NTNU
Norwegian University of
Science and Technology

Identification of hydro power frequency containment reserve dynamics using PMUs

Sigurd Hofsmo Jakobsen

Norwegian university of technology and science Department of electri
engineering

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Outline

About me

Background

Previous work using PMUs

Validation of the approach

Simulation results

Results from a real power plant

Conclusions and further work

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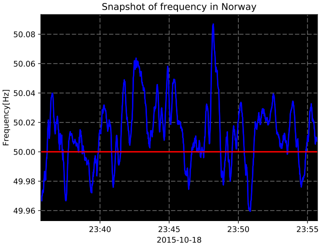
Outline

Frequency quality in the Nordics

- From 2008 the time the frequency has been outside its allowed band has increased
- The performance of hydro turbine governors play an important role



Challenges in operation

- Towards 100% renewable electricity generation
  - Larger variability
  - More uncertainty
  - Increasing complexity

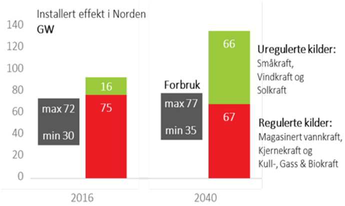


Figure: Present and future energy mix[Statnett]

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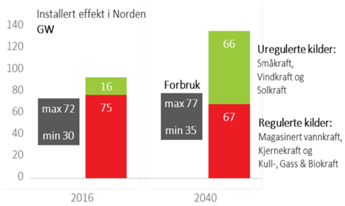

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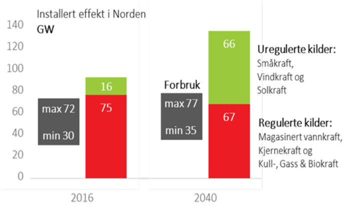

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Challenges in operation

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- Less time for actions
- **Hydropower** is the main resource for balancing

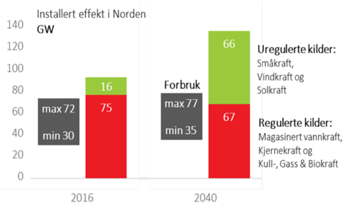
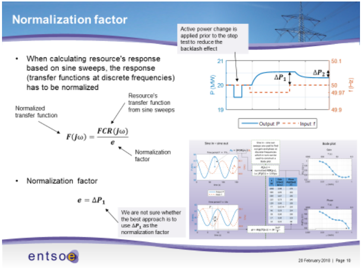


Figure: Present and future energy mix[Statnett]

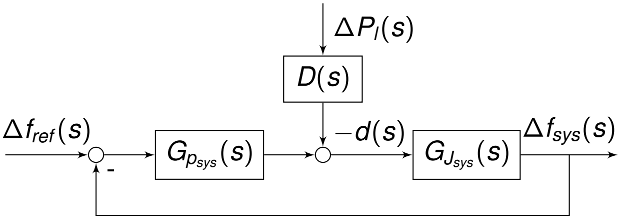
New requirements on FCR due to frequency quality

- Nordic TSOs are developing new requirements on FCR
- This includes offline testing and verification of performance



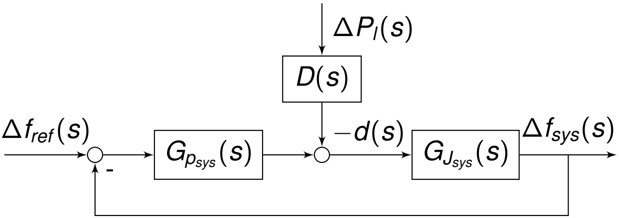
Theoretical background for new requirements

- Aggregated system model:



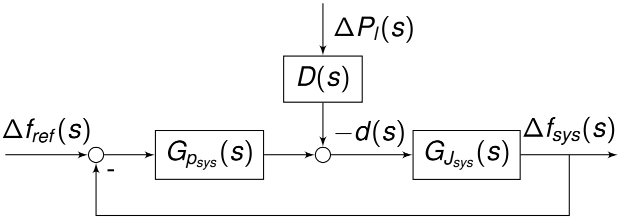
Theoretical background for new requirements

- Aggregated system model:
  - $G_{p_{sys}}(s)$: Aggregated model of FCR



Theoretical background for new requirements

- Aggregated system model:
  - $G_{p_{sys}}(s)$: Aggregated model of FCR
  - $G_{J_{sys}}(s)$: Aggregated model of swing dynamics



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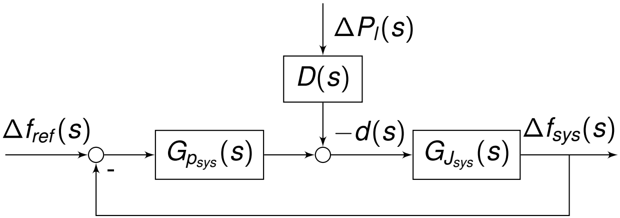
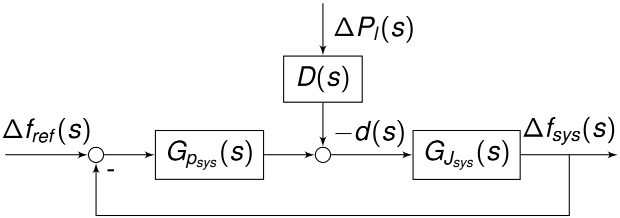
  - $\Delta P_l(s)$: Aggregated load changes



Theoretical background for new requirements

- Aggregated system model:
  - $G_{p_{sys}}(s)$: Aggregated model of FCR
  - $G_{J_{sys}}(s)$: Aggregated model of swing dynamics
  - $\Delta P_l(s)$: Aggregated load changes
- Stability requirement stated in terms of the system's sensitivity function

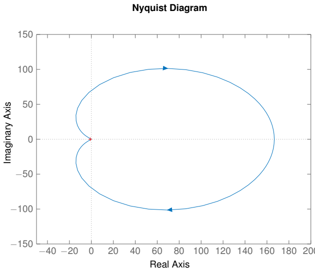
$$S_{sys}(s) = \frac{1}{1 + G_{p_{sys}}(s) G_{J_{sys}}(s)} \tag{1}$$



Stability using Nyquist

- Stability can be checked using:

$$L_{sys}(s) = G_{p_{sys}}(s)G_{J_{sys}}(s) \qquad (2)$$



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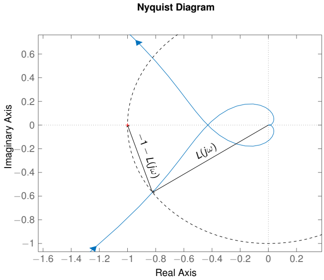
- Stability margin given by:

$$Ms = \min|-1 - L_{sys}(j\omega)| \qquad (3)$$



Stability using Nyquist

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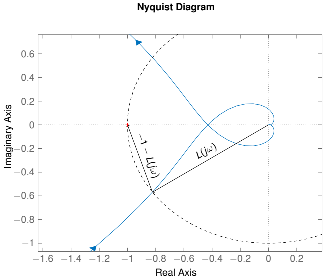
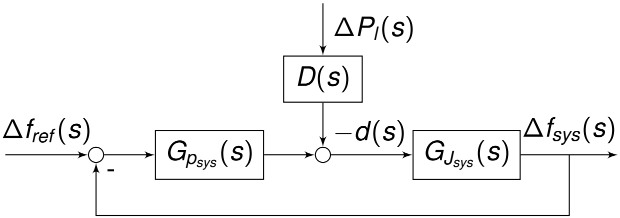
- Notice that

$$\min|-1 - L_{sys}(j\omega)| = \max|S_{sys}(j\omega)| \qquad (4)$$



Draft requirements for performance

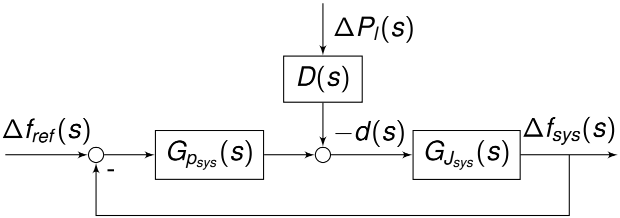
- For the performance we want to limit the change in frequency.



Draft requirements for performance

- For the performance we want to limit the change in frequency.
- The change in frequency is given by:

$$\Delta f_{sys}(s) = -2\pi G_{J_{sys}}(s) S_{sys}(s) d(s) = 2\pi G_{1_{sys}}(s) d(s) \qquad (5)$$



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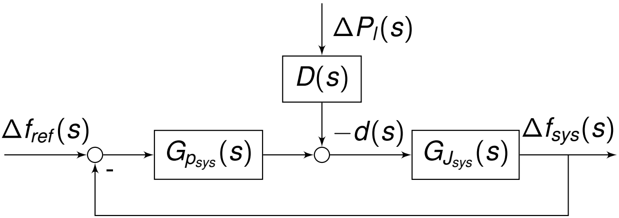
- The change in frequency is given by:

$$\Delta f_{sys}(s) = -2\pi G_{J_{sys}}(s) S_{sys}(s) d(s) = 2\pi G_{1_{sys}}(s) d(s) \tag{5}$$

- We can use this for defining the performance requirements:

$$|2\pi G_{1_{sys}}(j\omega)|^2 \phi_d(\omega) < \phi_{\Delta f}(\omega) = 0.1 \tag{6}$$



Draft requirements for power plant

1. Measure a plant’s response to ten sine injections

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Draft requirements for power plant

1. Measure a plant's response to ten sine injections
2. Estimate $G_p^{(p.u.)}(s)$ for the plant based on the sine injections
3. Use $G_p^{(p.u.)}(s)$ together with $G_{J_{sys}}^{(p.u.)}(s)$ to check.

$$|S(j\omega)| < \frac{1}{M_s} \tag{7}$$

and

$$|2\pi G_1(j\omega)|^2 \phi_d(\omega) < 0.1 \tag{8}$$

Drawbacks with the draft requirements

- One has to disconnect the plant to inject the sine waves.
- Injecting 10 sine waves take a lot of time.
- They assume the same swing dynamics for all plants.

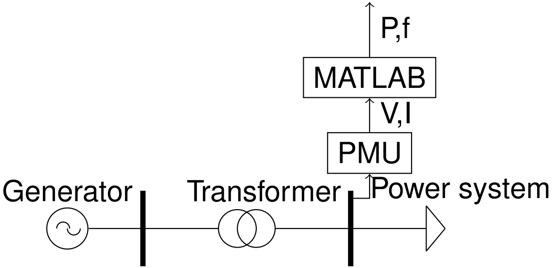
Research question

- Can the draft requirements be tested using PMU measurements from normal operation?

$$|S(j\omega)| < \frac{1}{M_s} \tag{9}$$

and

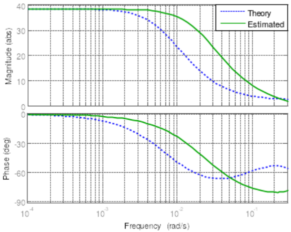
$$|2\pi G_1(j\omega)|^2 \phi_d(\omega) < 0.1 \tag{10}$$



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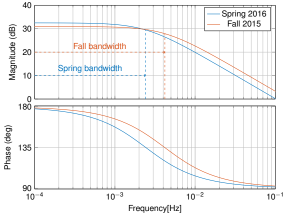
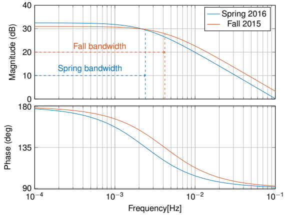
- A transfer function was identified from the electrical frequency to the electrical power under normal operation using the ARX model structure.
- A transfer function was identified from the electrical frequency to the electrical power under normal operation using vector fitting.



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.



Outline

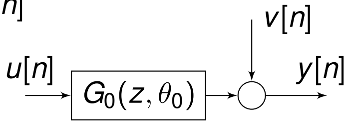
System identification basic

- Assume that a data set $Z^N = \{u[n], y[n] | n = 1 \dots N\}$ has been collected.
- The dataset Z^N is assumed generated by

$$\mathcal{S} : y[n] = G_1(z, \theta_1)u[n] + H_1(z, \theta_1)e[n] \tag{11}$$

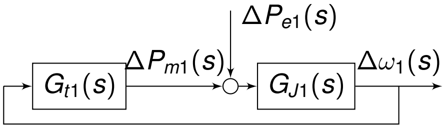
- Using the data set Z^N we want to find the parameter vector θ^N minimizing

$$\hat{\theta}_N = \arg\min_{\theta} \frac{1}{N} \sum_{n=1}^{N} \epsilon^2(n, \theta) \tag{12}$$



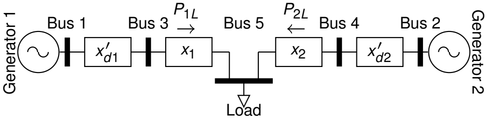
Modeling used for the validation

- The system we want to identify



Modeling used for the validation

- The system we want to identify
- We use a small power system



Modeling used for the validation

- The system we want to identify
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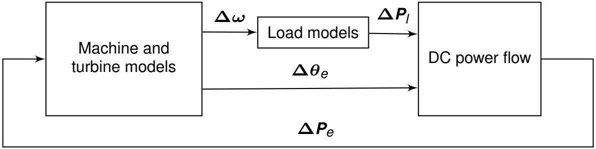
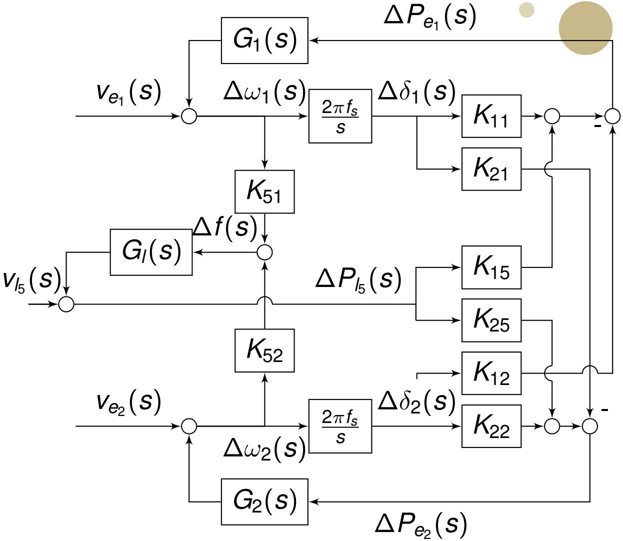
- We use a dc power flow



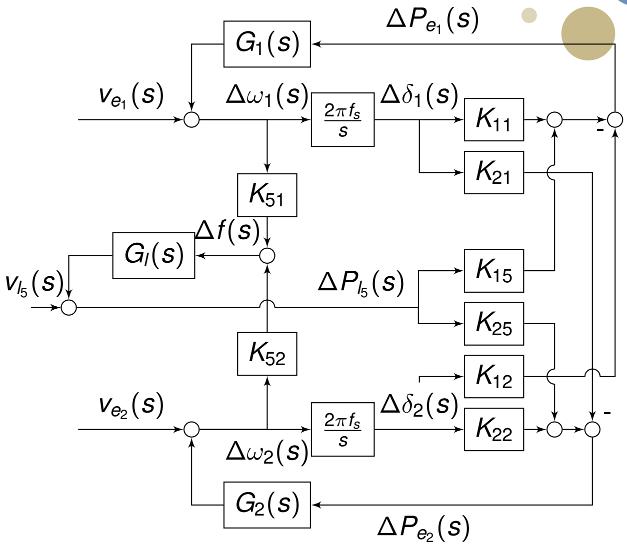
Modeling used for the validation

- The system we want to identify
- We use a small power system
- We use a dc power flow
- This results in the following block diagram



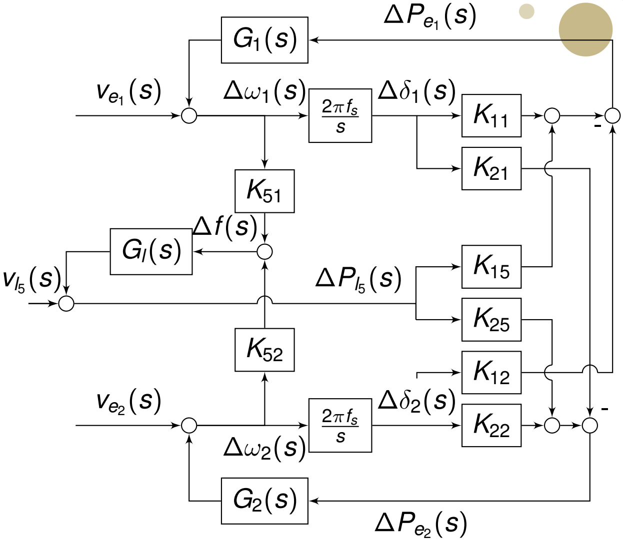
Conclusion from the identification analysis

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



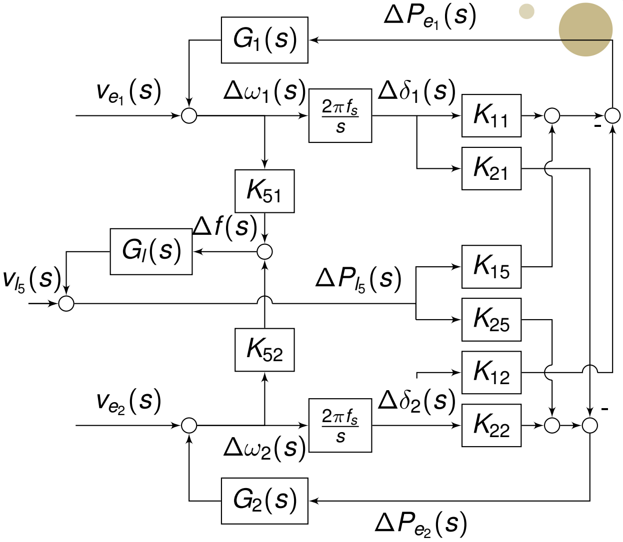
Conclusion from the identification analysis

- 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 $\Delta P_{e1}(s)$.



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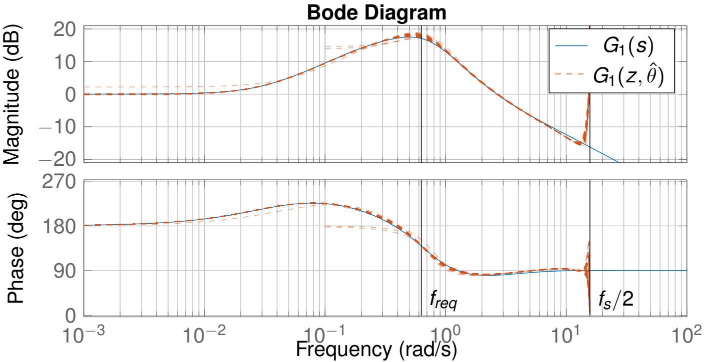
Example of identifying $G_1(s)$ in Simulink

- The simple power system presented was implemented in Simulink.



The identification experiment in the draft requirements

- In the draft requirements they require the power plant owners to replace the input to the governor with their own signal.

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- They then identify the transfer function from the input to the governor to the electrical power of the generator.

$$G_{req}(s) = -\frac{G_p(s)G_J(s)T(s)}{1 + G_J(s)T(s)} \tag{13}$$

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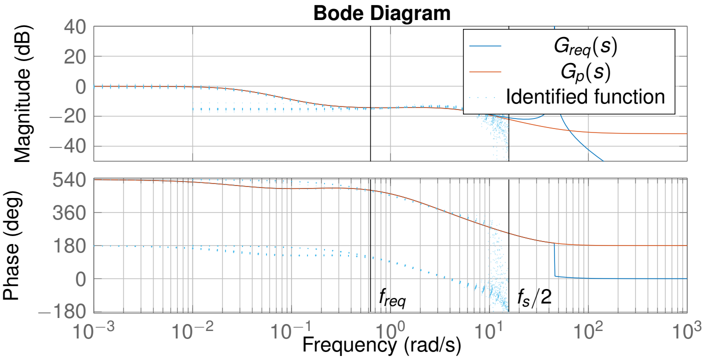
$$G_{req}(s) = -\frac{G_p(s)G_J(s)T(s)}{1 + G_J(s)T(s)} \tag{13}$$

- This is not $G_p(s)$

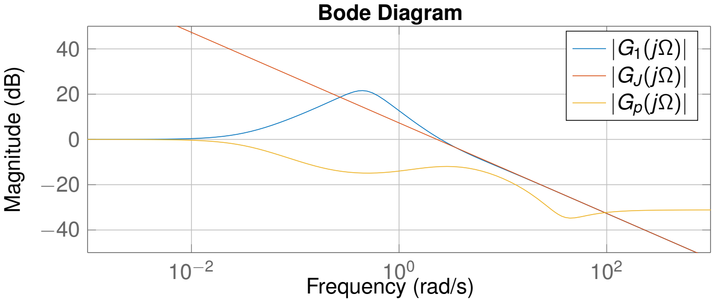
Example of identifying $G_{req}(s)$ in Simulink

- The transfer function specified in the draft requirements were also estimated in the simulations.



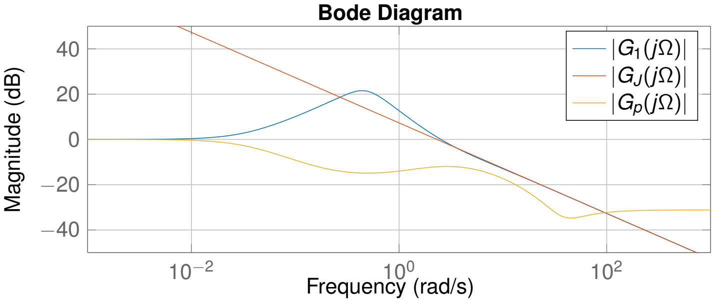
Estimating the swing dynamics of a power plant

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



Estimating the swing dynamics of a power plant

- To find $S(s)$ we need an estimate of $G_J(s)$.
- $$H \approx \frac{\Omega_2 - \Omega_1}{2\Omega_1\Omega_2(|G_1(j\Omega_1)| - |G_1(j\Omega_2)|)} \tag{14}$$



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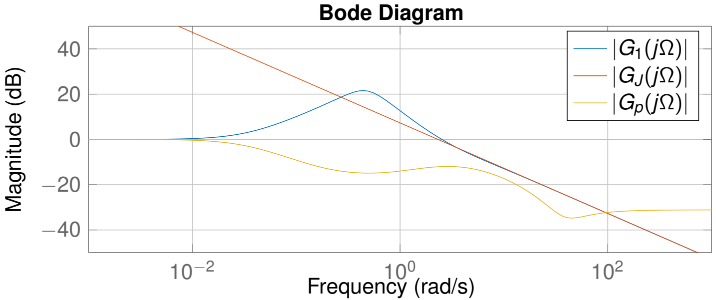
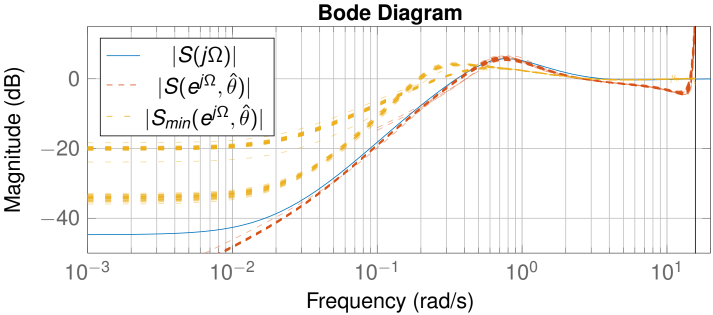
- $$S(s) \approx 2HsG_1(s) \tag{15}$$



Comparison of estimated sensitivity functions

$$G_{sys}(s) = \frac{600MW}{0.1Hz}\frac{f_0}{S_{sys}}\frac{1}{2H_{sys}s + K_{d_{sys}} * f_0} \tag{16}$$



Comparison of estimated $G_1(s)$

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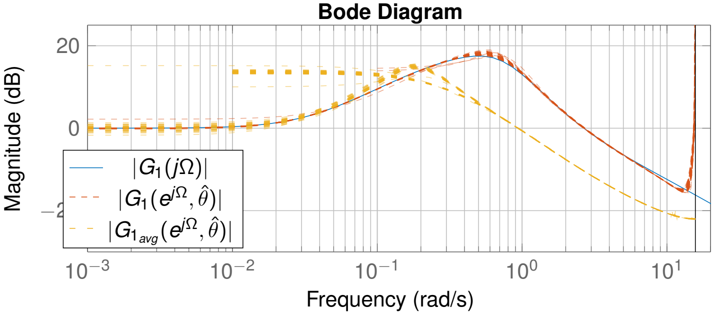

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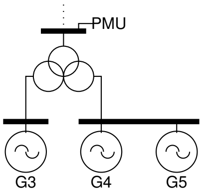
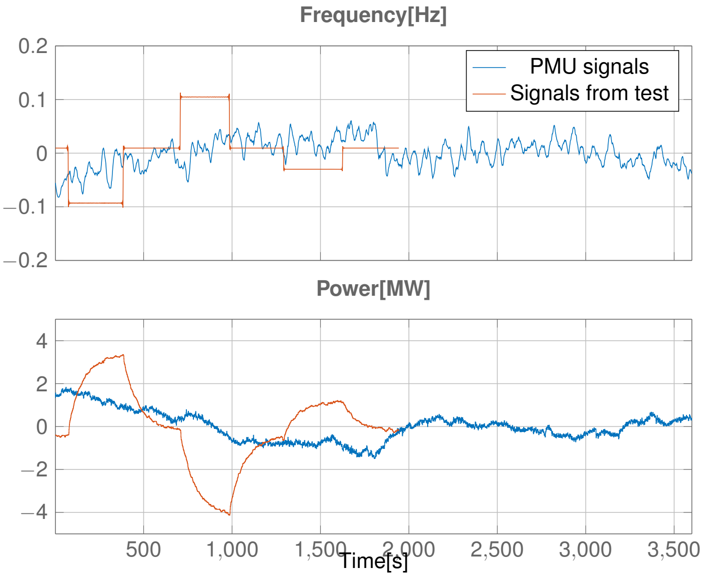
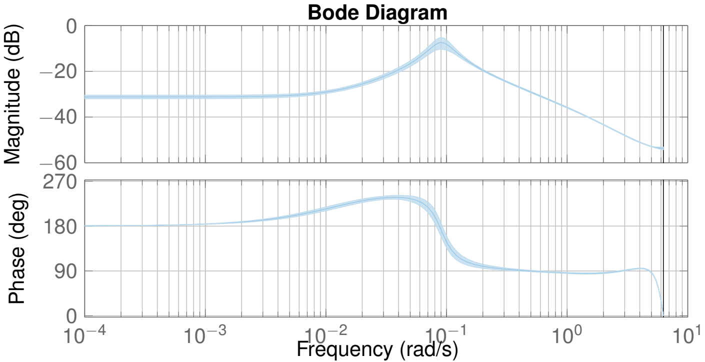
Single line diagram of the plant



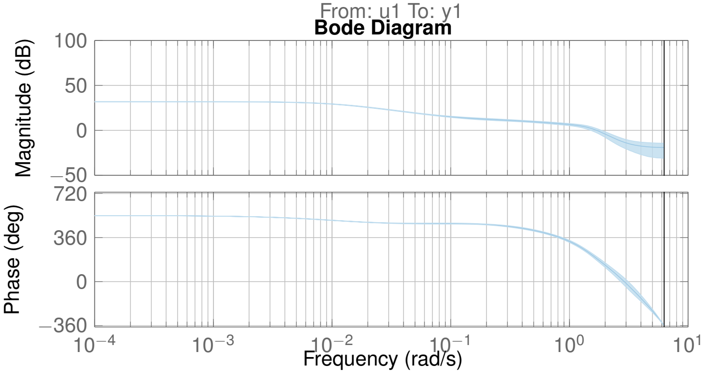
Datasets used



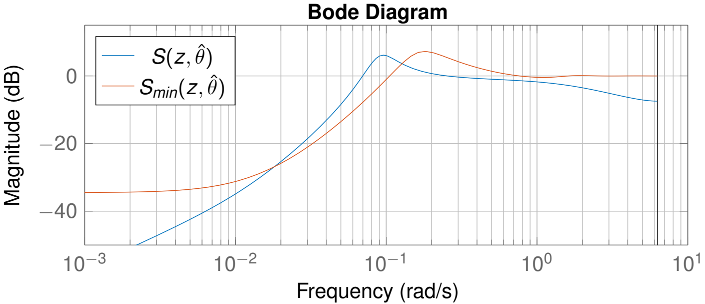
Identified $G_1(s)$ using pmu signals



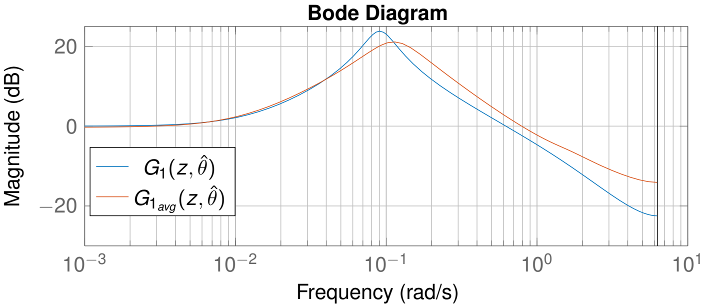
Identified $G_{req}(s)$ using control system signals



Estimated sensitivity functions



Estimated $G_1(s)$



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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 most likely to intrusive
- It should be investigated how one can use data from the control system to get better estimates.

Thanks for your attention.