NTNU
Norwegian University of Science and Technology

# Frequency control and stability requirements on hydro power plants

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# Outline

Problem

Initial tests using time domain vector fitting Paper I

Development of a simple test system Paper II

Theoretical validation of the PMU approach Paper III

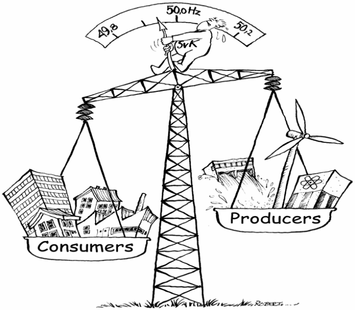
Comparison of a PMU-based approach and the draft requirements approach using tests from two of Statkraft's power plants Paper IV

An extension of Paper IV, with more discussion, simulation comparisons and more simulation validations Paper V

Checking the requirements using measurements from the control system of a hydro power plant Paper VI

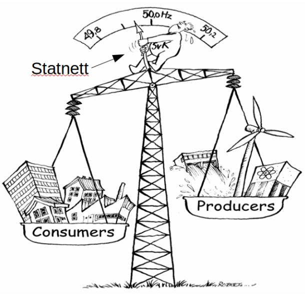
# Load and production balancing

— The power system frequency measures the power balance.



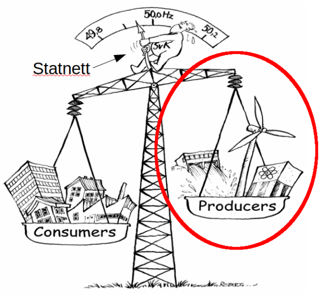
# Load and production balancing

- The power system frequency measures the power balance.
- It is the responsibility of Statnett to control the frequency.



# Load and production balancing

- The power system frequency measures the power balance.
- It is the responsibility of Statnett to control the frequency.
- However, it is the power plant owners who can control the frequency.



# Buying frequency control

— Statnett pays all power plant owners to provide frequency control.

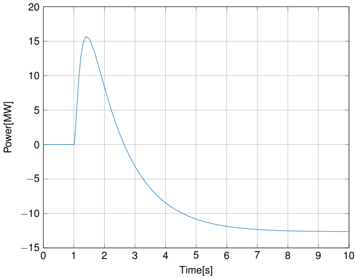



Figure: Frequency control response to step change in frequency

# Buying frequency control

- Statnett pays all power plant owners to provide frequency control.
- However, they don't provide the same quality of service.

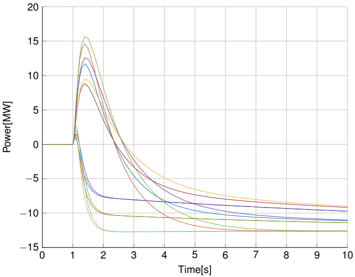



Figure: Frequency control response to step change in frequency

# Buying frequency control

- Statnett pays all power plant owners to provide frequency control.
- However, they don't provide the same quality of service.
- Renewable energy sources such as wind and solar don't contribute.

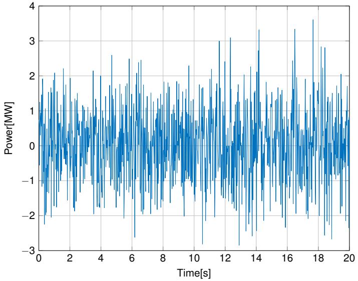



Figure: Frequency control response to step change in frequency

# Future of frequency control

- Power plants have to pass tests to get paid to provide frequency control.
- Only those who pass the tests get paid for the service.

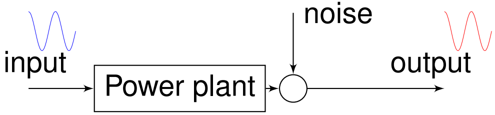
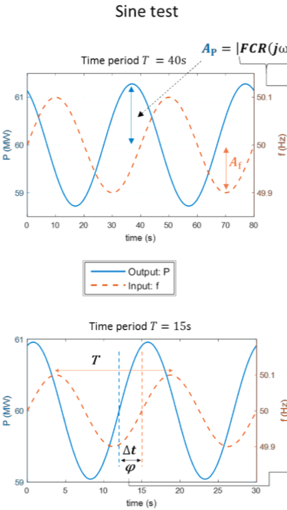



Figure: Test of power plant

# Tests proposed by the industry




Sine tests are used to find out gain and phase at discrete time periods which in turn can be used to construct a Bode plot

$F(j\omega) =$ normalized $\mathbf{FCR}(j\omega)$, i.e. $|F(j0)| = 1.00$pu

| $T$ (s) | Gain $\lvert F(j\omega)\rvert$ (p.u.) | Phase Arg($F(j\omega)$) (°) |
|---|---|---|
| 10 | 0.10 | 57 |
| 15 | 0.12 | 72 |
| 25 | 0.15 | 112 |
| 40 | 0.16 | 117 |
| 50 | 0.20 | 120 |
| 60 | 0.21 | 123 |
| 70 | 0.22 | 126 |
| 90 | 0.27 | 132 |
| 150 | 0.32 | 143 |
| 300 | 0.55 | 146 |

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

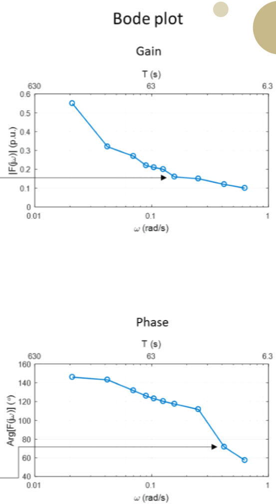
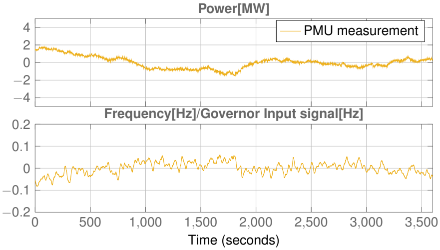



Figure: Testing procedure [source:ENTSO-E]

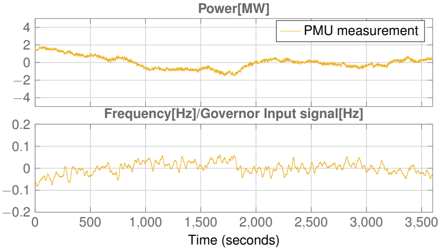
# Motivation

— The power system is never really in steady state.



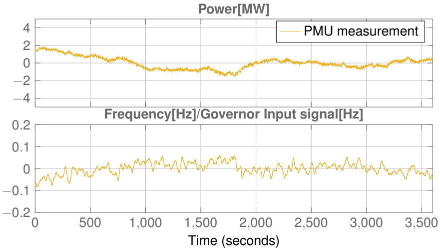
# Motivation

- The power system is never really in steady state.
- Can the power plant dynamics be identified from normal operation measurements?



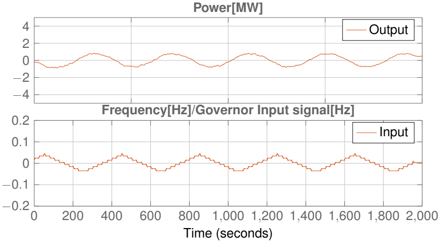
# Research questions

— Can power plant dynamics be identified using a PMU?



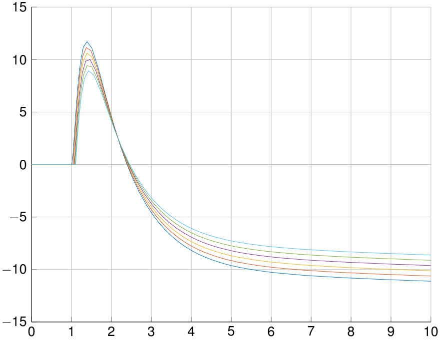
# Research questions

- Can power plant dynamics be identified using a PMU?
- Can power plant dynamics be identified using control system measurements without disturbing the operation of the plant?



# Research questions

- Can power plant dynamics be identified using a PMU?
- Can power plant dynamics be identified using control system measurements without disturbing the operation of the plant?
- What is the effect of nonlinearities on the identification?



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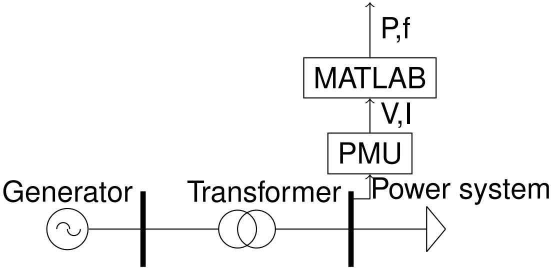
## Background

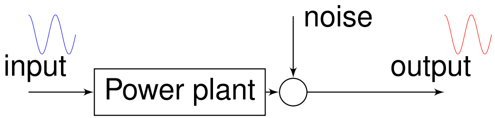
— Idea from[1] can the power plant dynamics be identified using PMUs




[1] Dinh Thuc Duong et al. "Estimation of Hydro Turbine-Governor's Transfer Function from PMU Measurements". In: IEEE PES General Meeting. Boston: IEEE, July 2016

# Background

- Idea from[1] can the power plant dynamics be identified using PMUs
- Uses the same input and output measurements as in the requirements:
  - Input: Power system frequency.
  - Output: Electric power.

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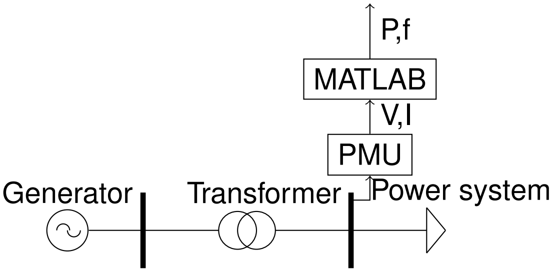
# Methodology

- Collect several datasets from PMUs.
- Calculate power and frequency from the measurements.
- Identify dynamics using vector fitting.
- Compare models.



# Vector fitting basics

$$Y(s) = H(s) \cdot U(s) \tag{1}$$

— Vector fitting fits a transfer function to measured input and output data

# Vector fitting basics

- Vector fitting fits a transfer function to measured input and output data
- It assumes the system to have the following structure.

$$Y(s) = H(s) \cdot U(s) \tag{1}$$

$$H(s) = d + \sum_{i=1}^{n_p} \frac{r_i}{s - p_i} \tag{2}$$

# Vector fitting basics

- Vector fitting fits a transfer function to measured input and output data
- It assumes the system to have the following structure.
- In time domain it is.

$$Y(s) = H(s) \cdot U(s) \tag{1}$$

$$H(s) = d + \sum_{i=1}^{n_p} \frac{r_i}{s - p_i} \tag{2}$$

$$y(t) \approx \tilde{d}x(t) + \sum_{i=1}^{n_p} \tilde{r}_i x_i - \sum_{i=1}^{n_p} \tilde{k}_i y_i \tag{3}$$

$$x_i = \int_0^t e^{\tilde{p}_i(t-\tau)} x_i(\tau) d\tau \tag{4}$$

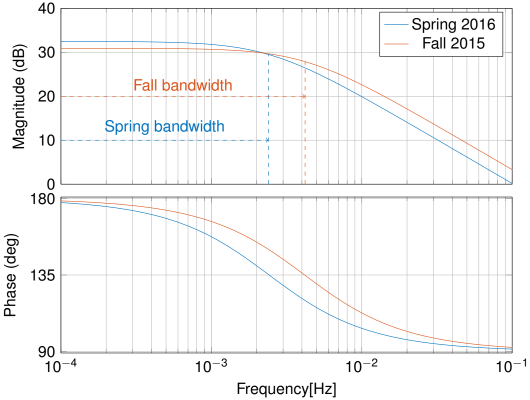
$$y_i = \int_0^t e^{\tilde{p}_i(t-\tau)} y_i(\tau) d\tau \tag{5}$$

# Vector fitting basics ctd.

— Find $\tilde{d}$, $\tilde{r}_i$ and $\tilde{k}_i$ to minimize:

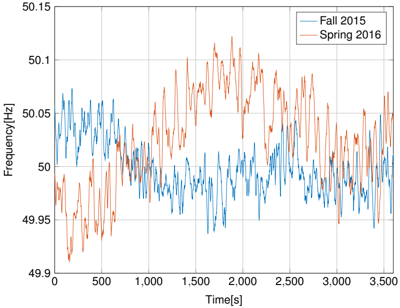
$$y(t) - (\tilde{d}x(t) + \sum_{i=1}^{n_p} \tilde{r}_i x_i - \sum_{i=1}^{n_p} \tilde{k}_i y_i) \tag{6}$$

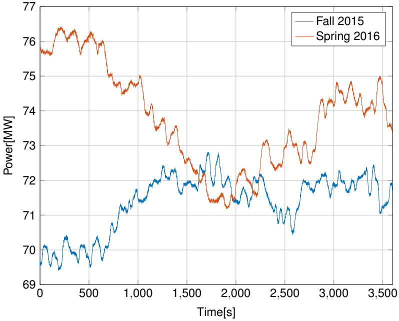
# Estimated droop and bandwidth



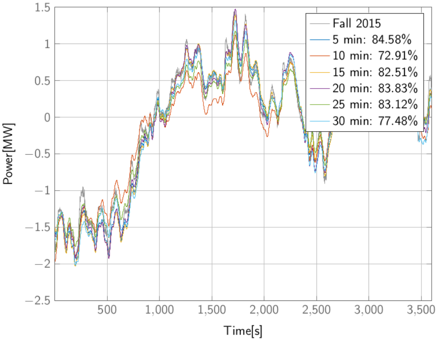

| Dataset | Droop[%] | Bandwidth[mHz] |
|---|---|---|
| Fall 2015 | 10 | 4.16 |
| Spring 2016 | 8 | 2.41 |

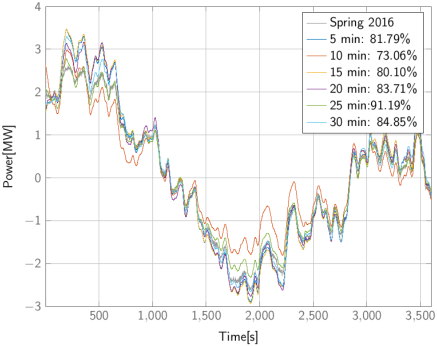
# Cross validation using distant data sets



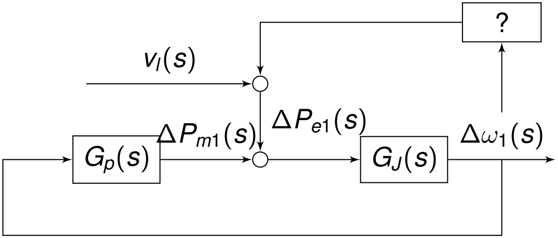
# Cross validation using distant data sets



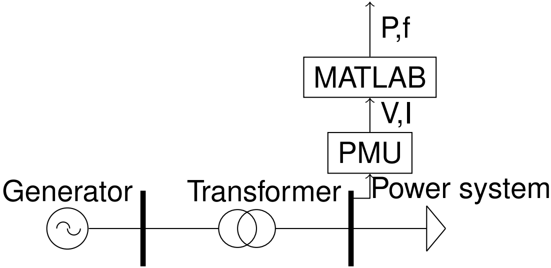
# Shortcoming with the paper

- No theoretical validation of the results.
- No simulation validation of the results.



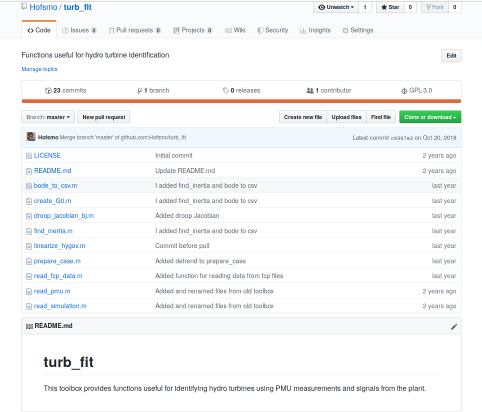
## Main contributions to the research questions

— Promising results for 19 datasets.



# Main contributions to the research questions

- Promising results for 19 datasets.
- Developed code for interfacing with the PMU data.



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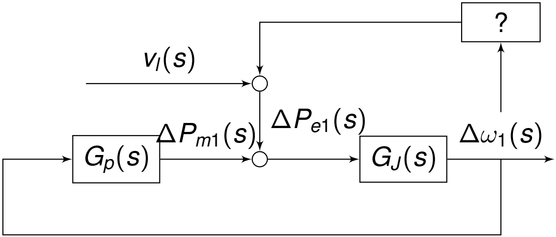
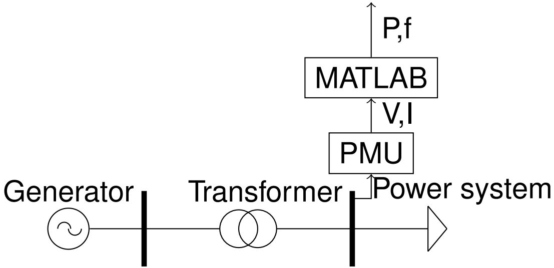
# Motivation

- Explain the problem to my co-supervisor.
- Create a model for analysing the identifiability of hydro power plant dynamics.



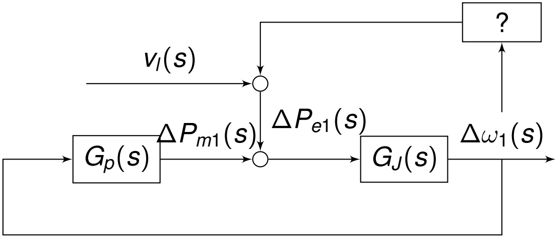
# What do we need to model?

— From the PMU we get



## What do we need to model?

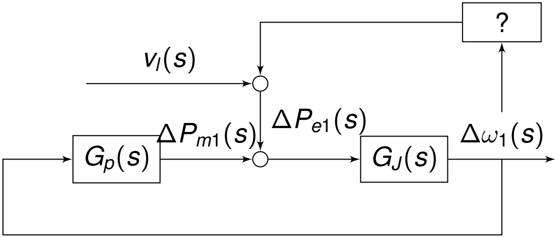
- From the PMU we get
  - Power: $\Delta P_{e1}(s)$.



# What do we need to model?

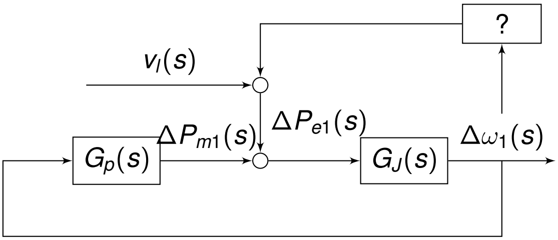
— From the PMU we get

- Power: $\Delta P_{e1}(s)$.
- Frequency: $\Delta f(s)$.



# What do we need to model?

- From the PMU we get
  - Power: $\Delta P_{e1}(s)$.
  - Frequency: $\Delta f(s)$.
- We need to model how $\Delta P_{e1}(s)$ and $\Delta f(s)$ is related through the power system.



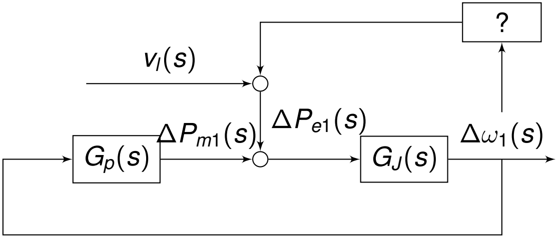
## What do we need to model?

— From the PMU we get

- Power: $\Delta P_{e1}(s)$.
- Frequency: $\Delta f(s)$.

— We need to model how $\Delta P_{e1}(s)$ and $\Delta f(s)$ is related through the power system.

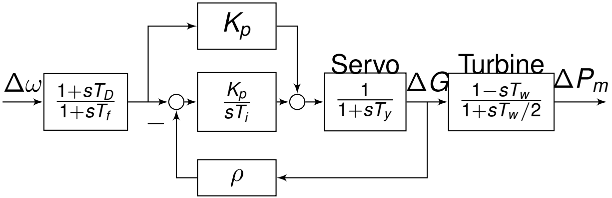
— We also need to model the power plant consisting of $G_p(s)$ and $G_J(s)$.



# Power plant model

- Model for $G_p(s)$
- Model for $G_J(s)$

$$G_J(s) = \frac{1}{2Hs + K_d} \tag{7}$$



## Power system model

— The frequency and power system angle is related.

$$\Delta\theta(s) = \frac{2\pi f_s}{s} f(s) \tag{8}$$

# Power system model

- The frequency and power system angle is related.
- The angle and power is related.

$$\Delta\theta(s) = \frac{2\pi f_s}{s} f(s) \qquad (8)$$

$$P_k \approx \sum_{m \in \Omega_k} x_{km}^{-1} \theta_{km} \qquad (9)$$

# Power system model

- The frequency and power system angle is related.
- The angle and power is related.
- On matrix form.

$$\Delta\theta(s) = \frac{2\pi f_s}{s} f(s) \qquad (8)$$

$$P_k \approx \sum_{m \in \Omega_k} x_{km}^{-1} \theta_{km} \qquad (9)$$

$$\mathbf{P} = \mathbf{Y}\theta \qquad (10)$$

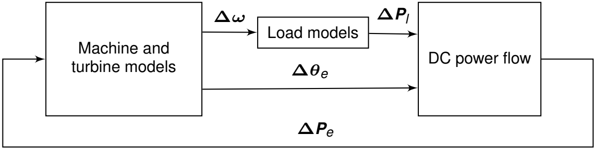
# Power system model

- The frequency and power system angle is related.
- The angle and power is related.
- On matrix form.
- In software

$$\Delta\theta(s) = \frac{2\pi f_s}{s} f(s) \tag{8}$$

$$P_k \approx \sum_{m \in \Omega_k} x_{km}^{-1} \theta_{km} \tag{9}$$

$$\mathbf{P} = \mathbf{Y}\theta \tag{10}$$



# Test system

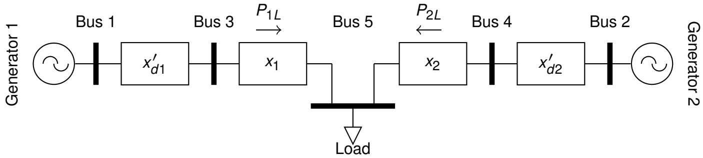
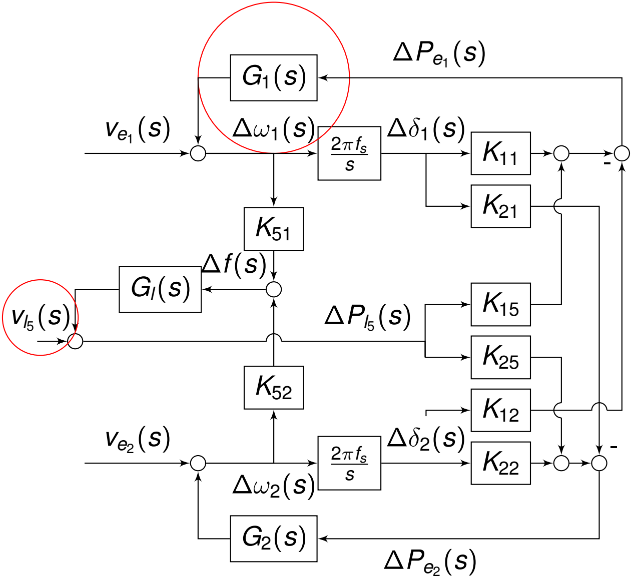


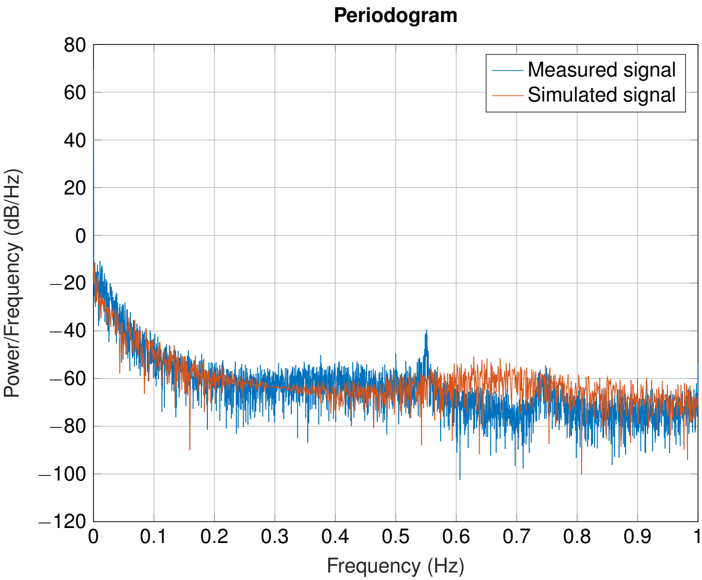

Figure: Single line diagram

# Test system



$\Delta P_{e_1}(s)$
$G_1(s)$
$v_{e_1}(s)$
$\Delta\omega_1(s)$
$\frac{2\pi f_s}{s}$
$\Delta\delta_1(s)$
$K_{11}$
$K_{21}$
$K_{51}$
$\Delta f(s)$
$G_l(s)$
$v_{l_5}(s)$
$\Delta P_{l_5}(s)$
$K_{15}$
$K_{25}$
$K_{52}$
$K_{12}$
$v_{e_2}(s)$
$\frac{2\pi f_s}{s}$
$\Delta\delta_2(s)$
$K_{22}$
$\Delta\omega_2(s)$
$G_2(s)$
$\Delta P_{e_2}(s)$

# Simulation Result



# Main contributions

- Developed simple test system for analysing power plant identifiability using PMUs.
- Developed simple test system used in the proceeding papers for simulations.

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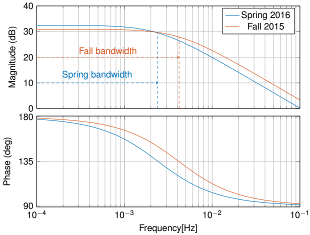
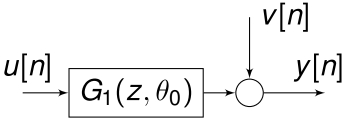
# Background

- Why do we get different results?



# Background

- Why do we get different results?
- The signals we use are corrupted by noise.



## Background

- Why do we get different results?
- The signals we use are corrupted by noise.
- From system identification we have that the error will be asymptotic normally distributed

$$\sqrt{N}(\hat{\theta}_n - \theta^*) \in AsN(0, P_\theta)$$

# Background

— Why do we get different results?

— The signals we use are corrupted by noise.

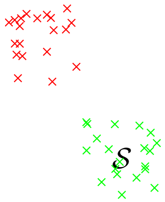
— From system identification we have that the error will be asymptotic normally distributed

— However, first we need to prove the identifiability of the system

True system: $\mathcal{S}$

x: unbiased

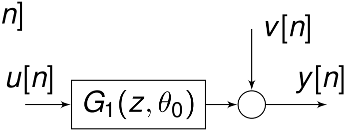
x: biased



## 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

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



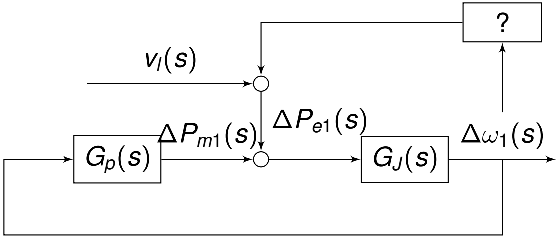

- Using the data set $Z^N$ we want to find the parameter vector $\theta^N$ minimizing

$$\hat{\theta}_N = \arg\min_{\theta} \frac{1}{N} \sum_{n=1}^{N} [H_1^{-1}(z,\theta)(y[n] - G_1(z,\theta)u[n])]^2 \tag{12}$$

# Modeling used for the validation

— The system we are identifying

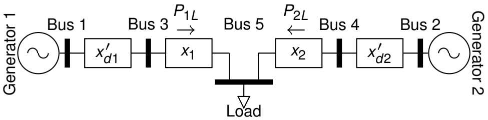
$$G_1(s) = \frac{G_p(s)}{1 + G_p(s)G_J(s)} \tag{13}$$



# Modeling used for the validation

- The system we are identifying
- We use a small power system

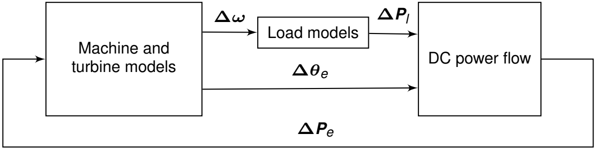
(13)



# Modeling used for the validation

- The system we are identifying
- We use a small power system
- We use a dc power flow

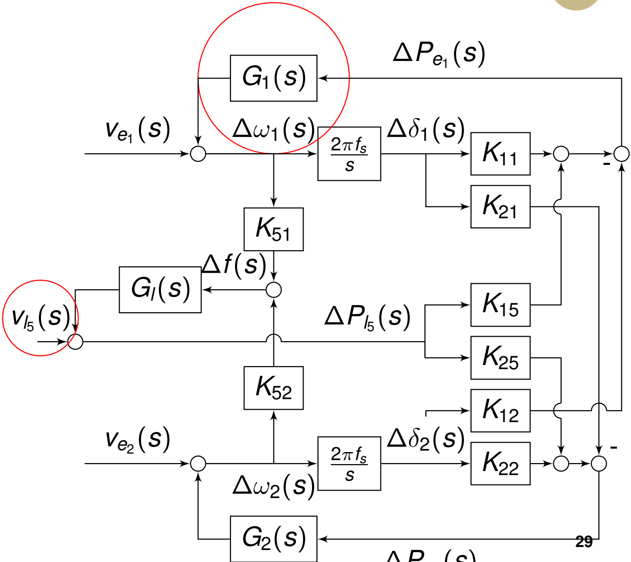
(13)



# Modeling used for the validation

(13)

- The system we are identifying
- We use a small power system
- We use a dc power flow
- This results in the following block diagram



## Results from the theoretical validation

— A consistent estimate of the closed loop transfer function of the turbine and electromechanical dynamics can be obtained by using:

# Results from the theoretical validation

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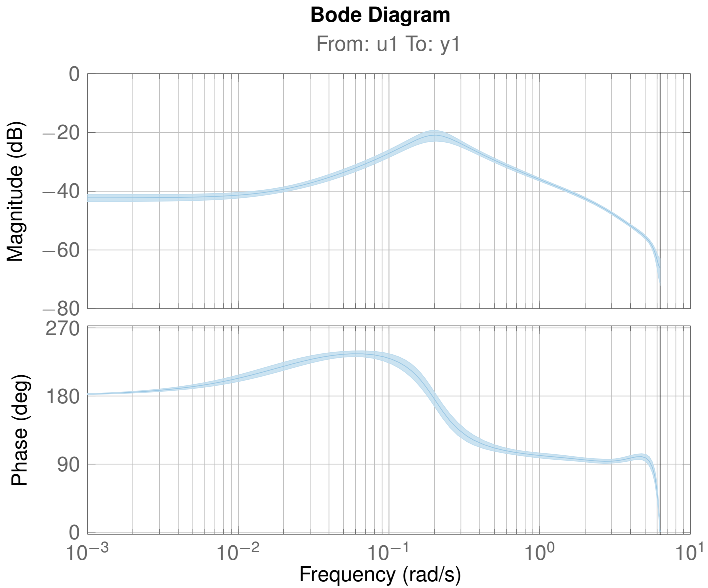
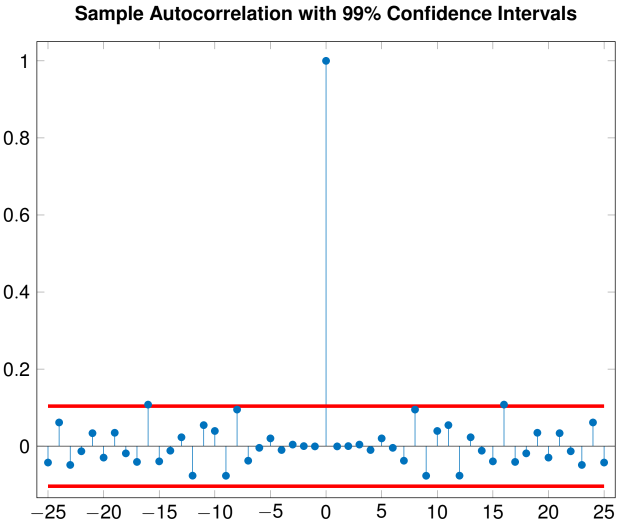
## Results from the theoretical validation

- A consistent estimate of the closed loop transfer function of the turbine and electromechanical dynamics can be obtained by using:
  - Measured PMU frequency as the output $u[n]$
  - Measured PMU power as the input $y[n]$
- The proof was done with the following assumptions.
  - The system is excited by a load acting as a filtered white noise process
  - The measurement error of the electrical power is negligible.
  - The measured frequency is a good estimate of the generator speed.

# Model obtained using PMU data



# Whiteness test on model identified using PMU data



## Main contributions

- To show that the transfer function one is identifying using PMUs is $G_1(s)$.
- To prove under which conditions a consistent estimate of $G_1(s)$ is possible.
- To demonstrate the theory for identification of $G_1(s)$ on real datasets.

# Outline

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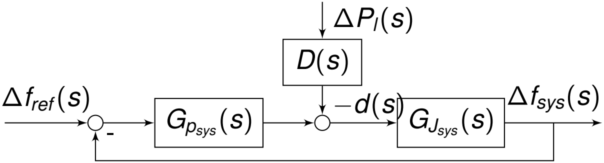
# Motivation

- Relate the results from Paper III and the new requirements.
- Test the methods on more real datasets.
- Demonstrate that industry proposed tests can be done easier.
- Less theoretical presentation in a more industry focused conference.

# The new requirements

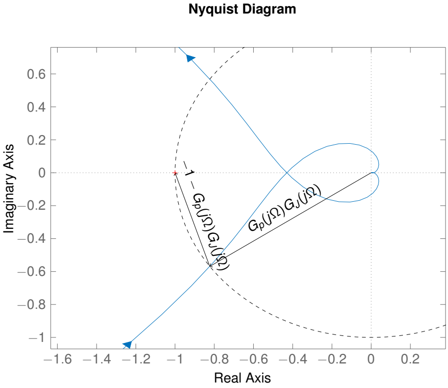
— Puts requirements on an aggregated system model.



# The new requirements

- Puts requirements on an aggregated system model.
- Stability requirement

$$M_s = \max \left| \frac{1}{1 + G_p(j\Omega)G_J(j\Omega)} \right| = \max |S(j\Omega)| \tag{14}$$



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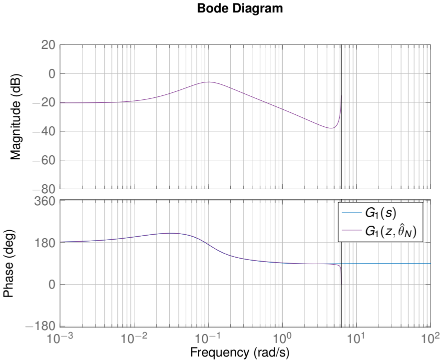
- Performance requirement

$$|G_1(j\Omega)| < \frac{\sigma_{\omega_{req}}}{\sqrt{\phi_{P_e}(j\Omega)}} \tag{15}$$



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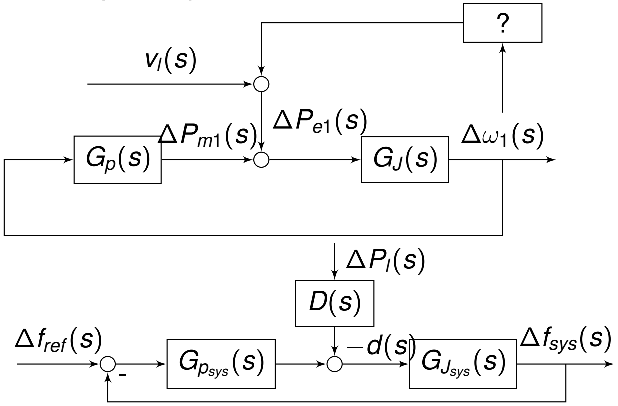
$$|G_1(j\Omega)| < \frac{\sigma_{\omega_{req}}}{\sqrt{\phi_{P_e}(j\Omega)}} \qquad (15)$$

- Requirement per plant stated using a per unit conversion

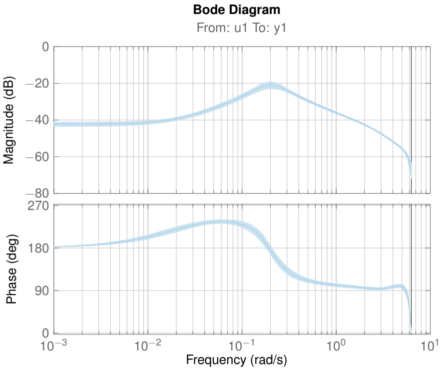
# Alternative requirements

— Place requirements directly on one power plant.



# Alternative requirements

- Place requirements directly on one power plant.
- We already have an estimate of $G_1(s)$.



# Alternative requirements

— Place requirements directly on one power plant.

— We already have an estimate of $G_1(s)$.

— We need to find $S(s)$

# Estimating $S(s)$

—

$$G_1(s) = G_J(s)S(s) \tag{16}$$

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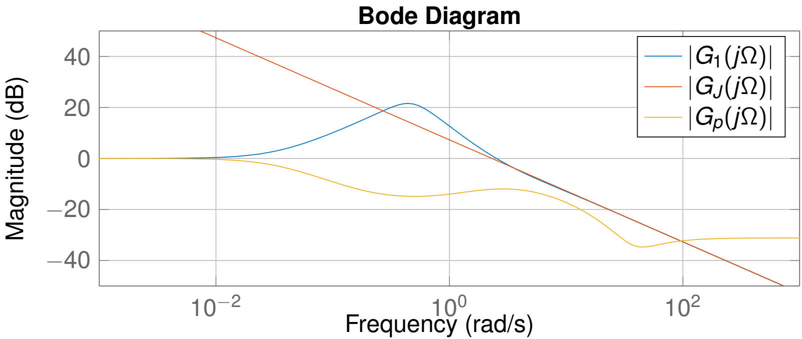
—

$$S(s) \approx 2HsG_1(s) \tag{19}$$

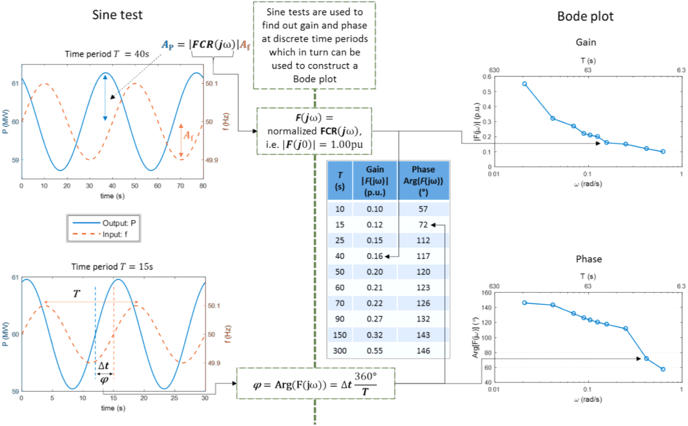
— Need to estimate $H$

# Estimating $H$



# Dataset from Statkraft

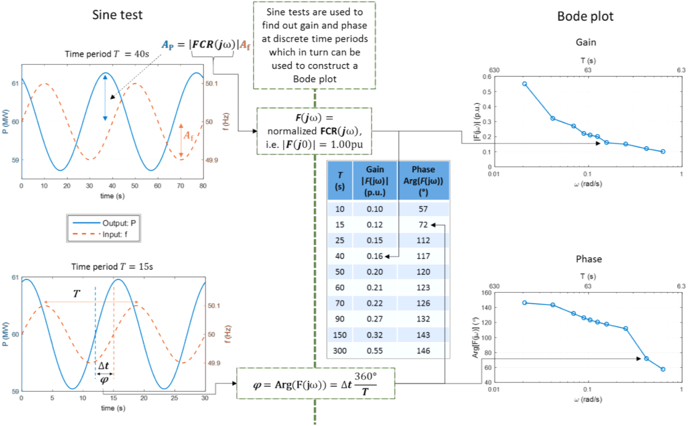
— One of Norway's biggest power producers.




| T (s) | Gain \|F(jω)\| (p.u.) | Phase Arg(F(jω)) (°) |
|---|---|---|
| 10 | 0.10 | 57 |
| 15 | 0.12 | 72 |
| 25 | 0.15 | 112 |
| 40 | 0.16 | 117 |
| 50 | 0.20 | 120 |
| 60 | 0.21 | 123 |
| 70 | 0.22 | 126 |
| 90 | 0.27 | 132 |
| 150 | 0.32 | 143 |
| 300 | 0.55 | 146 |

# Dataset from Statkraft

- One of Norway’s biggest power producers.
- They performed the tests from the draft requirements




| $T$ (s) | Gain $\lvert F(j\omega)\rvert$ (p.u.) | Phase $\mathrm{Arg}(F(j\omega))$ (°) |
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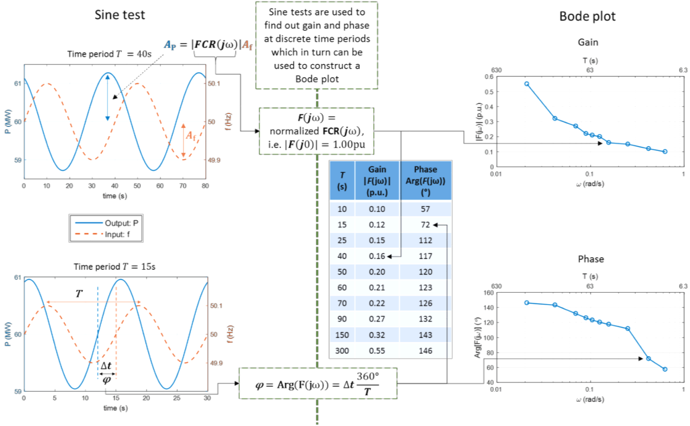
# Dataset from Statkraft

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

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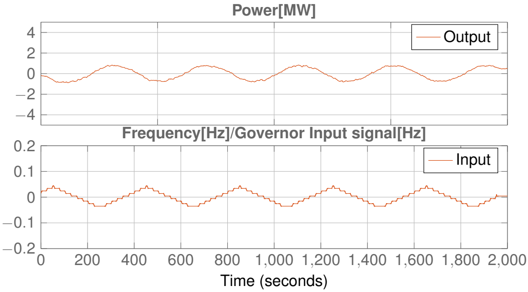
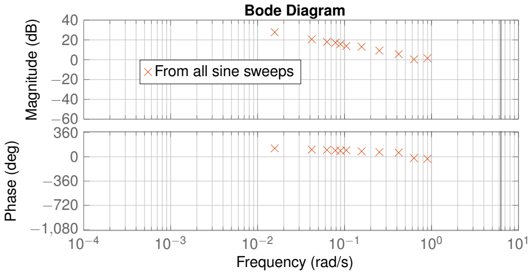
# Can the industry proposed tests be done easier?



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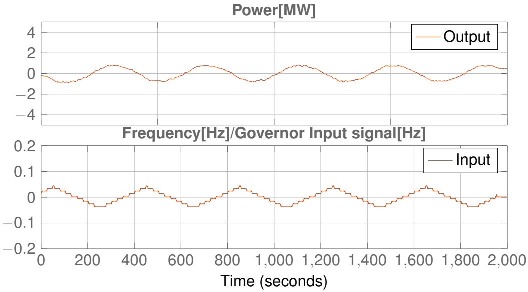
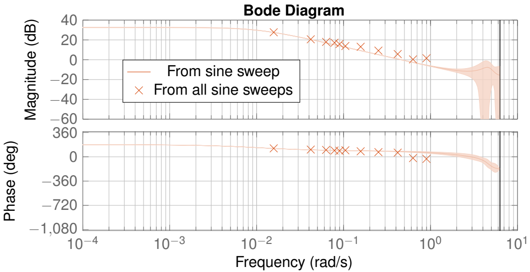
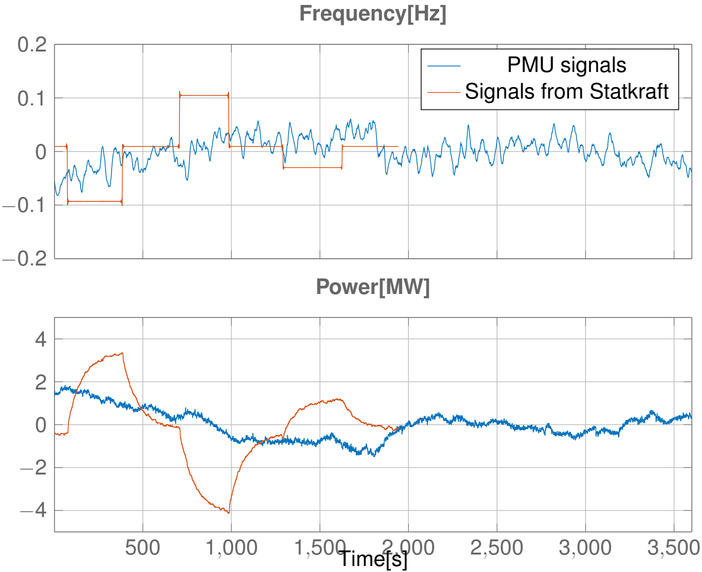
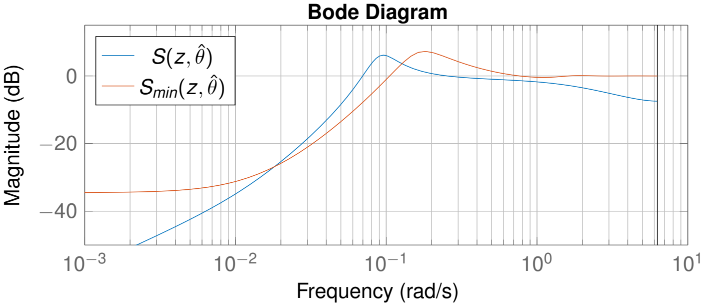


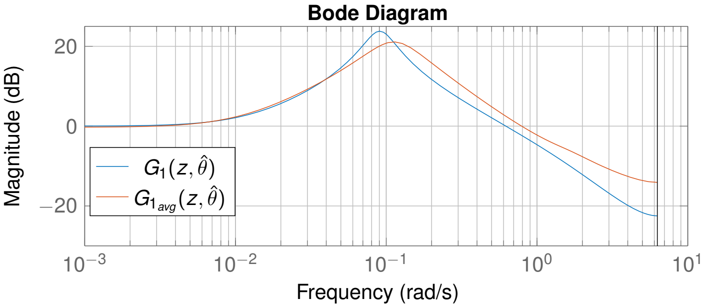
# Datasets used



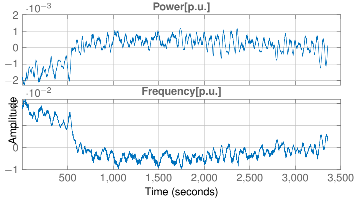
# Estimated sensitivity functions

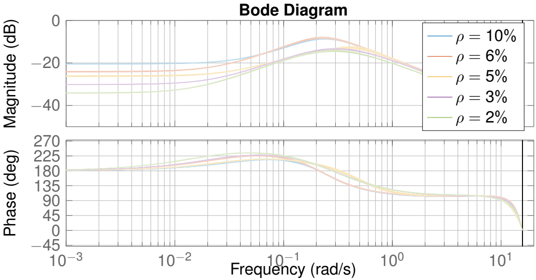


# Estimated $G_1(s)$



# Control system data in closed loop



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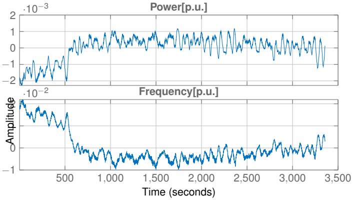


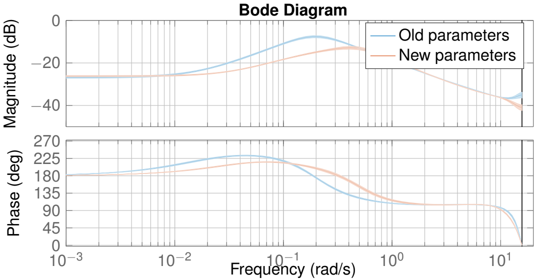

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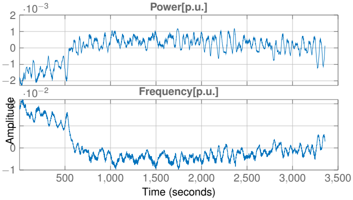


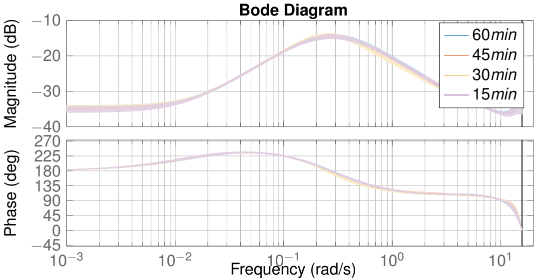

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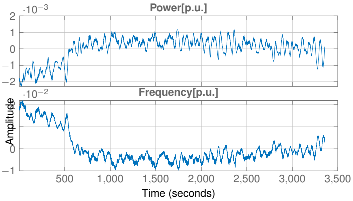


| Droop | 60min | 45min | 30min | 15min |
|---|---|---|---|---|
| 10% | 9.5% | 9.5% | 9.5% | 9.5% |
| 6% | 6.2% | 6.0% | 5.9% | 6.1% |
| 5% | 4.9% | 4.9% | 5.0% | 5.1% |
| 3% | 3.1% | 3.1% | 3.1% | 2.9% |
| 2% | 2.0% | 1.8% | 1.8% | 1.7% |

## Main Contributions

- Proposal for alternative tests.
- Demonstrating that the proposed methods can detect parameter changes.
- Demonstrated that the industry proposed tests can be done easier.

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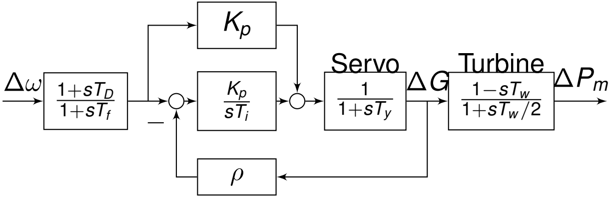
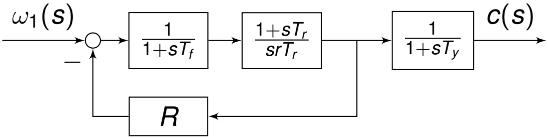
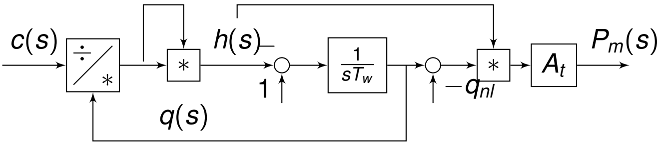
# Motivation

- Test with a more detailed power plant model.
- Test with a more detailed power system model.
- Investigate some of the assumptions from previous papers.

# More detailed power plant model



# More detailed power system model

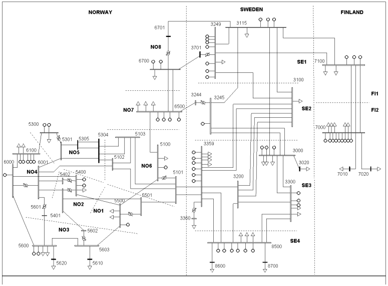
— Added the frequency divider formula to the simple test system.

$$\omega_I = \mathbf{1} + \mathbf{D}(\omega_e - \mathbf{1}) \qquad (20)$$

where

$$\mathbf{D} = -\mathbf{B}_{22}^{-1}\mathbf{B}_{21} \qquad (21)$$

# More detailed power system model

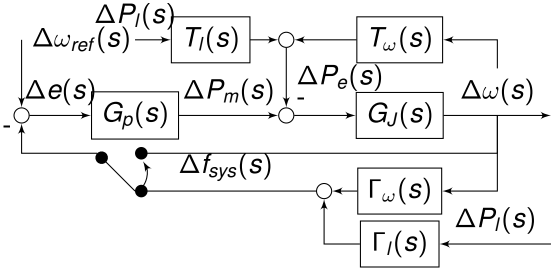



— Added the frequency divider formula to the simple test system.

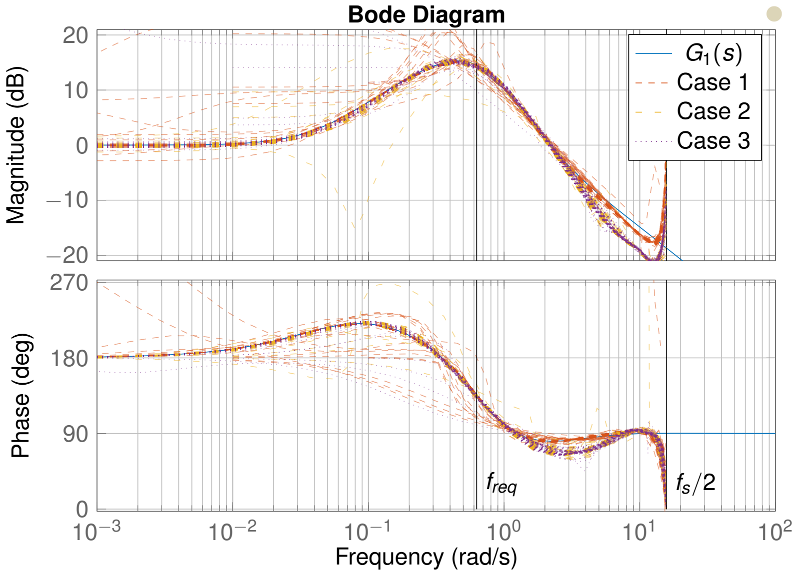
— Used the Nordic 44 test system in PSS/E.

# Identification cases

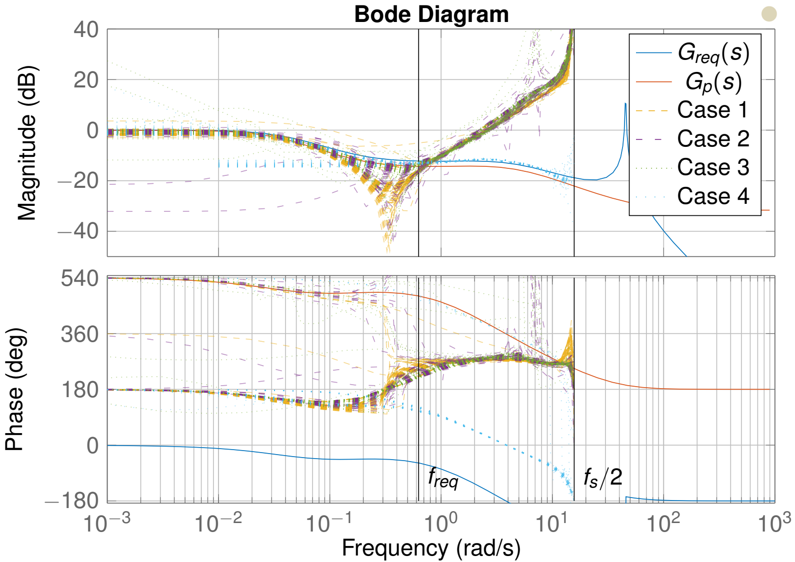
1. **Case 1** Normal operation and speed feedback.
2. **Case 2** Normal operation, speed feedback and PMU.
3. **Case 3** Normal operation, frequency feedback and PMU.
4. **Case 4** Open loop operation.



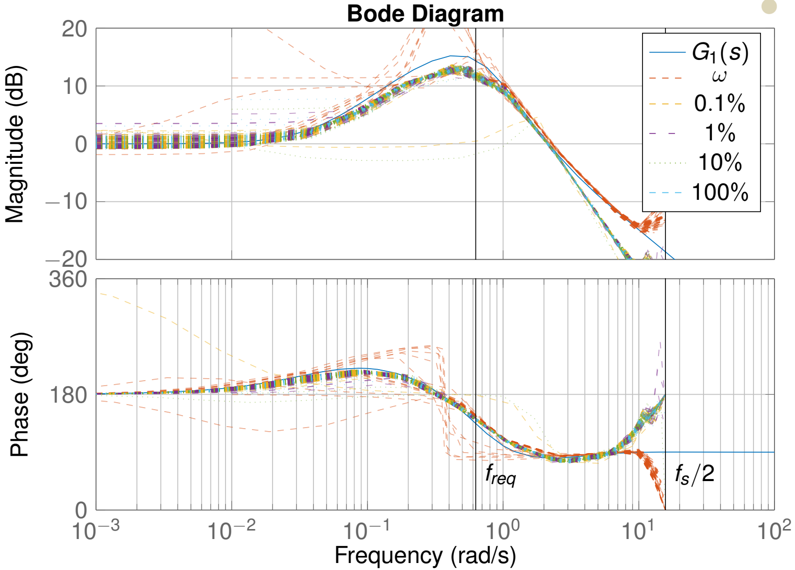
# Test the different cases



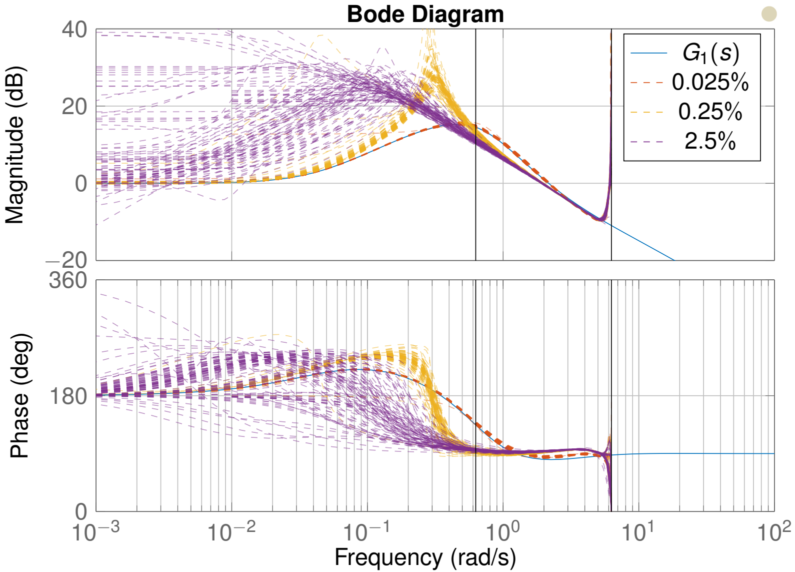
# Test the different cases



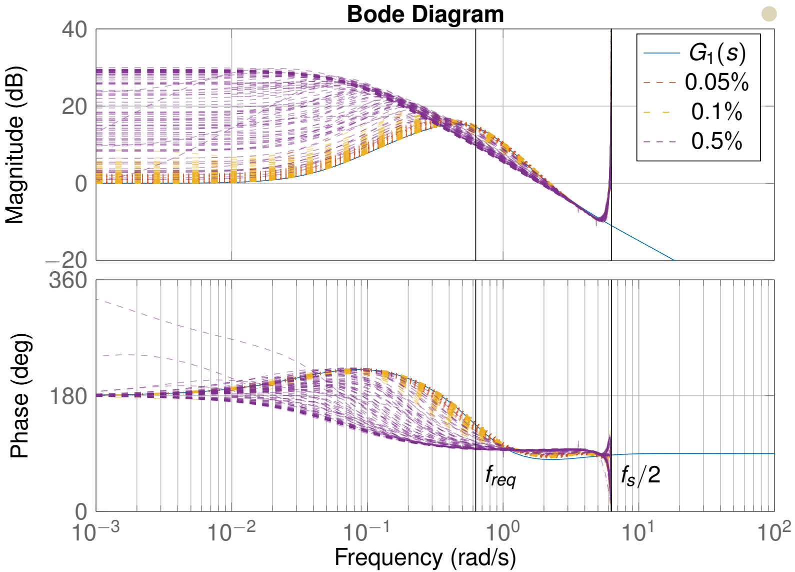
# Test frequency assumption



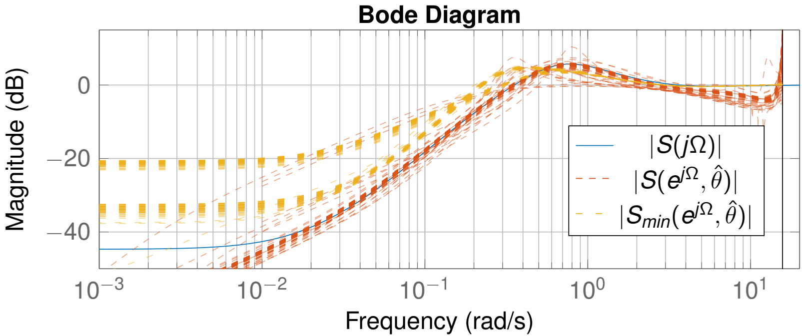
# Test backlash



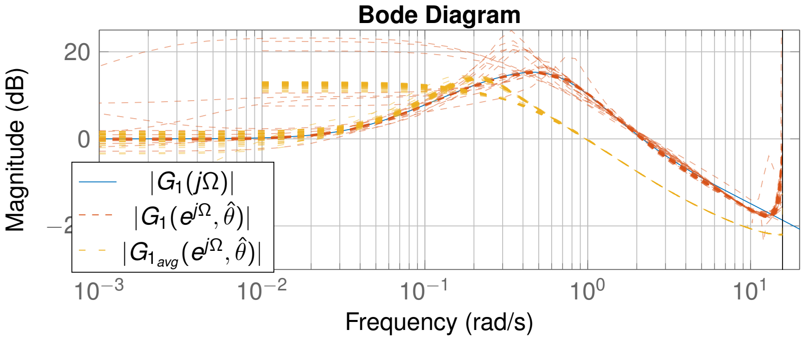
# Test deadband



# Sensitivity function $S(s)$



# Disturbance rejection function $G_1(s)$



## Comparison of stability margins

| Method | Median | Root mean square error (RMSE) |
|---|---|---|
| $\max \lvert S(j\Omega) \rvert$ | 1.84 | 0 |
| $\max \lvert S(e^{j\Omega}, \hat{\theta}) \rvert$, Case 1 | 1.84 | 0.25 |
| $\max \lvert S(e^{j\Omega}, \hat{\theta}) \rvert$, Case 2 | 1.75 | 0.34 |
| $\max \lvert S(e^{j\Omega}, \hat{\theta}) \rvert$, Case 3 | 1.74 | 0.39 |
| $\max \lvert S_{\min}(e^{j\Omega}, \hat{\theta}) \rvert$ | 1.66 | 0.25 |

## Comparison of estimated inertias

| Case | Median | RMSE |
|---|---|---|
| Actual | 3.5 | 0 |
| Case 1 | 3.40 | 0.46 |
| Case 2 | 3.33 | 0.40 |
| Case 3 | 3.27 | 0.43 |

# Major contributions

- Tested the methods with a more detailed power plant model.
- Tested the methods with a more detailed power system model.
- Investigate some of the assumptions from previous papers.

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# Motivation

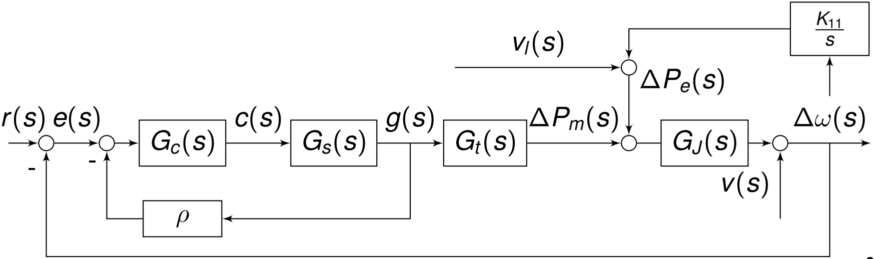
— How to best identify hydro power plant dynamics given access to control system data.

# Systems to be identified

$$e(s) = G_1(s)\Delta P_{e1}(s) + S(s)r(s) \tag{22}$$

$$\Delta\omega_1(s) = G_s(s)G_t(s)G_J(s)c(s) - G_J(s)\Delta P_{e1}(s) \tag{23}$$

$$G_p(s) = \frac{G_c(s)G_s(s)G_t(s)G_J(s)}{G_J(s)(1+\rho G_c(s)G_s(s))} \tag{24}$$



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— Two approaches.

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— Two approaches.

— Extra excitation is needed.

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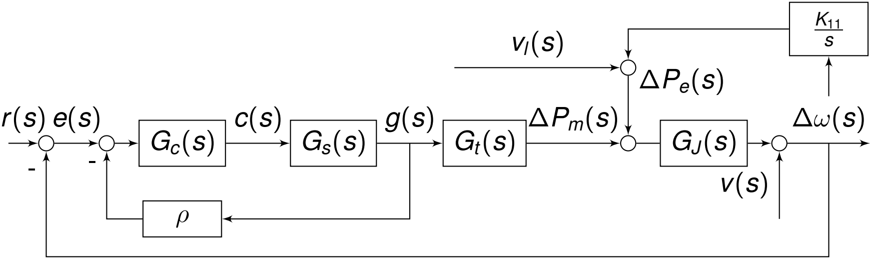
— Two approaches.

— Extra excitation is needed.

— PMU approach is a special case without extra excitation.

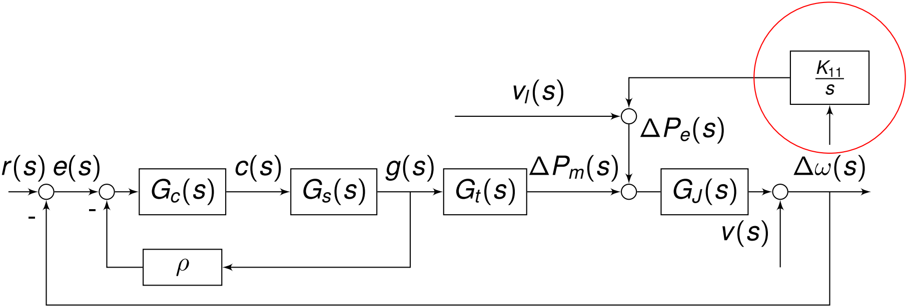
# Identifiability

— The systems can be identified



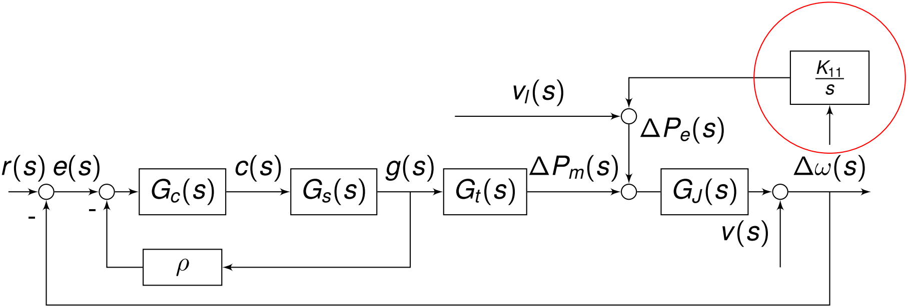
# Identifiability

- The systems can be identified
- However, there is a lack of delay



# Identifiability

- The systems can be identified
- However, there is a lack of delay
- This is no problem if $v(s) << v_l(s)$.



# Identifying $G_p(s)$ and $G_J(s)$

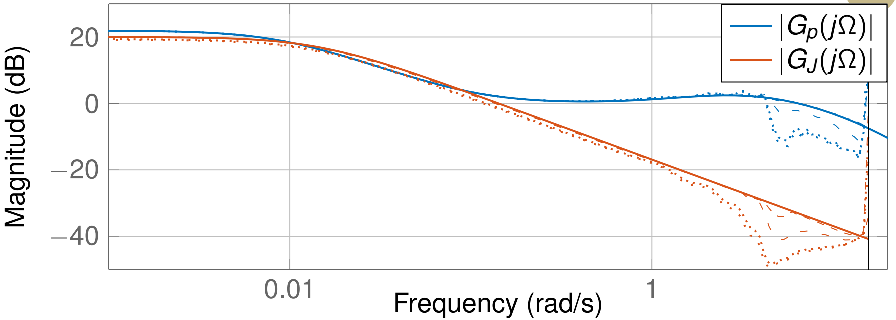



Figure: The mean value of $|G_p(e^{j\Omega}, \hat{\theta}_N)|$ and $|G_J(e^{j\Omega}, \hat{\theta}_N)|$ calculated from the MCS. The solid lines are the analytical calculated versions and the dashed loosely dashed dotted and loosely dotted lines represent an SNR of $50dB$, $26dB$, $6dB$, and $3dB$ respectively

# Identifying $S(s)$

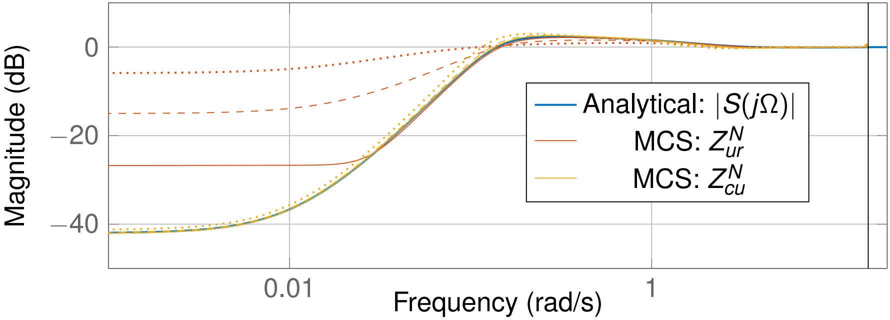



Figure: The mean value of $|S(e^{j\Omega}, \hat{\theta}_N)|$ calculated analytical and from the MCS. The solid, dashed and dotted lines represent an SNR of $50dB$, $26dB$, and $6dB$ respectively

# Identifying $G_1(s)$

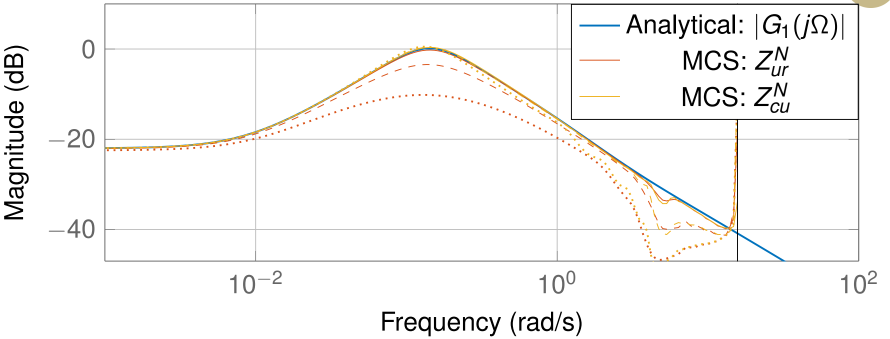



Figure: The mean value of $|G_1(e^{j\Omega}, \hat{\theta}_N)|$ calculated analytical and from the MCS. The solid, dashed and dotted lines represent an SNR of $50dB$, $26dB$, and $6dB$ respectively

# Major contributions

— Demonstrated two methods for finding transfer functions for checking the requirements in closed loop.

— Analytical validation of the demonstrated methods.

— Addressed the delay condition.

# Outline

Problem

Initial tests using time domain vector fitting Paper I

Development of a simple test system Paper II

Theoretical validation of the PMU approach Paper III

Comparison of a PMU-based approach and the draft requirements approach using tests from two of Statkraft's power plants Paper IV

An extension of Paper IV, with more discussion, simulation comparisons and more simulation validations Paper V

Checking the requirements using measurements from the control system of a hydro power plant Paper VI

# Conclusions

- The requirements can be checked using PMU-measurements, however, the results will be biased for faster dynamics.
- The requirements can be checked using control system measurements in normal operation, however, the results may be biased for faster dynamics.
- The requirements can be checked using measurement from normal operation with extra excitation

# Further work

- Validate approaches in the lab
- Solve the delay condition.
- Handle backlash.
- Investigate the alternative requiremens.