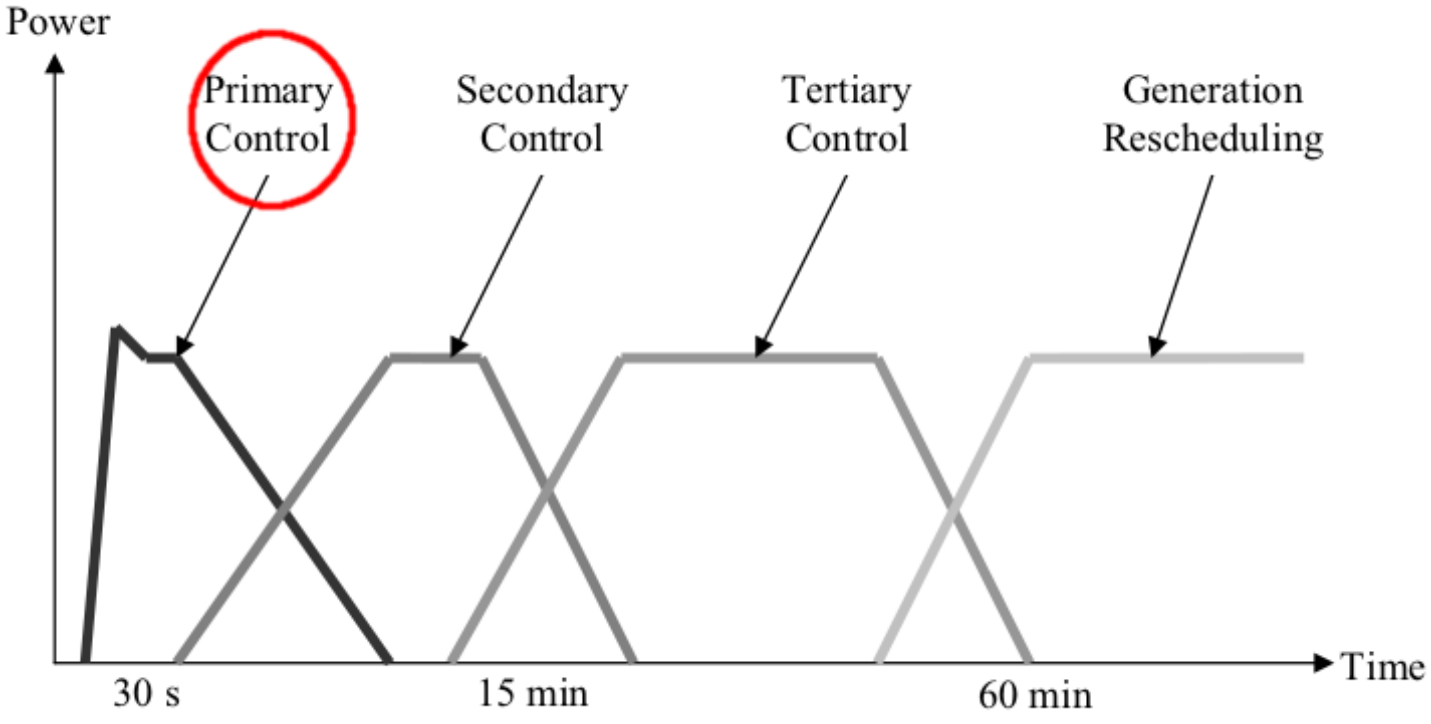

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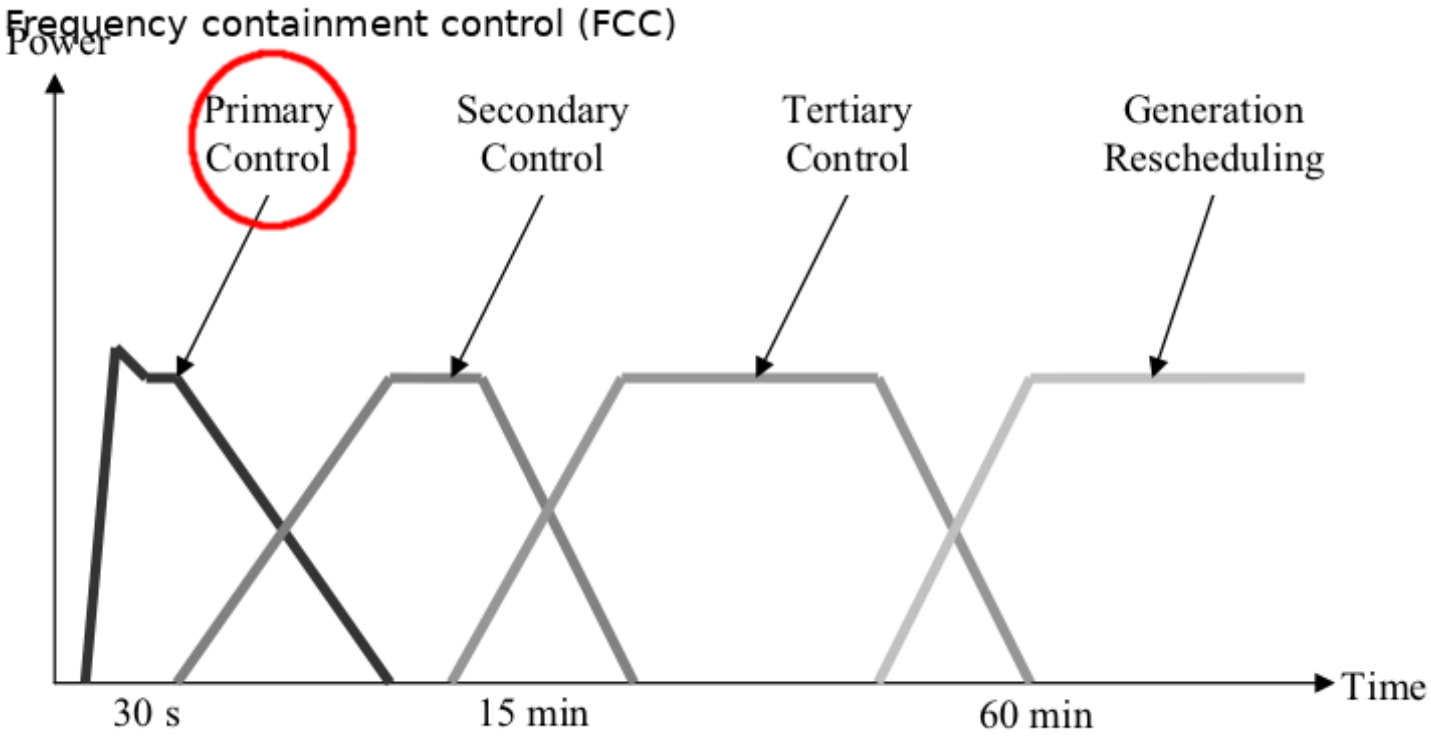
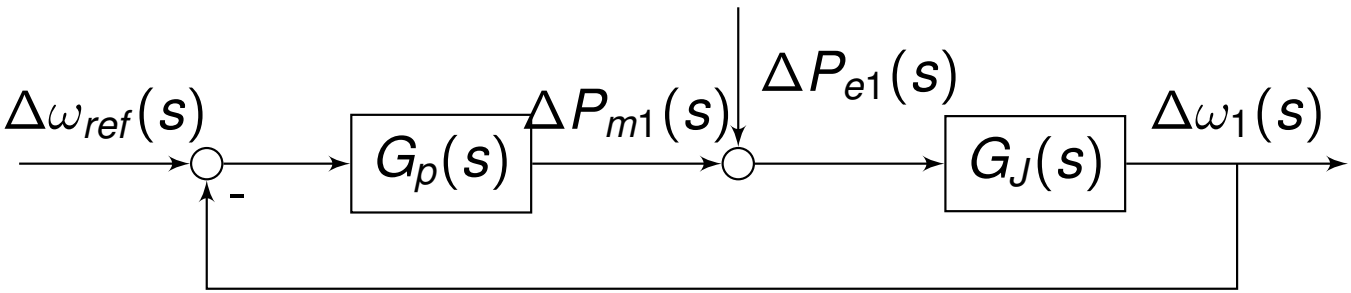


Frequency containment control

- Each plant has to provide FCC
- the amount is given by

$$\Delta P_{m1} = G_p(0)\Delta\omega_1 \tag{3}$$



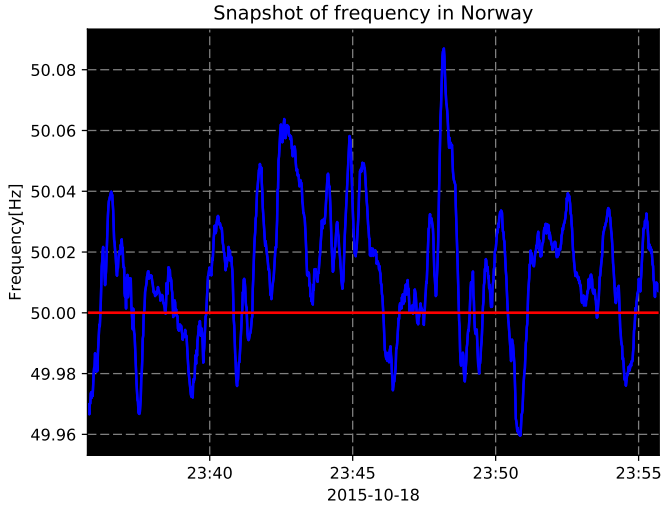
Determining the amount of FCC in the system

- The maximum allowed frequency deviation is $\pm 0.1 Hz$.
- The largest power production unit in Norway is $1450 MW$.
- This gives us

$$\sum_{i}^{N} G_{pi}(0) = \frac{1450 MW}{0.2\pi rad/s} \tag{4}$$

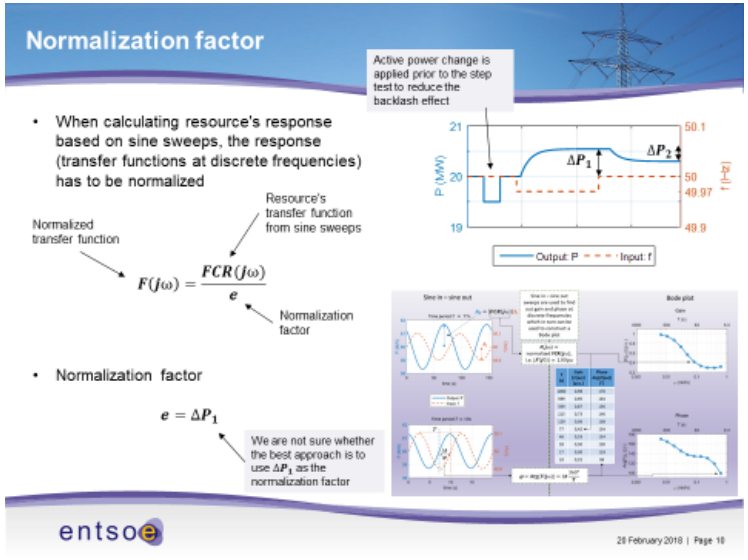
The industry's response to the frequency quality

- Remember the frequency concern?



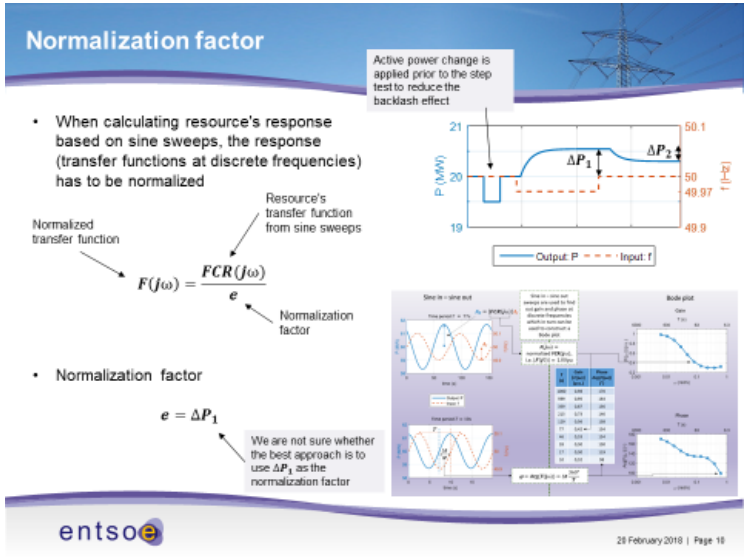
The industry's response to the frequency quality

- Remember the frequency concern?
- Nordic TSOs are developing new requirements for FCR.



The industry's response to the frequency quality

- Remember the frequency concern?
- Nordic TSOs are developing new requirements for FCR.
- This includes offline testing of hydro power plants.



Draft requirements proposed by industry

- Check the plant's stability margin using the sensitivity function

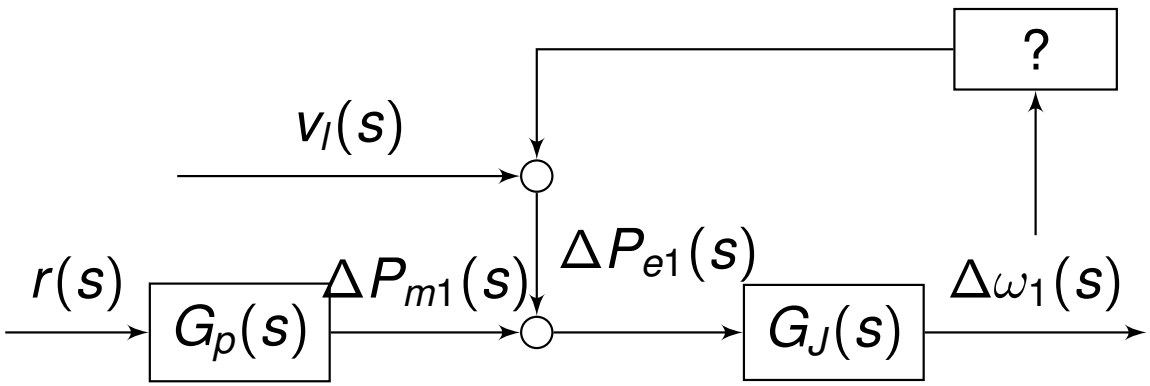
$$S(s) = \frac{1}{1 + G_p(s)G_J(s)} \tag{5}$$

- Check the disturbance rejection

$$G_1(s) = -G_J(s)S(s) \tag{6}$$

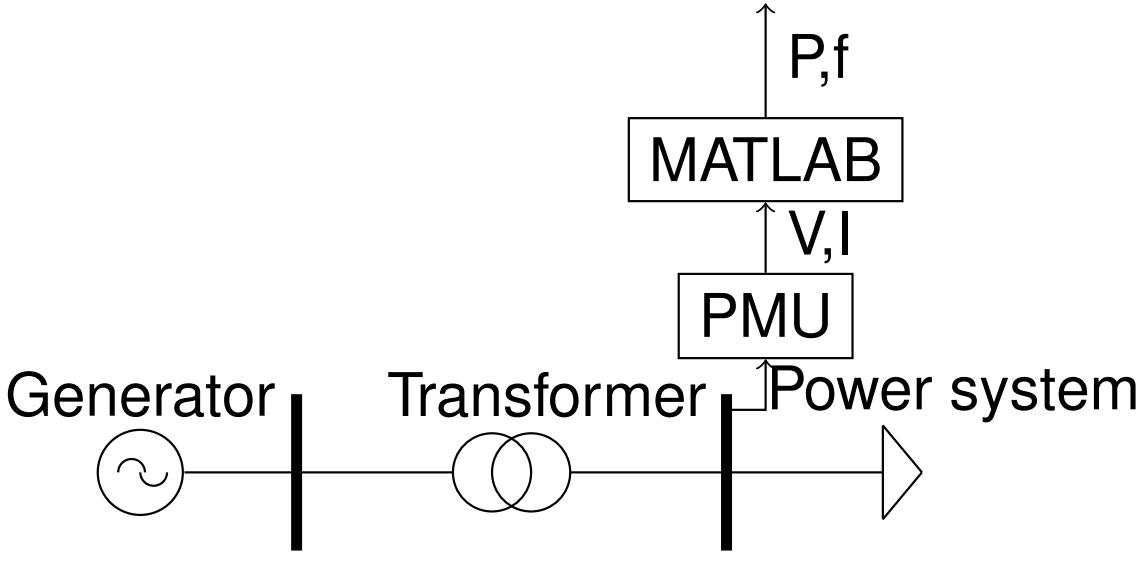
Drawbacks with the draft requirements

- The plant has to be operated in open loop
- Injecting 10 sine waves take a lot of time.
- They assume the same swing dynamics for all plants.(use same $G_J(s)$)



Research question

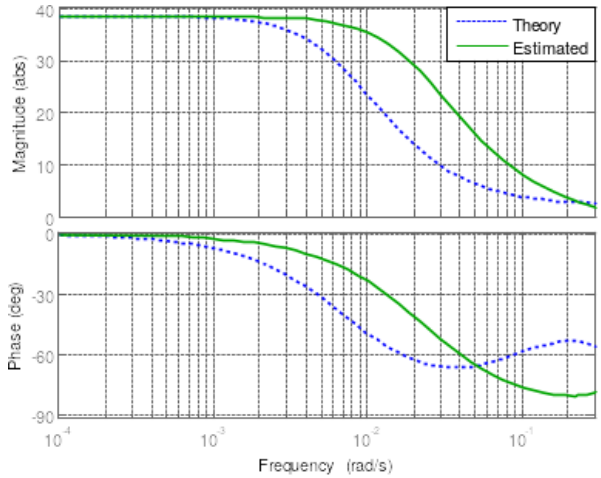
- Can the draft requirements be tested using PMU measurements from normal operation?
- Can we check if the plant's deliver the amount of FCR ($G_p(0)$) as they are supposed to using PMUs?
- Or if not what can we say about a power plant's performance using PMU measurements?



Outline

Previous work at NTNU

- A transfer function was identified from the electrical frequency to the electrical power under normal operation using the ARX model structure.



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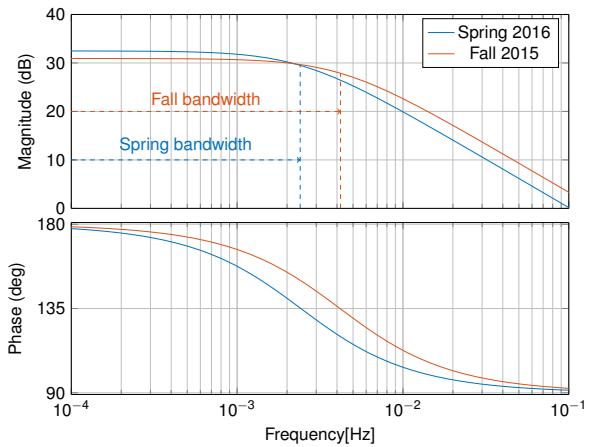
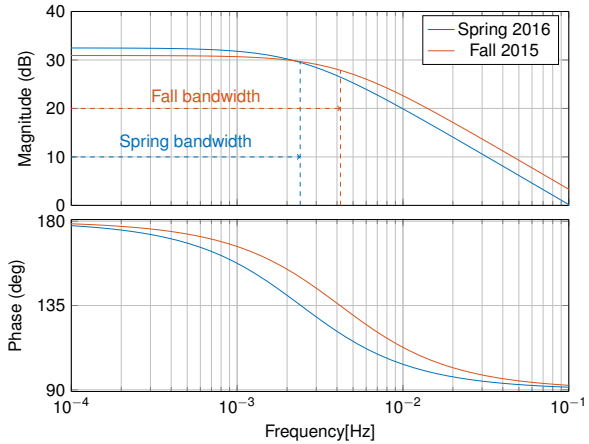
- A transfer function was identified from the electrical frequency to the electrical power under normal operation using vector fitting.



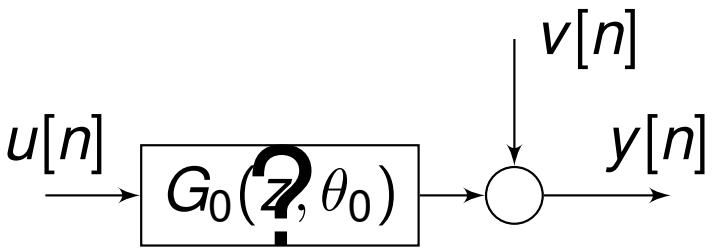
Previous work at NTNU

- A transfer function was identified from the electrical frequency to the electrical power under normal operation using the ARX model structure.
- A transfer function was identified from the electrical frequency to the electrical power under normal operation using vector fitting.
- There are also papers in the literature using other methods for online identification, however, mostly relying on data from disturbance recordings.



Problems with previous work

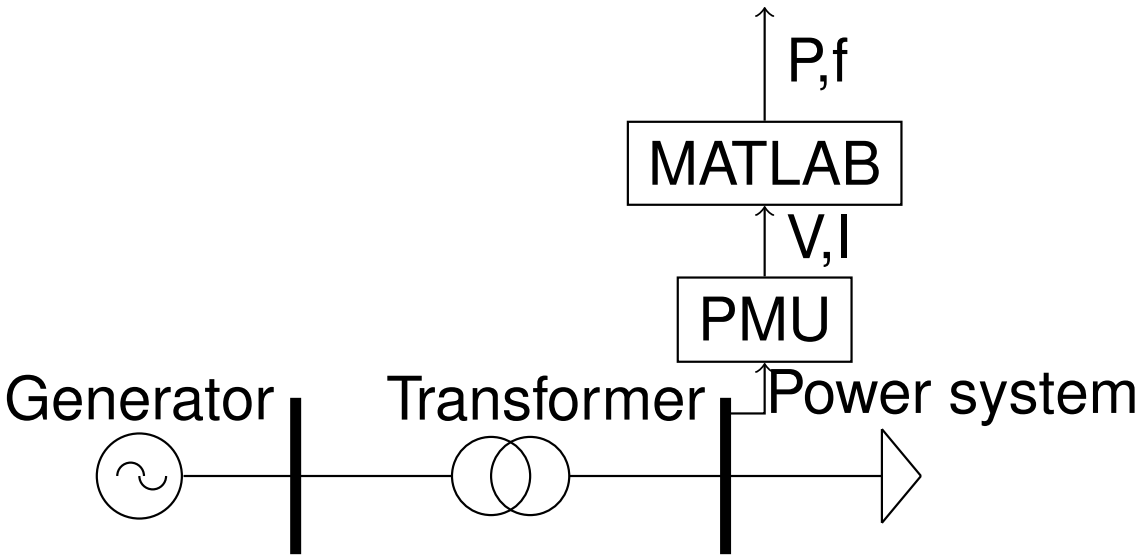
- No analysis was done to check whether or not the correct transfer function could be identified.



Outline

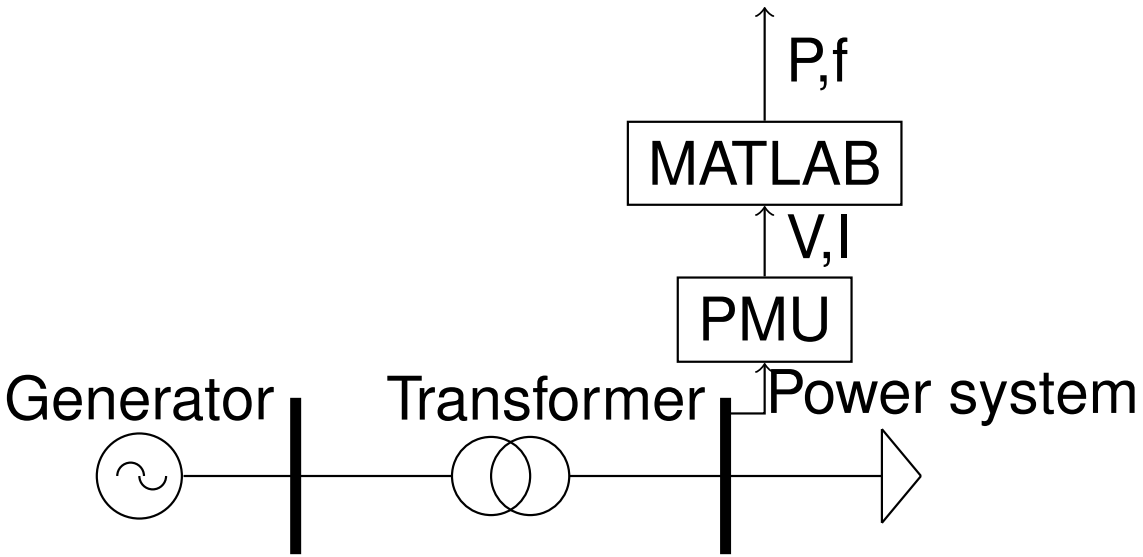
What can we identify using a PMU

- A PMU measures



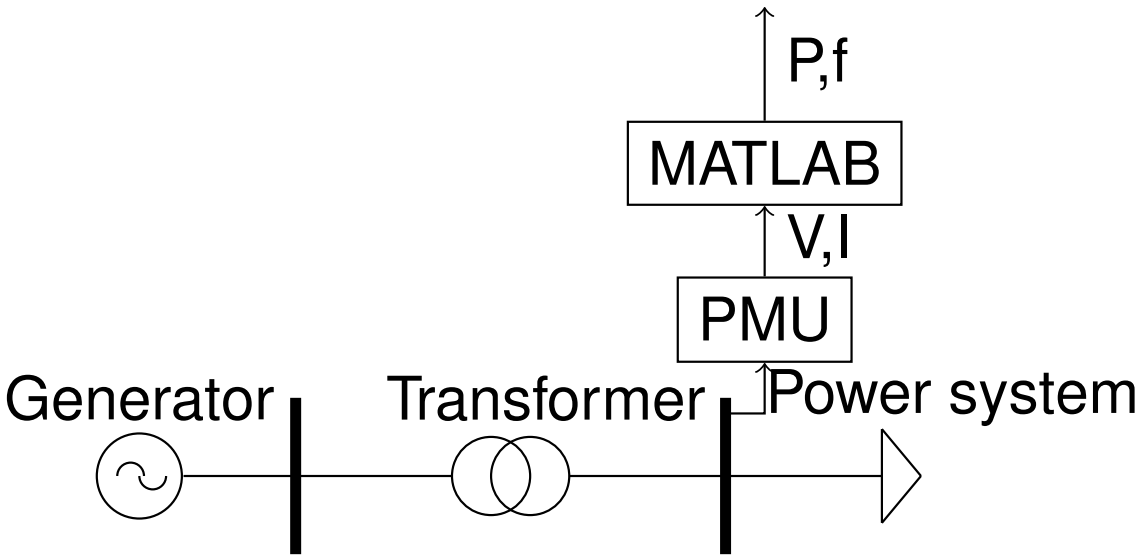
What can we identify using a PMU

- A PMU measures
  - Power : ΔP_{e1}



What can we identify using a PMU

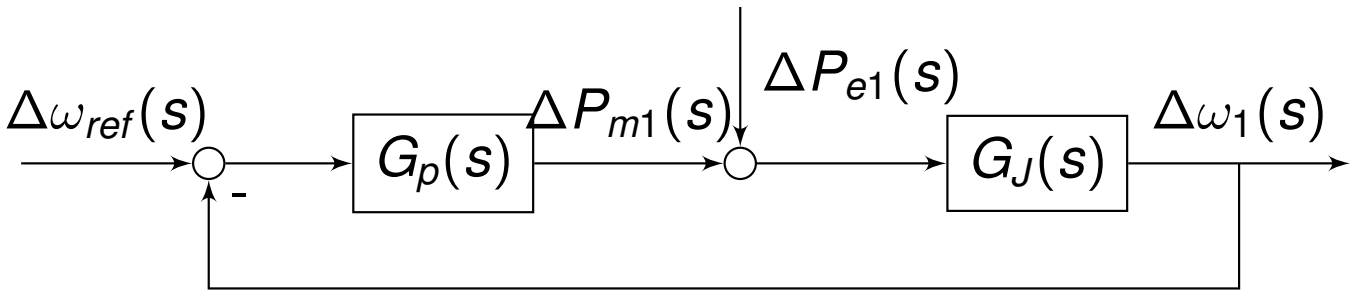
- A PMU measures
  - Power : ΔP_{e1}
  - frequency: Δf assumed to be a good estimate of $\Delta\omega_1$.



What can we identify using a PMU

- A PMU measures
  - Power : ΔP_{e1}
  - frequency: Δf assumed to be a good estimate of $\Delta\omega_1$.
- If we can identify anything it will be.

$$G_1(s) = -\frac{G_J(s)}{1 + G_p(s)G_J(s)} = -G_J(s)S(s) \tag{7}$$



Identification approach

- Collect a data set $Z^N = \{u[n], y[n] | n = 1 \dots N\}$
- Z^N is assumed generated by

$$\mathcal{S} : y[n] = G_1(z, \theta_1)u[n] + H_1(z, \theta_1)e[n] \tag{8}$$

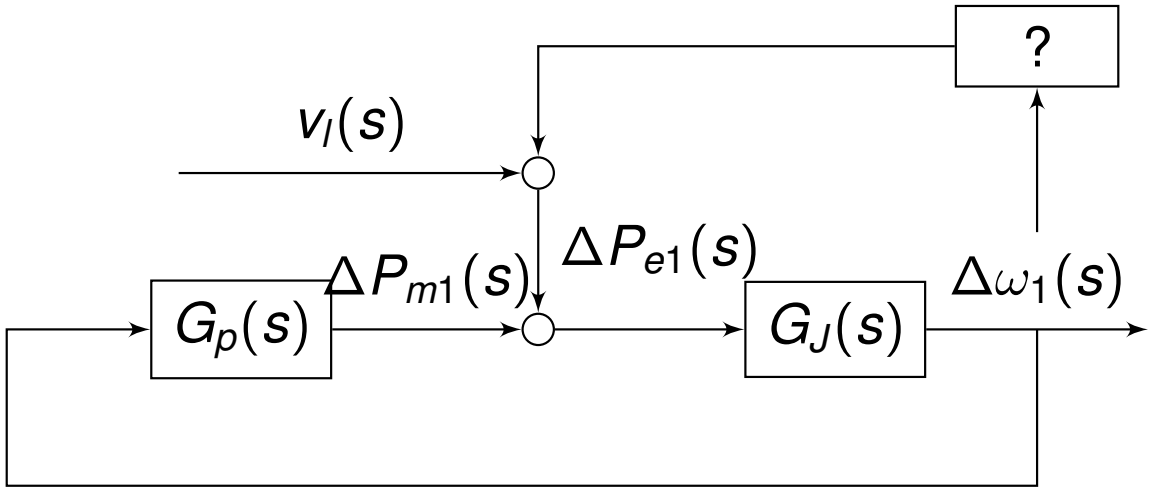
- Given a full order model structure $\mathcal{M} = \{G_1(z, \theta), H_1(z, \theta)\}$ and the dataset Z^N we want to find:

$$\hat{\theta}_N = \arg\min_{\theta} \frac{1}{N} \sum_{n=1}^{N} \epsilon^2(n, \theta) \tag{9}$$

- We need to check if we get a consistent estimate if $u[n]$ is a sampled version of $\Delta P_{e1}(s)$.

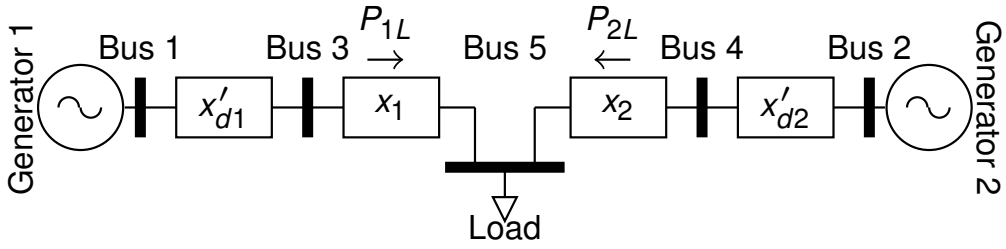
Modeling used for the validation

- We need to analyse how $\Delta P_{e1}(s)$ is generated.



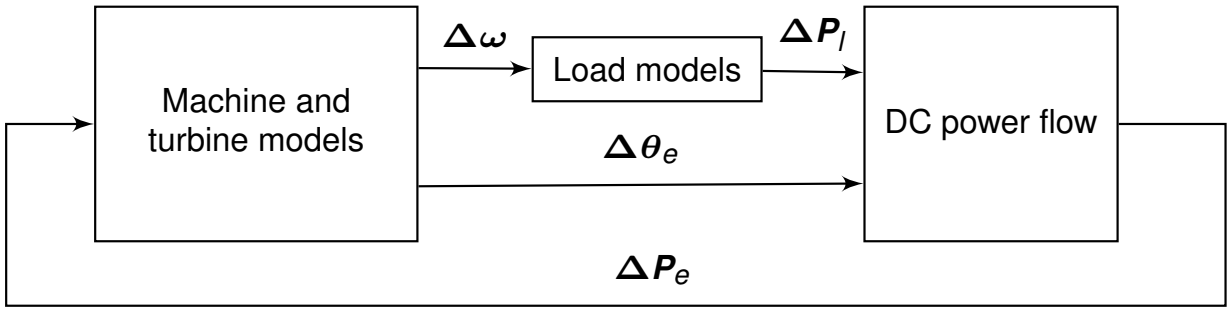
Modeling used for the validation

- We need to analyse how $\Delta P_{e1}(s)$ is generated.
- We assume a small power system.



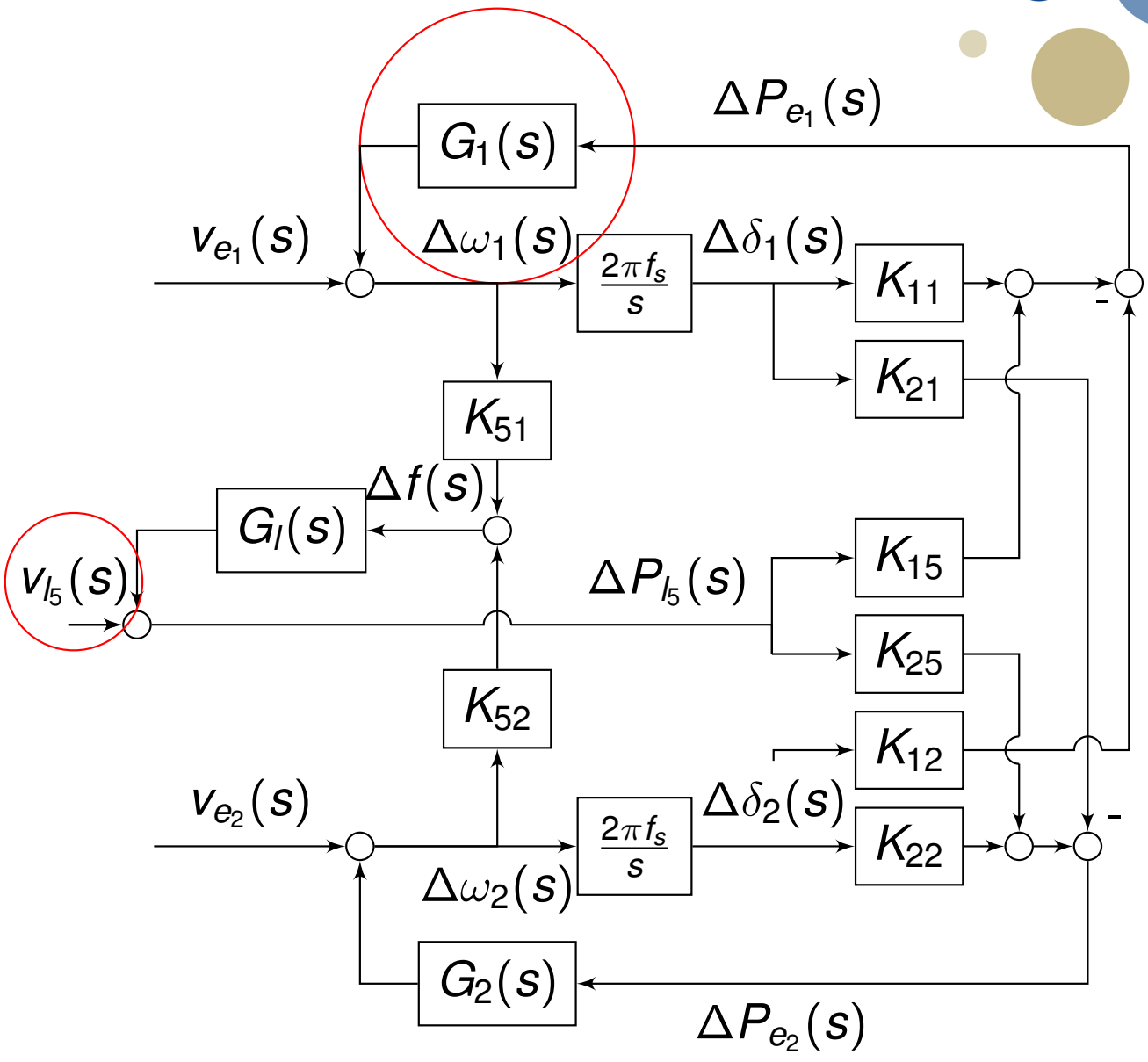
Modeling used for the validation

- We need to analyse how $\Delta P_{e1}(s)$ is generated.
- We assume a small power system.
- Power flow modelled using a dc power flow



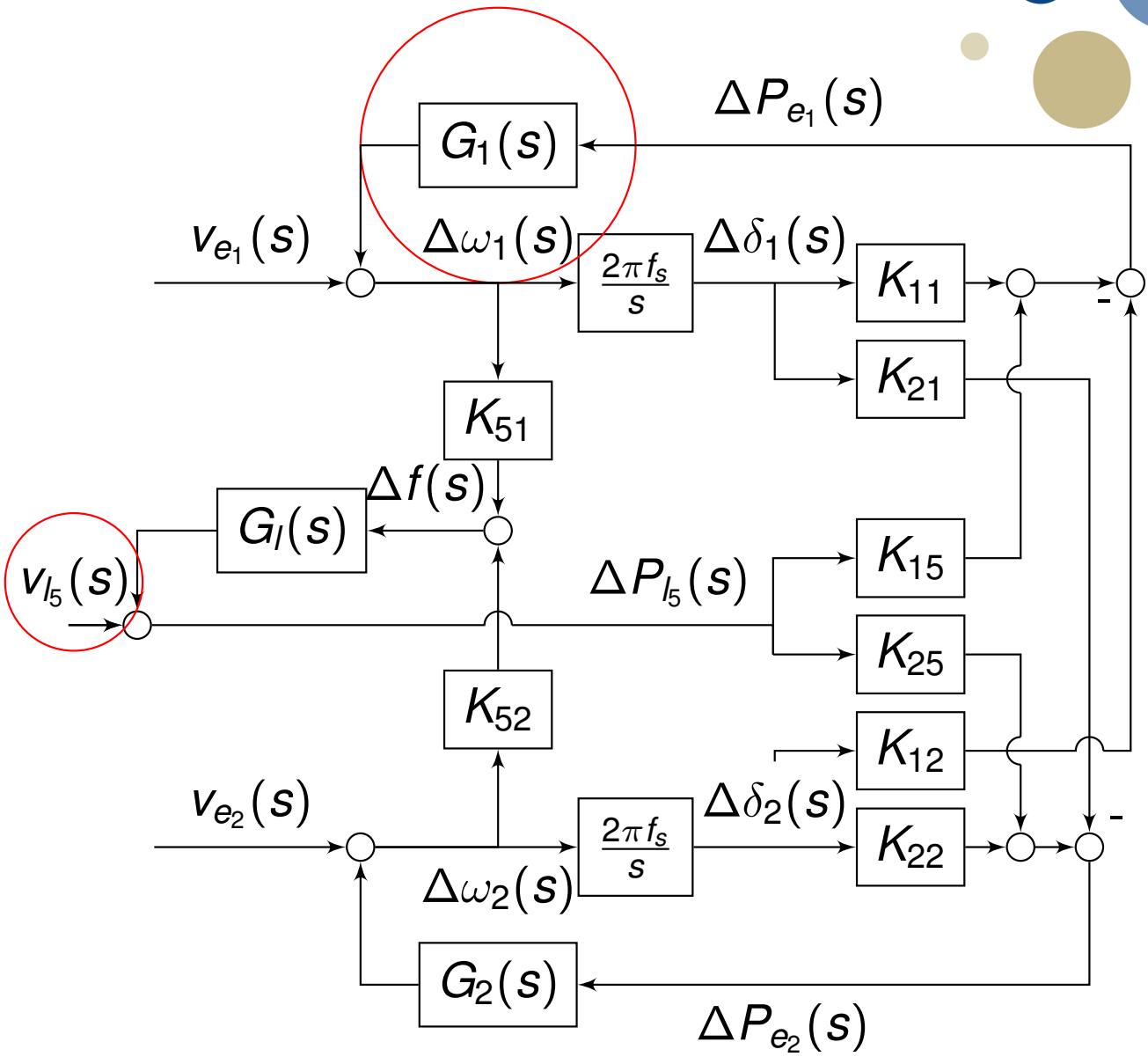
Modeling used for the validation

- We need to analyse how $\Delta P_{e1}(s)$ is generated.
- We assume a small power system.
- Power flow modelled using a dc power flow
- We have identification of a module in a network



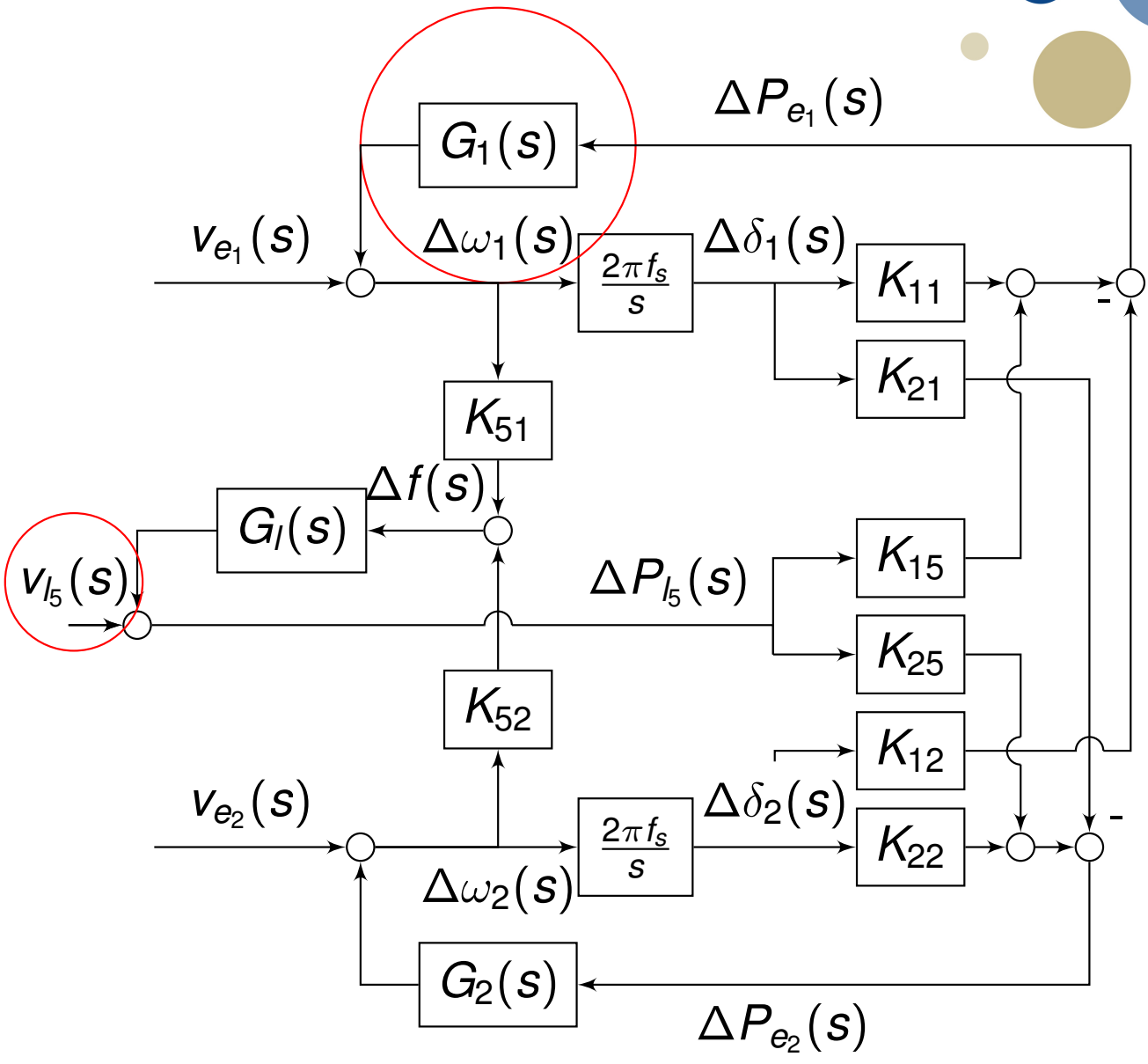
Conclusion from the identification analysis

- We can identify a consistent estimate of $G_1(s)$



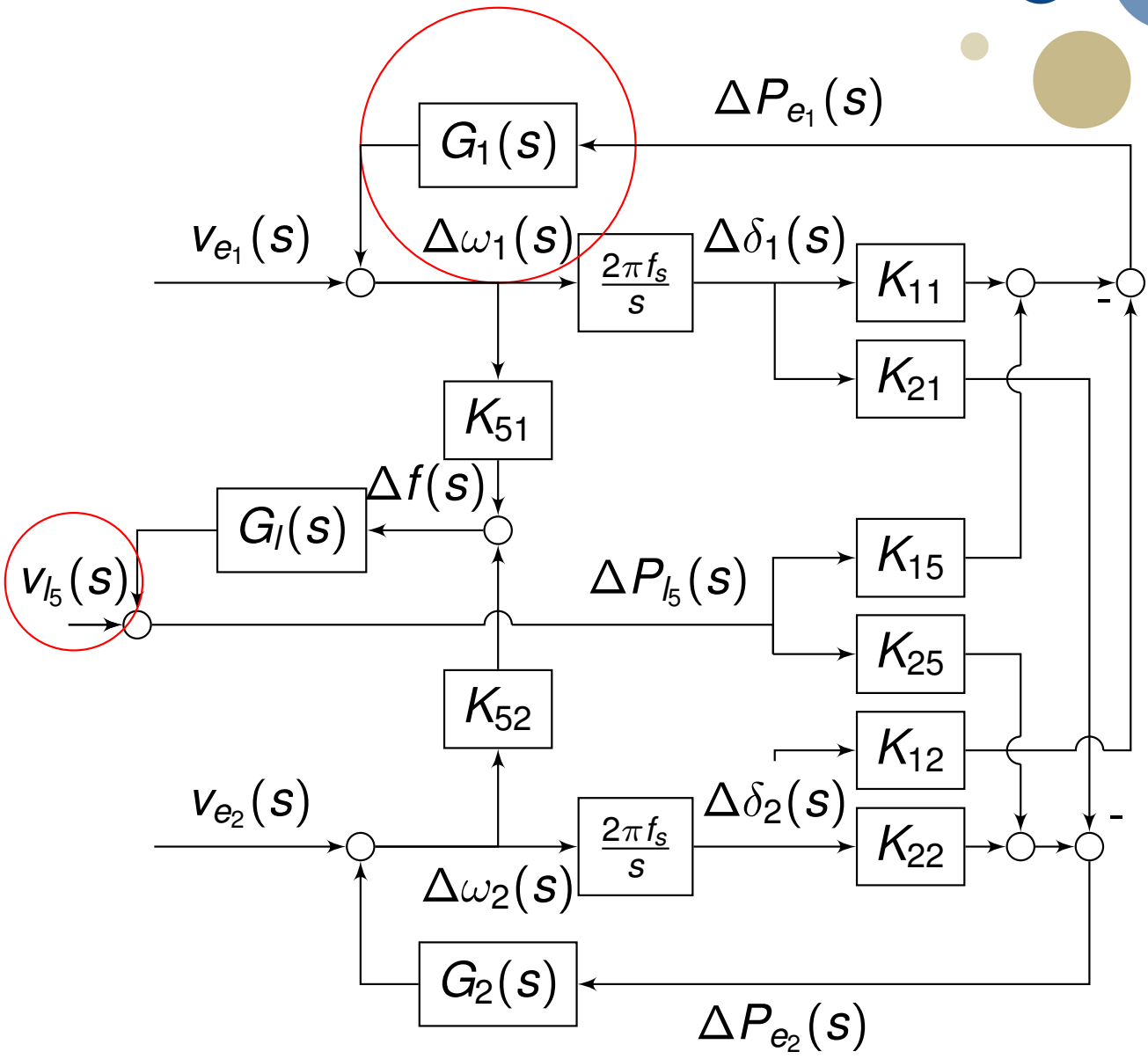
Conclusion from the identification analysis

- We can identify a consistent estimate of $G_1(s)$
  - If $v_{l5}(s)$ excites the system sufficiently,



Conclusion from the identification analysis

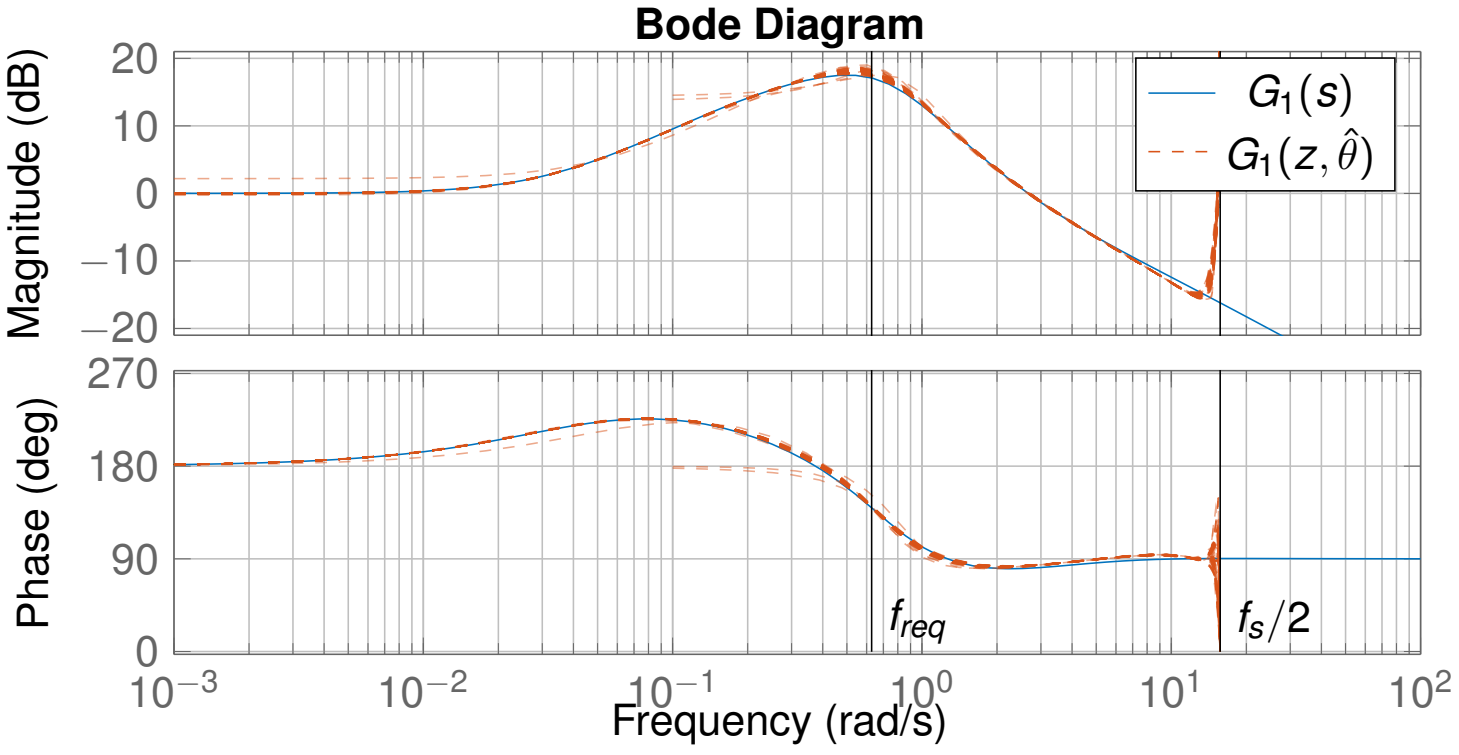
- We can identify a consistent estimate of $G_1(s)$
  - If $v_{l5}(s)$ excites the system sufficiently,
  - and there is a delay in either $G_1(s)$ of the transfer function from $\Delta\omega_1(s)$ to $\Delta P_{e1}(s)$.



Outline

Example of identifying $G_1(s)$ in Simulink

- The simple power system presented was implemented in Simulink.



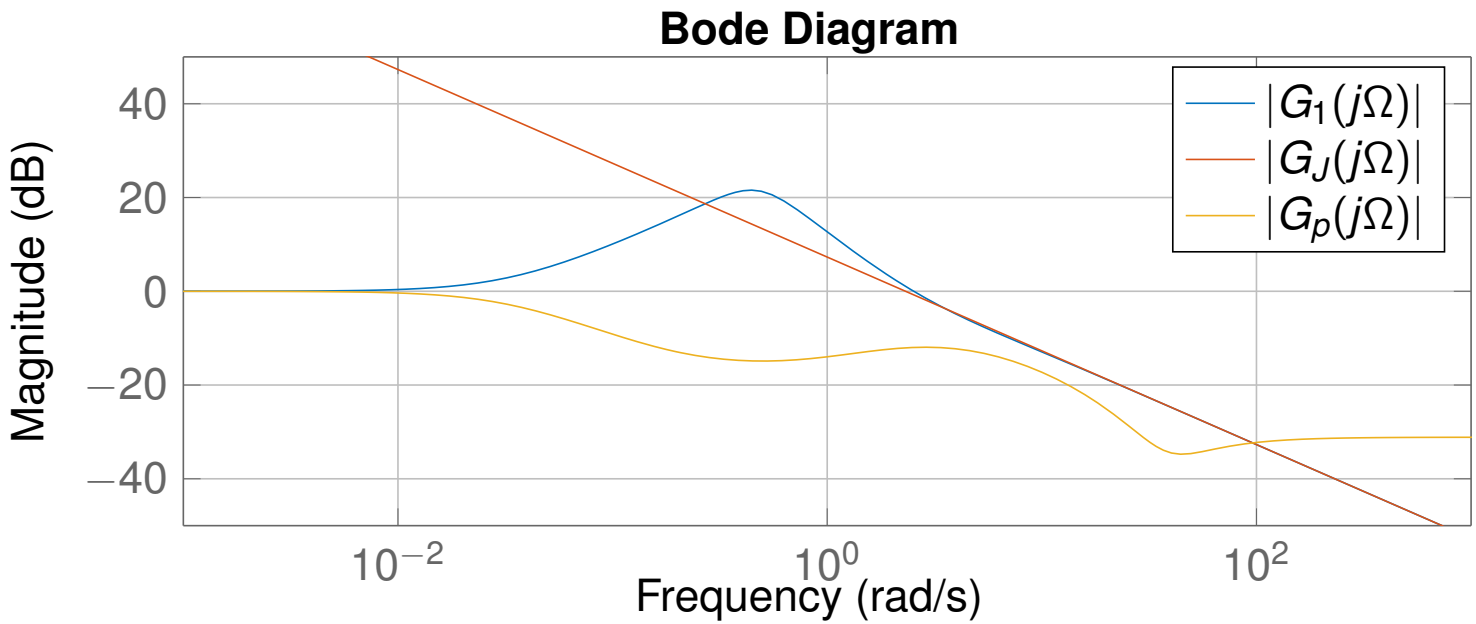
Can we find $S(s)$ without using a PMU

- To find $S(s)$ we need an estimate of $G_J(s)$.

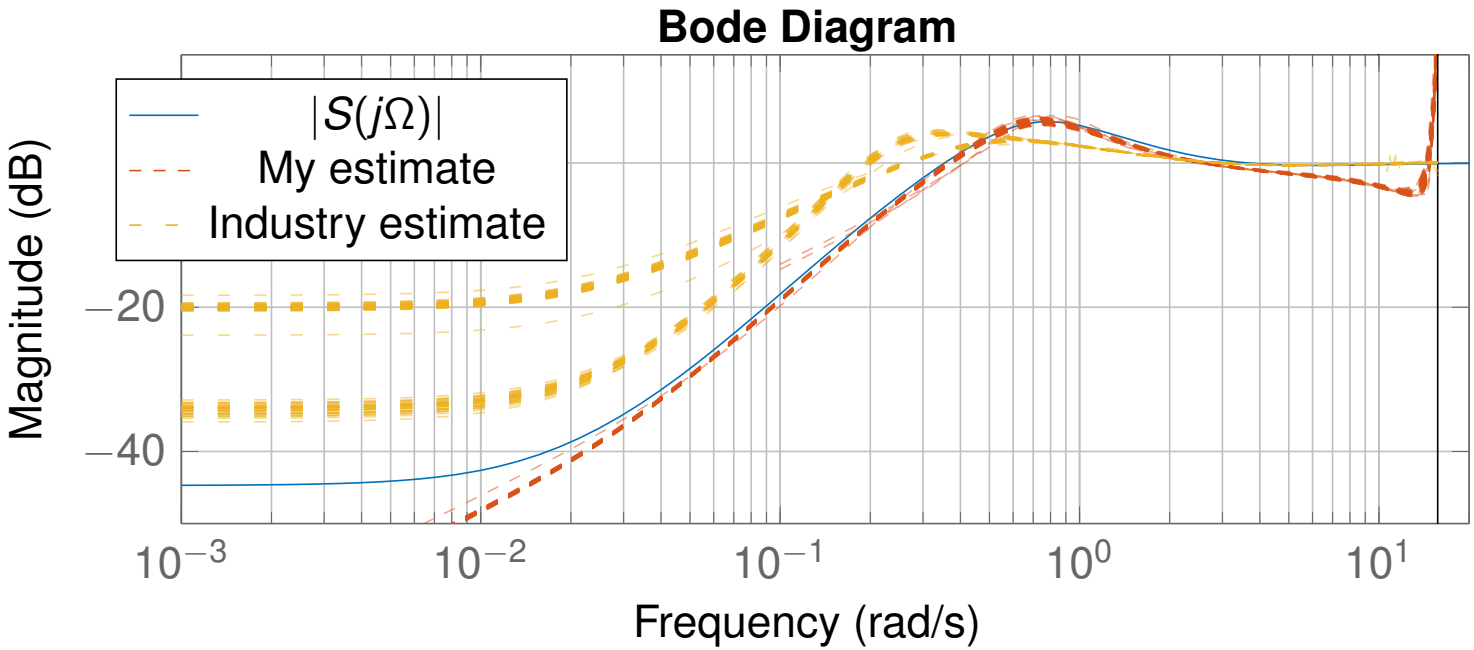
$$G_J(s) = \frac{1}{2Hs + K_d} \tag{10}$$

$$2H >> K_d \tag{11}$$

$$S(s) \approx 2HsG_1(s) \tag{12}$$



Comparison of estimated sensitivity functions



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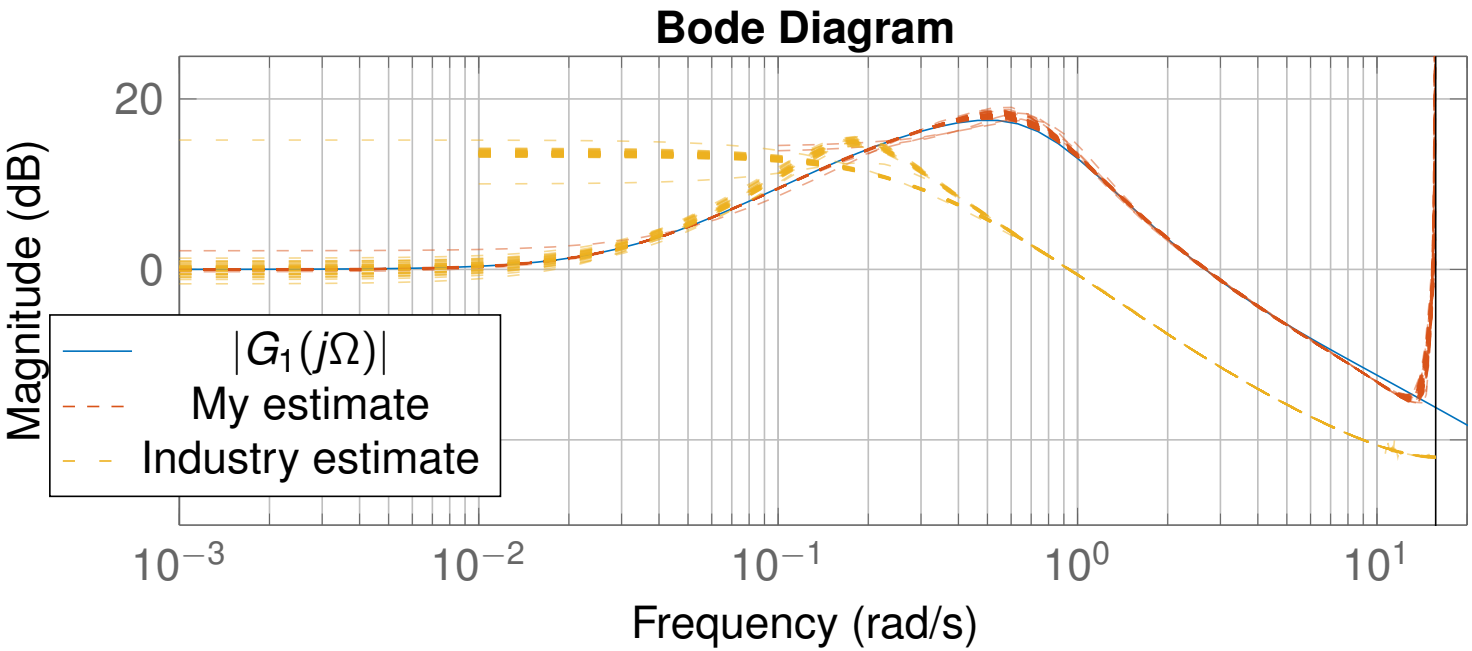


Outline

Dataset from Statkraft

- One of Norway's biggest power producers.

Normalization factor

- When calculating resource's response based on sine sweeps, the response (transfer functions at discrete frequencies) has to be normalized

Normalized transfer function

Resource's transfer function from sine sweeps

$$F(j\omega) = \frac{FCR(j\omega)}{e}$$

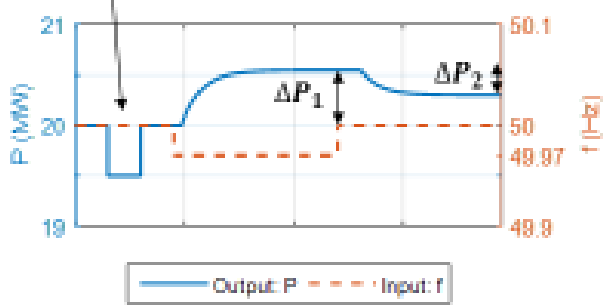
Normalization factor

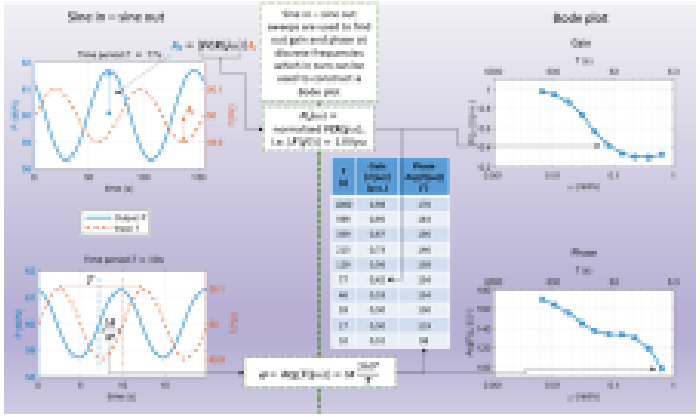
- Normalization factor

$$e = \Delta P_1$$

We are not sure whether the best approach is to use ΔP_1 as the normalization factor

Active power change is applied prior to the step test to reduce the backlash effect





Dataset from Statkraft

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- They performed the tests from the draft requirements

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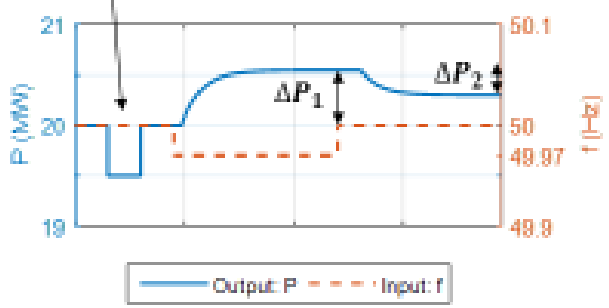

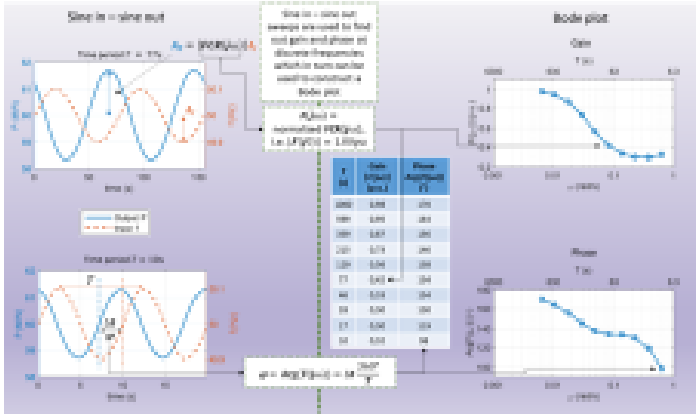

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- One of Norway's biggest power producers.
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- By chance I had PMU measurements from the same plant.

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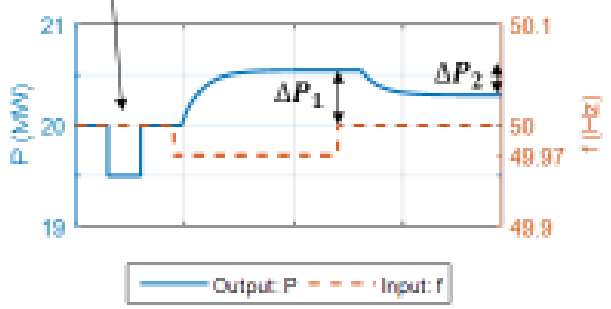
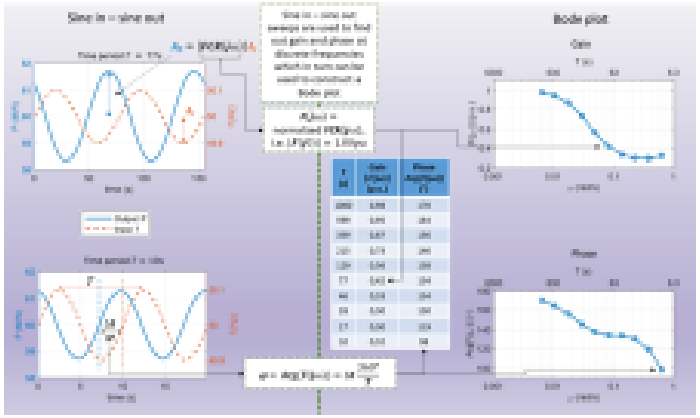
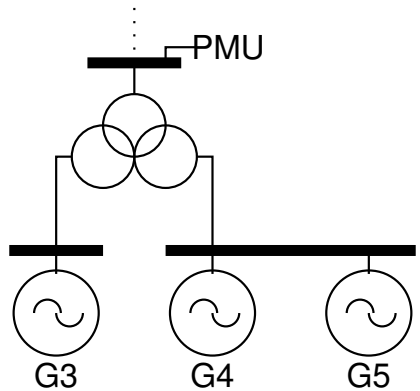
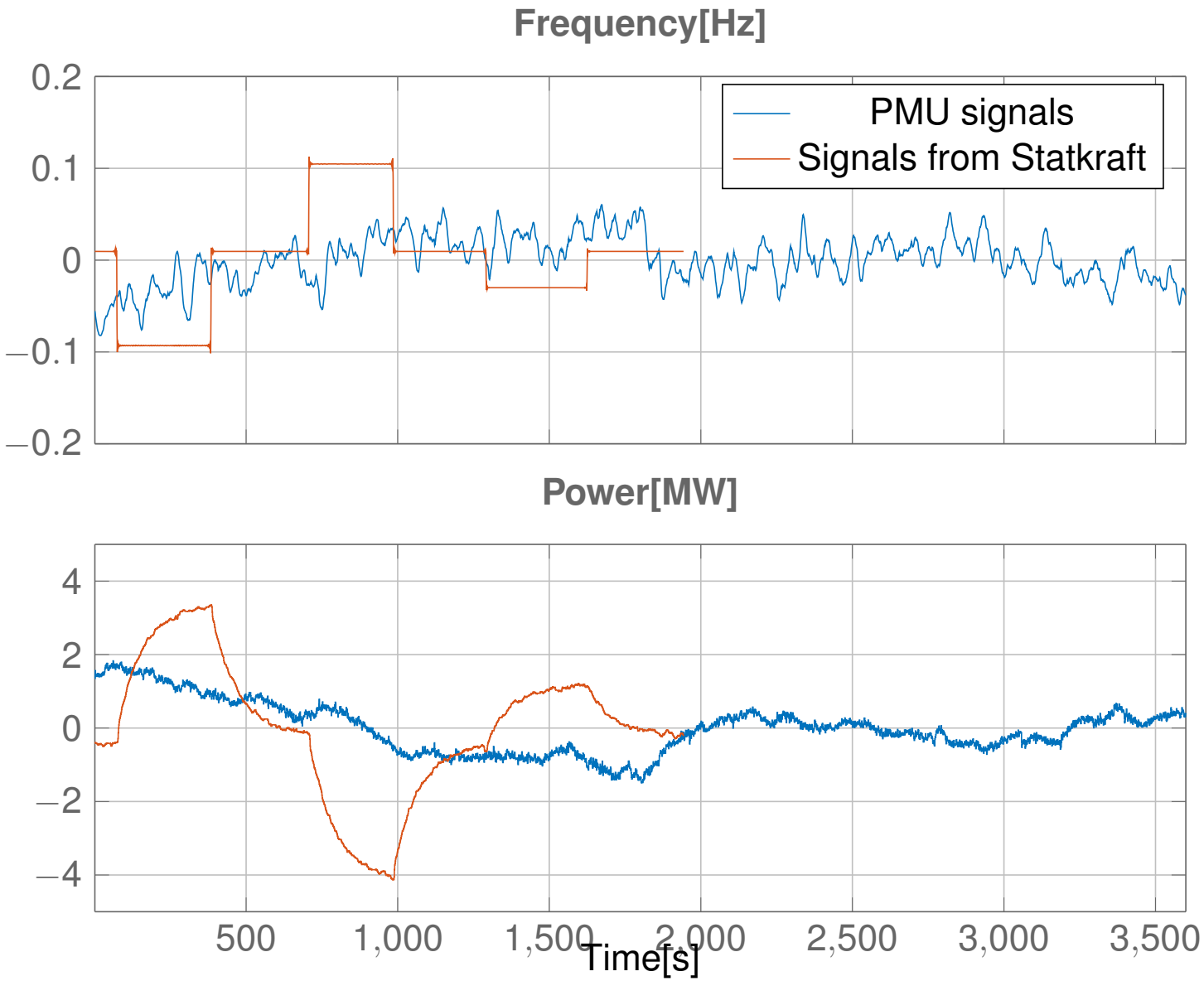




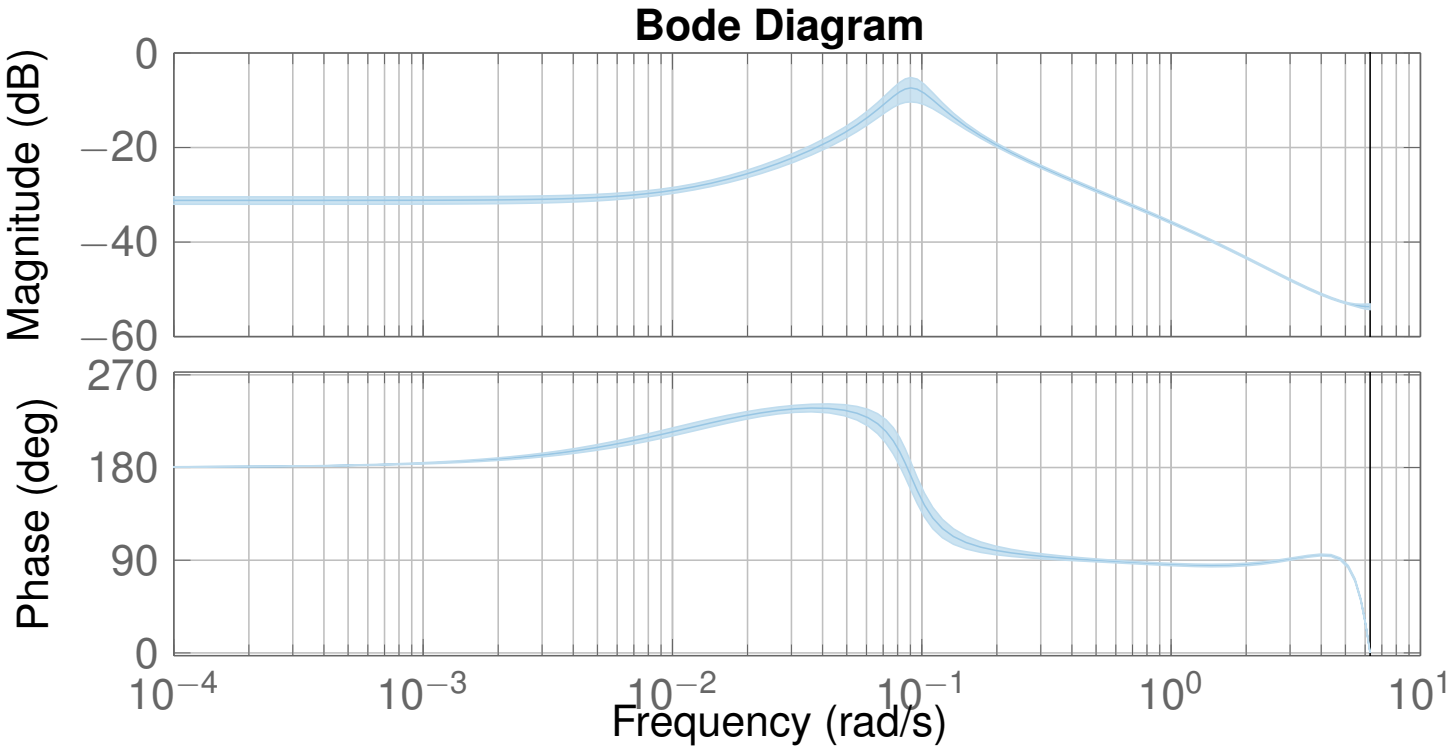
Single line diagram of the plant



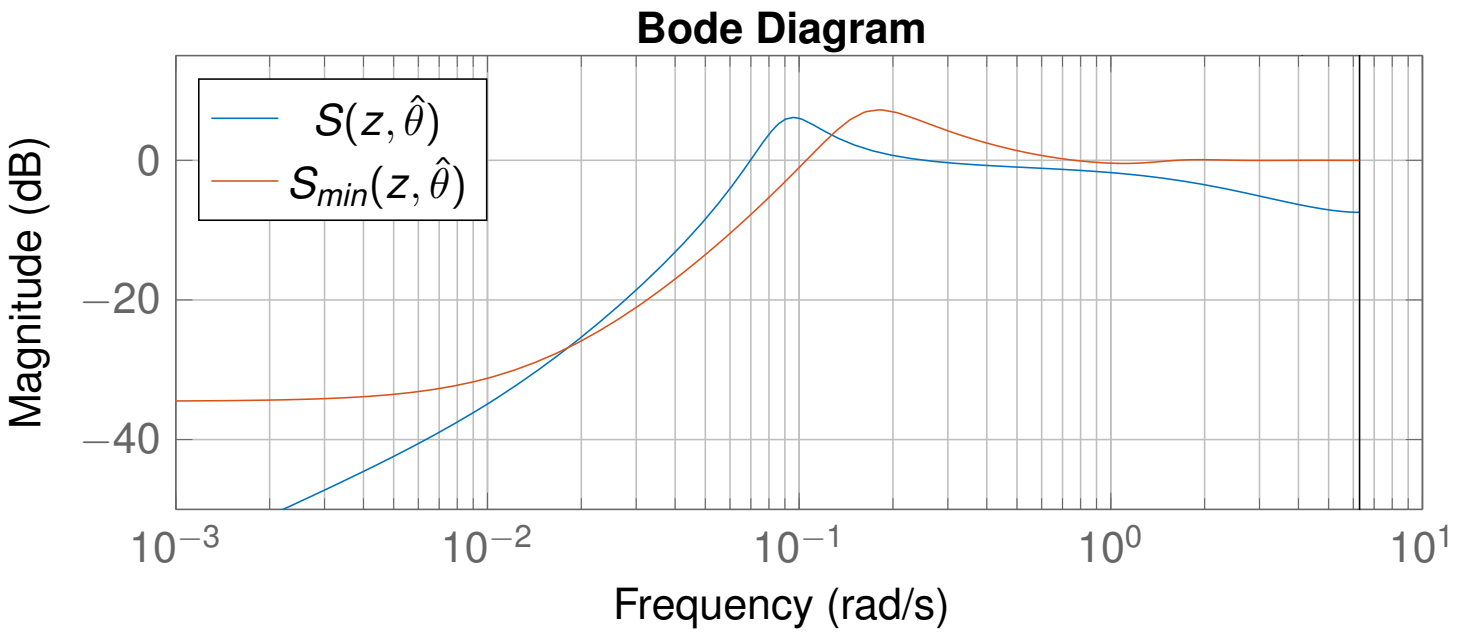
Datasets used



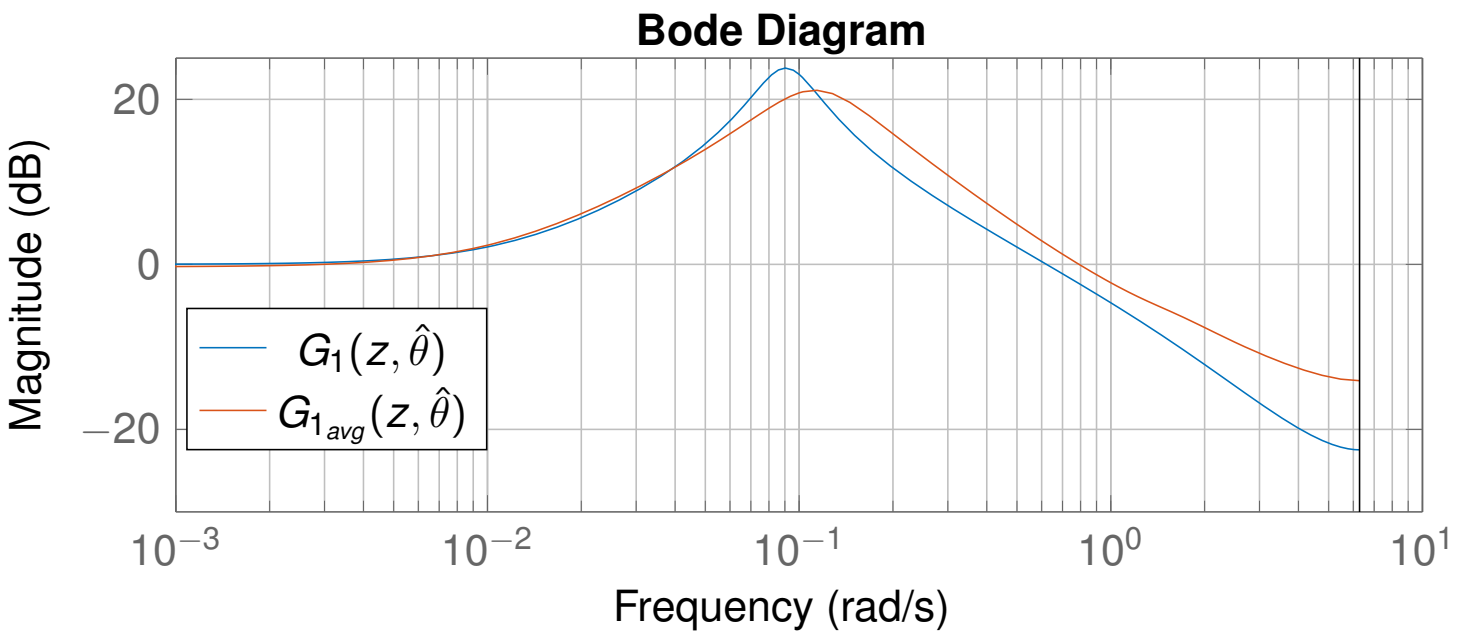
Identified $G_1(s)$ using pmu signals



Estimated sensitivity functions



Estimated $G_1(s)$



Outline

Conclusions and further work

- It is indeed possible to identify the turbine dynamics(closed loop with electromechanical dynamics) using PMU measurements.
- The identified transfer functions can be used for checking the requirements
- The tests in the requirements are intrusive
- It should be investigated how one can use data from the control system to get better estimates.

Further work

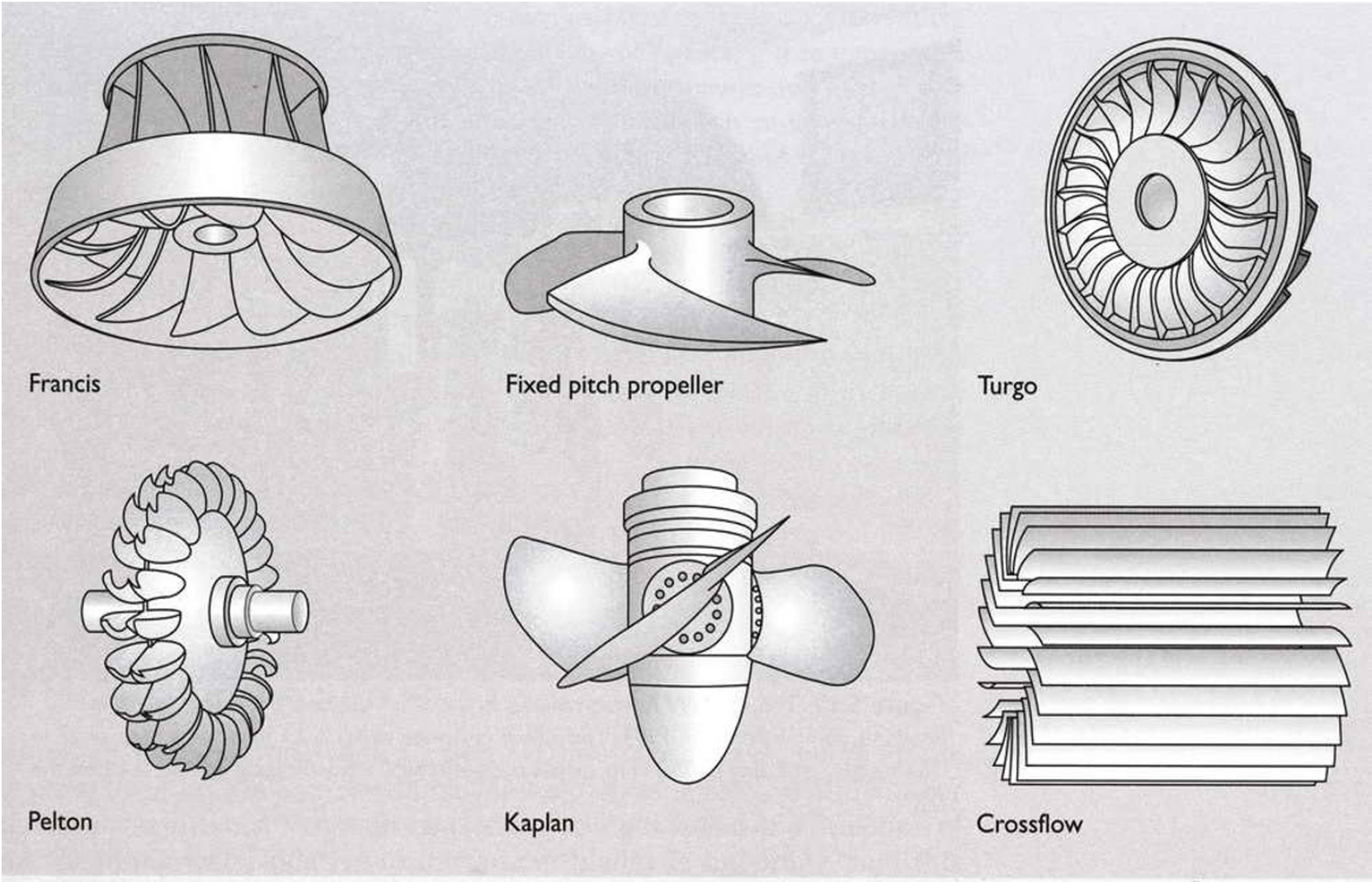


Figure 5.15 Types of turbine runner

Thanks for your attention.