NTNU
Norwegian University of
Science and Technology

Frequency control and stability requirements on hydro power plants

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October 24, 2019

Outline

Problem

Methodology Paper I

Simple test system Paper II

Theoretical validation Paper III

Tests at Statkraft's power plants Paper IV

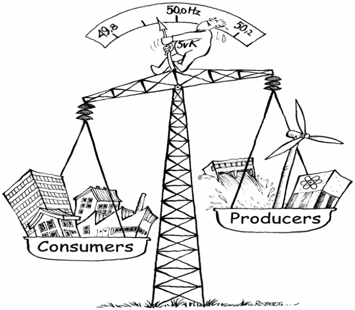
Simulation studies Paper V

The best way to do the identification Paper VI

Conclusions and further work

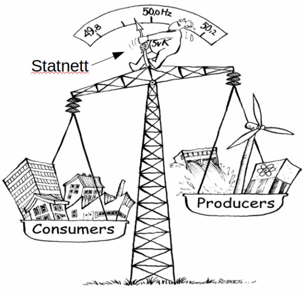
Load and production balancing

— The power system frequency measures the power balance.



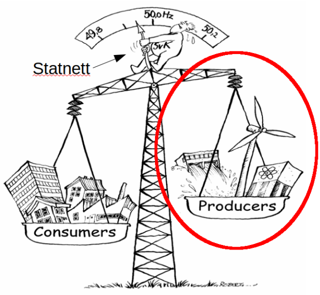
Load and production balancing

- 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.(droop $\rho = \Delta f / \Delta P$)

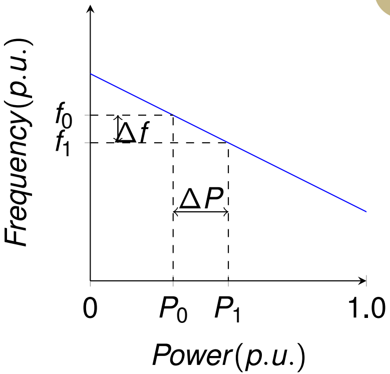


Figure: Frequency control response to step change in frequency

Buying frequency control

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- However, the system is not in steady state.

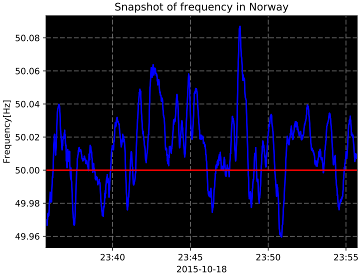

Figure: Frequency control response to step change in frequency

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- Plants with the same droop settings don't have to behave the same.

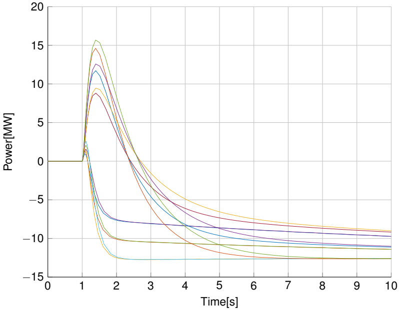


Figure: Frequency control response to step change in frequency

Buying frequency control

- Statnett pays all power plant owners to provide frequency control.(droop $\rho = \Delta f / \Delta P$)
- However, the system is not in steady state.
- Plants with the same droop settings don't have to behave the same.
- Renewable energy sources such as wind and solar don't contribute.

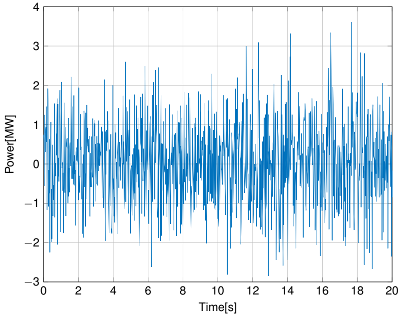
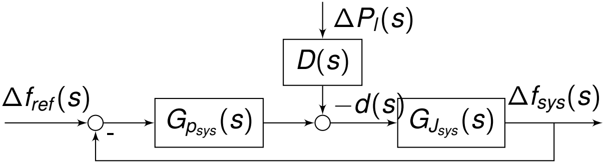


Figure: Frequency control response to step change in frequency

New requirements for frequency control

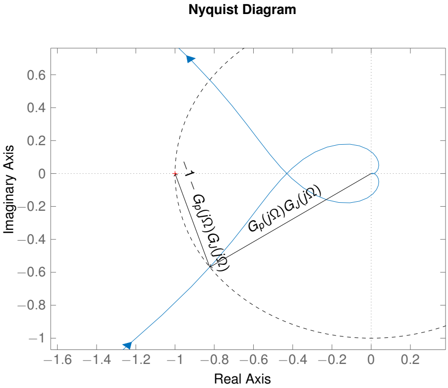
— Puts requirements on an aggregated system model.



New requirements for frequency control

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

$$
\begin{aligned}
M_s &= \max \left| \frac{1}{1 + G_p(j\Omega)G_J(j\Omega)} \right| \\
&= \max |S(j\Omega)| \qquad (1)
\end{aligned}
$$



New requirements for frequency control

- Puts requirements on an aggregated system model.
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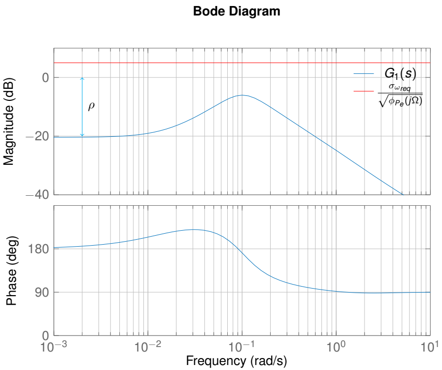
$$M_s = \max\left|\frac{1}{1+G_p(j\Omega)G_J(j\Omega)}\right| = \max|S(j\Omega)| \quad (1)$$

- Performance requirement

$$|G_1(j\Omega)| < \frac{\sigma_{\omega req}}{\sqrt{\phi_{P_e}(j\Omega)}} \quad (2)$$

$$G_1(s) = S(s)G_J(s) \quad (3)$$



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- Requirement per plant stated using a per unit conversion

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.

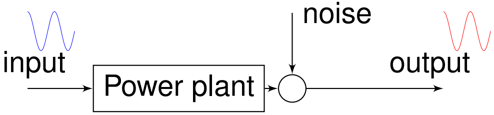
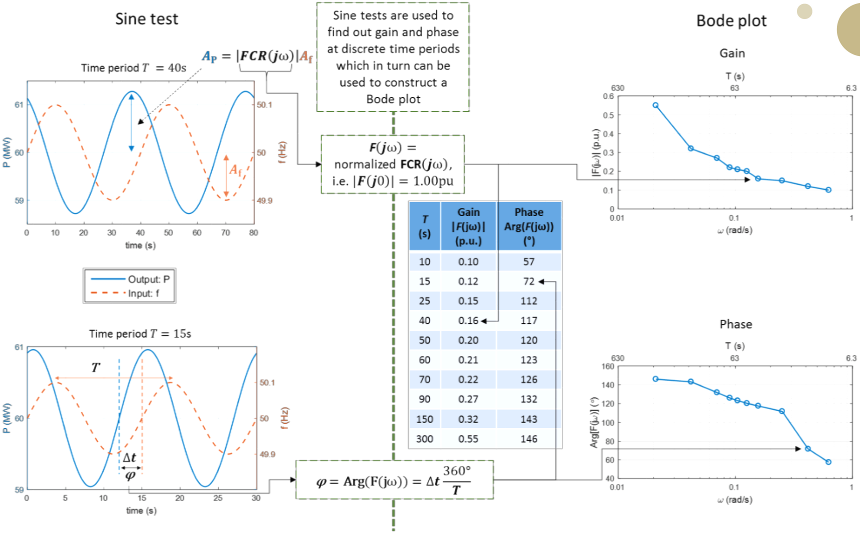


Figure: Test of power plant

Tests proposed by the industry

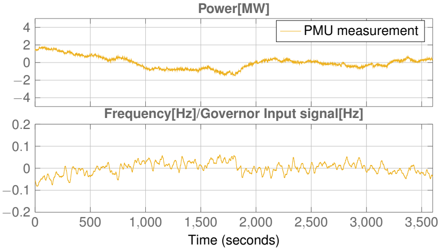


T (s)	Gain $\lvert F(j\omega)\rvert$ (p.u.)	Phase Arg($F(j\omega)$) (°)
10	0.10	57
15	0.12	72
25	0.15	112
40	0.16	117
50	0.20	120
60	0.21	123
70	0.22	126
90	0.27	132
150	0.32	143
300	0.55	146

Figure: Testing procedure [source:ENTSO-E]

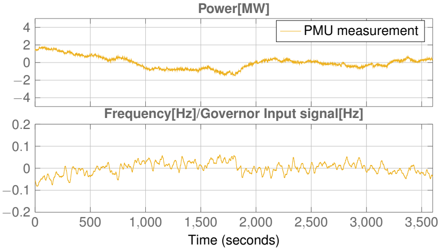
Motivation

— The power system is never really in steady state.



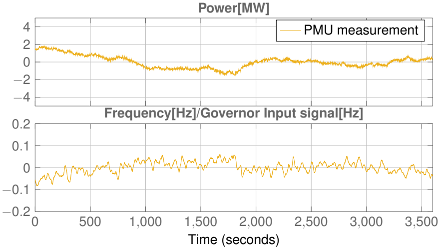
Motivation

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



Research questions

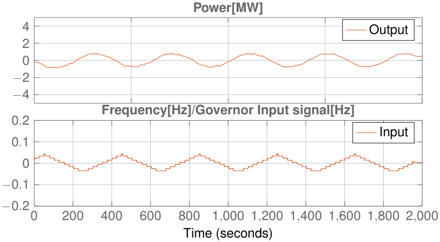
— Can power plant dynamics be identified using a PMU?



Research questions

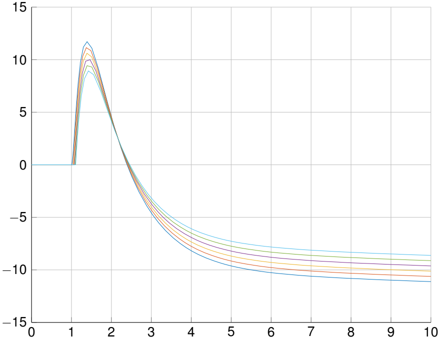
— Can power plant dynamics be identified using a PMU?

— 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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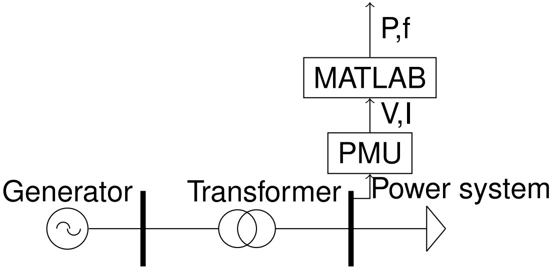
Conclusions and further work

Background

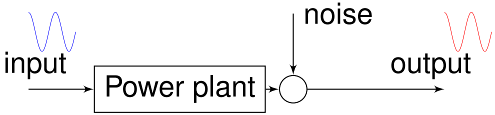
- Idea from[1] can the power plant dynamics be identified using PMUs



[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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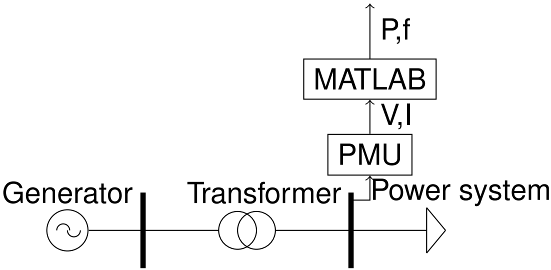
Methodology

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



Vector fitting basics

$$Y(s) = H(s) \cdot U(s) \tag{4}$$

— 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.

$$Y(s) = H(s) \cdot U(s) \tag{4}$$

$$H(s) = d + \sum_{i=1}^{n_p} \frac{r_i}{s - p_i} \tag{5}$$

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.

$$Y(s) = H(s) \cdot U(s) \tag{4}$$

$$H(s) = d + \sum_{i=1}^{n_p} \frac{r_i}{s - p_i} \tag{5}$$

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

$$x_i = \int_0^t e^{\tilde{p}_i(t-\tau)} x_i(\tau) d\tau \tag{7}$$

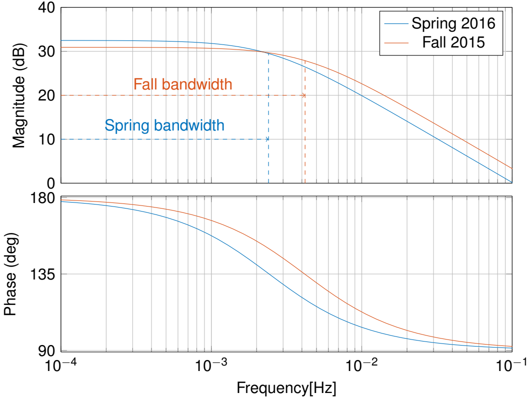
$$y_i = \int_0^t e^{\tilde{p}_i(t-\tau)} y_i(\tau) d\tau \tag{8}$$

Vector fitting basics ctd.

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

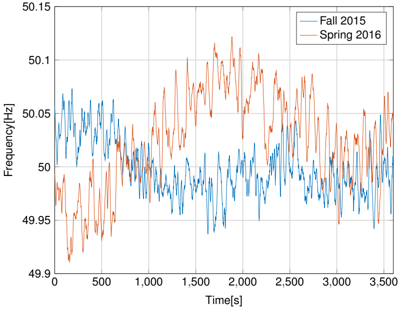
$$y(t) - (\tilde{d}x(t) + \sum_{i=1}^{n_p} \tilde{r}_i x_i - \sum_{i=1}^{n_p} \tilde{k}_i y_i) \tag{9}$$

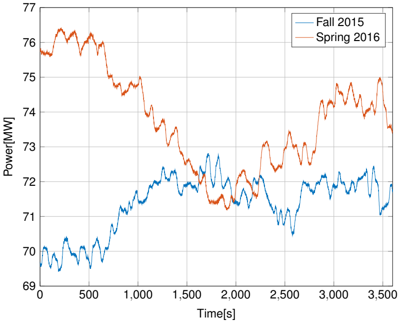
Estimated droop and bandwidth



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

Cross validation using distant data sets





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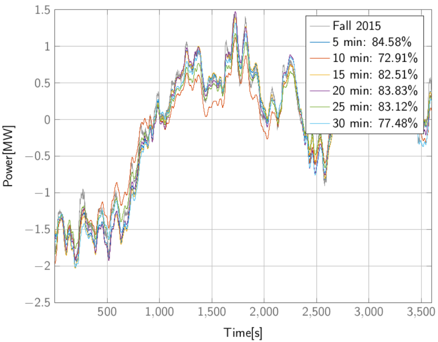
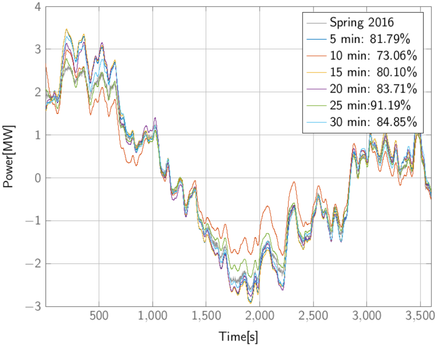
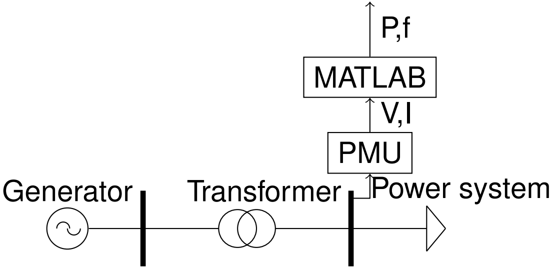




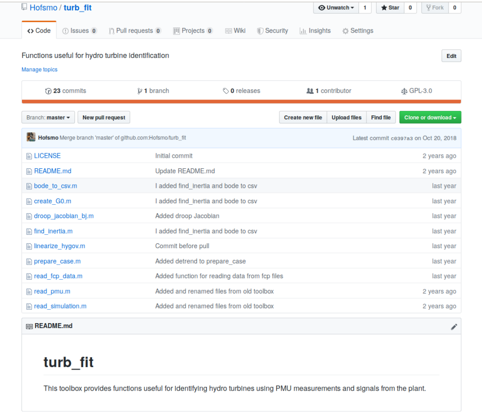
Main contributions to the research questions

— 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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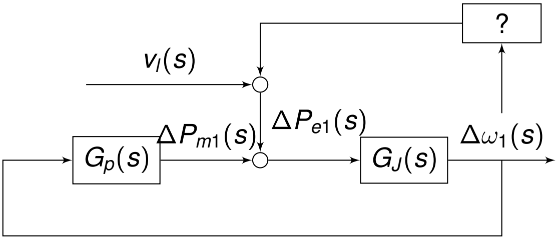
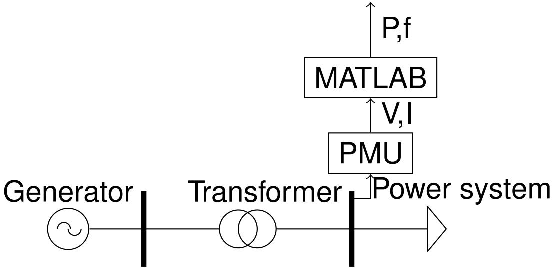
Motivation

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



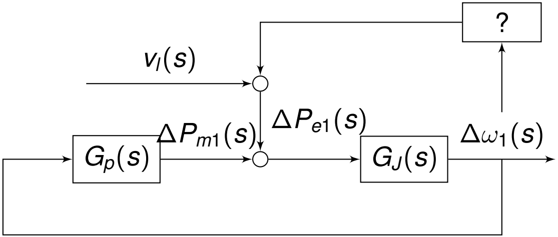
What do we need to model?

— 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?

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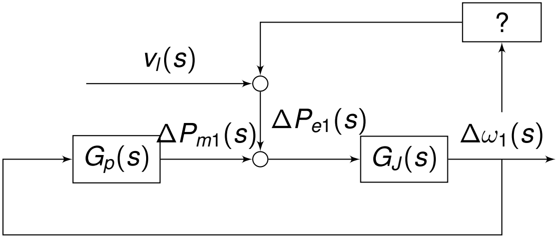
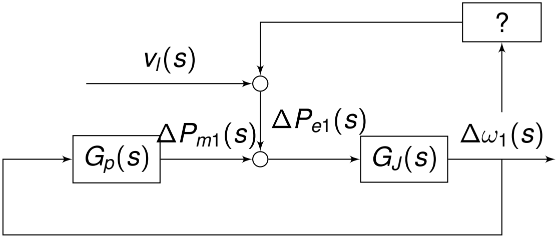
- Power: $\Delta P_{e1}(s)$.
- Frequency: $\Delta f(s)$.



What do we need to model?

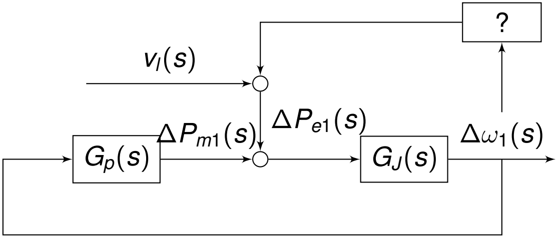
— From the PMU we get
- Power: $\Delta P_{e1}(s)$.
- Frequency: $\Delta f(s)$.

— 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?

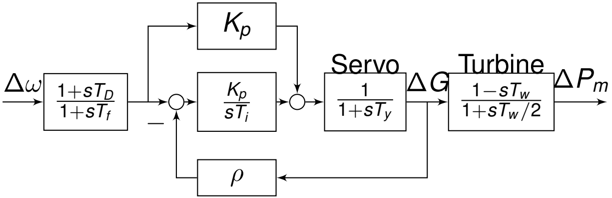
- From the PMU we get
  - Power: $\Delta P_{e1}(s)$.
  - Frequency: $\Delta f(s)$.
- We need to model how $\Delta P_{e1}(s)$ and $\Delta f(s)$ is related through the power system.
- We also need to model the power plant consisting of $G_p(s)$ and $G_J(s)$.



Power plant model

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

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



Power system model

— The frequency and power system angle is related.

$$\Delta\theta(s) = \frac{2\pi f_s}{s} f(s) \tag{11}$$

Power system model

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

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$$P_k \approx \sum_{m \in \Omega_k} x_{km}^{-1} \theta_{km} \tag{12}$$

Power system model

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

$$\Delta\theta(s) = \frac{2\pi f_s}{s} f(s) \tag{11}$$

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$$\mathbf{P} = \mathbf{Y}\theta \tag{13}$$

Power system model

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

$$\Delta\theta(s) = \frac{2\pi f_s}{s} f(s) \tag{11}$$

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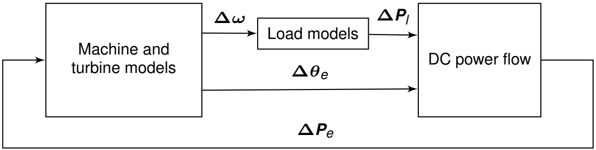


Test system

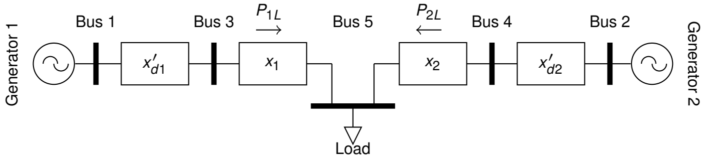
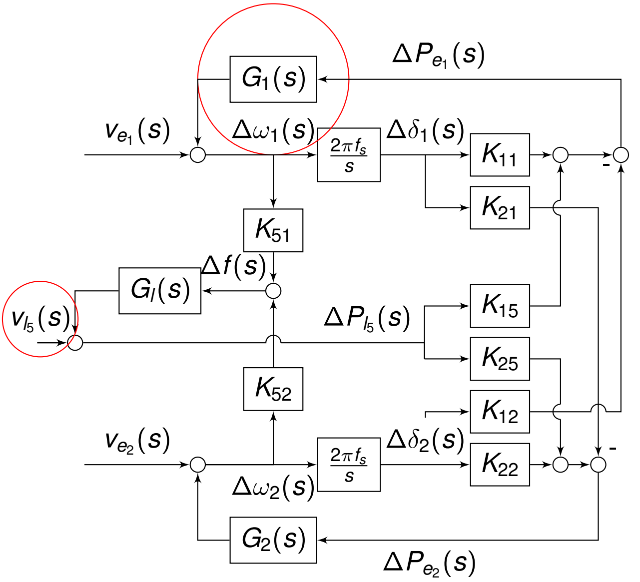


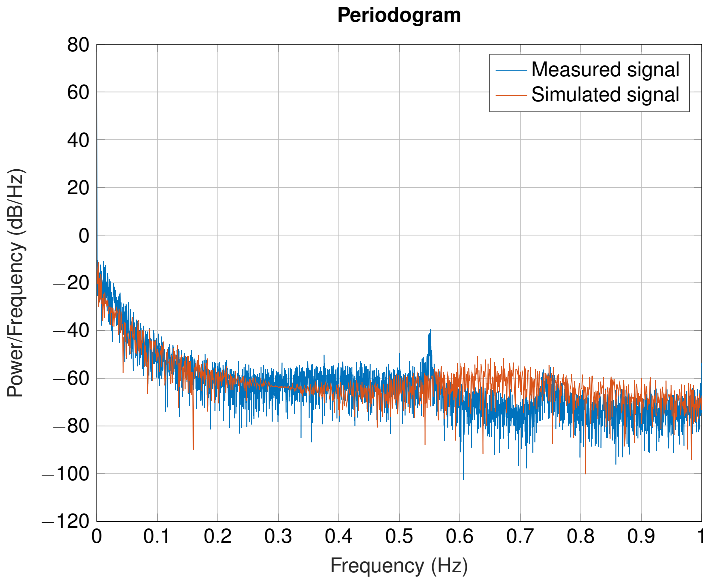
Figure: Single line diagram

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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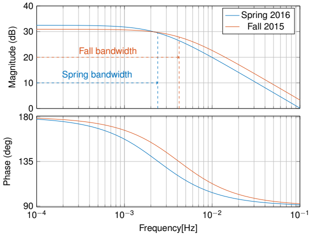
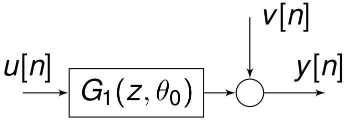
— Why do we get different results?



Background

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



Background

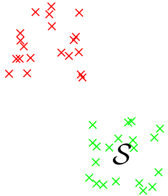
- Why do we get different results?
- The signals we use are corrupted by noise.
- From system identification we have that the error will be asymptotic normally distributed

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

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

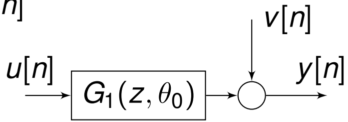
True system: $\mathcal{S}$
x: unbiased
x: biased



System identification basic

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

$$\mathcal{S} : y[n] = G_1(z, \theta_1)u[n] + H_1(z, \theta_1)e[n] \tag{14}$$



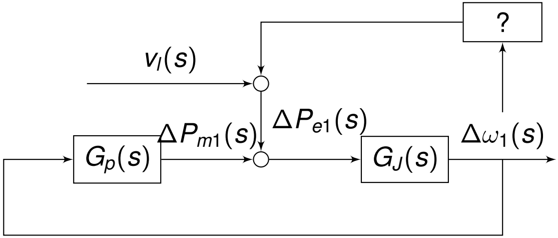
- Using the data set Z^N we want to find the parameter vector θ^N minimizing

$$\hat{\theta}_N = \arg\min_{\theta} \frac{1}{N} \sum_{n=1}^{N} [H_1^{-1}(z, \theta)(y[n] - G_1(z, \theta)u[n])]^2 \tag{15}$$

Modeling used for the validation

— The system we are identifying

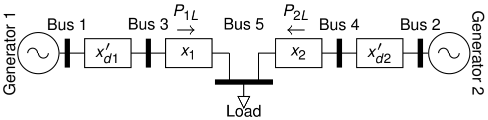
$$G_1(s) = \frac{G_p(s)}{1 + G_p(s)G_J(s)} \tag{16}$$



Modeling used for the validation

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

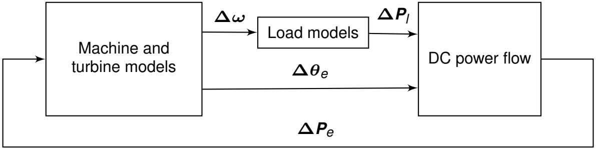
(16)



Modeling used for the validation

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

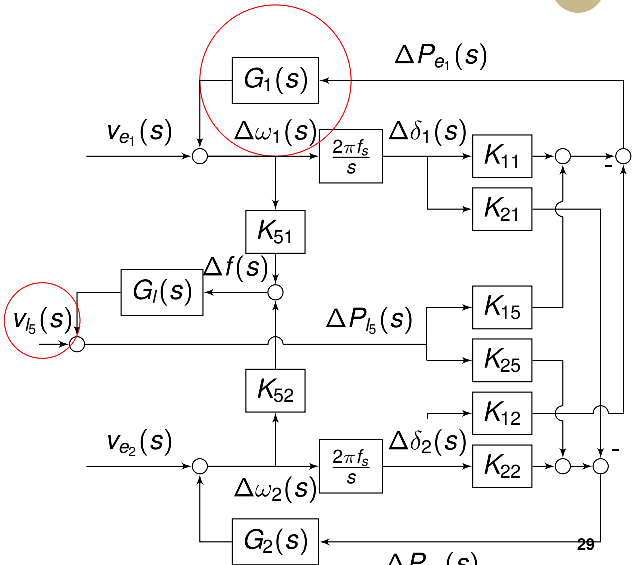
(16)



Modeling used for the validation

(16)

- 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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- Measured PMU frequency as the output $u[n]$

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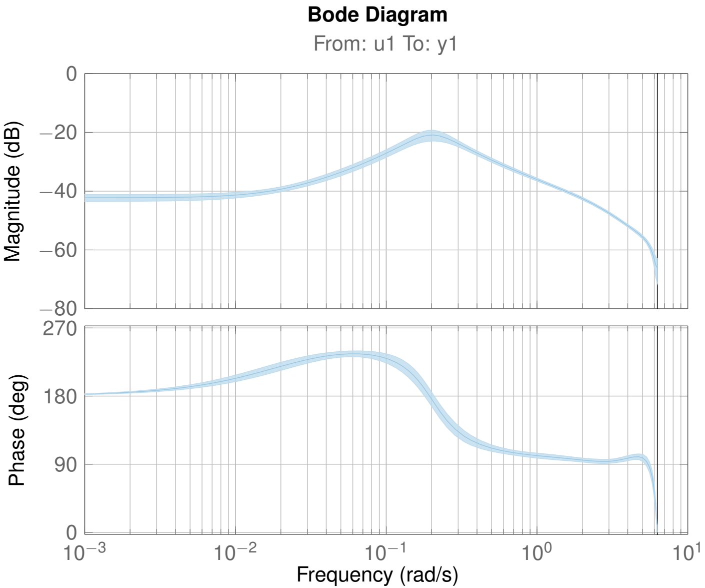
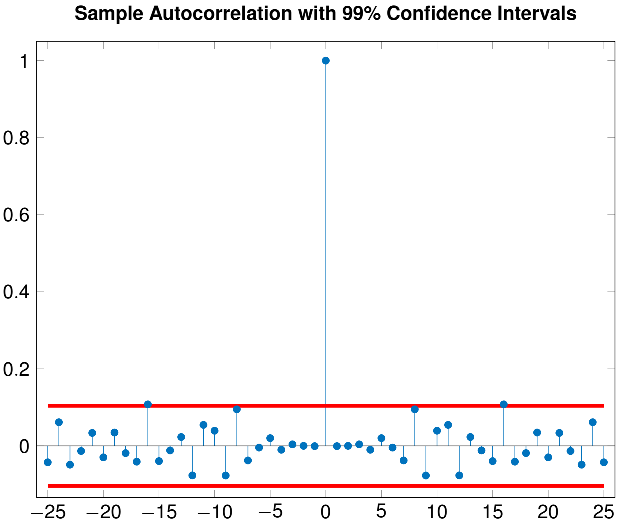
Results from the theoretical validation

- 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

Problem

Methodology Paper I

Simple test system Paper II

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Simulation studies Paper V

The best way to do the identification Paper VI

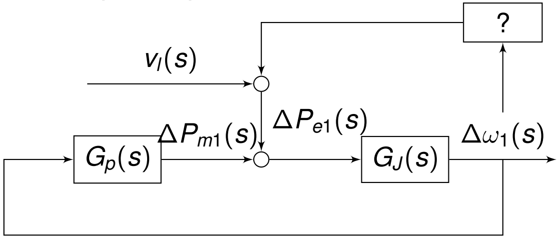
Conclusions and further work

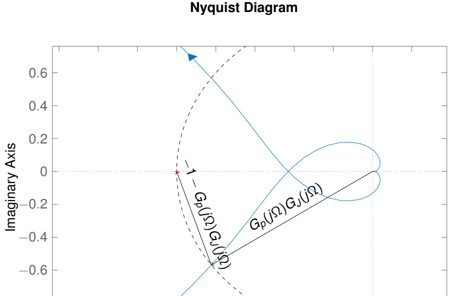
Motivation

- 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.

Alternative requirements

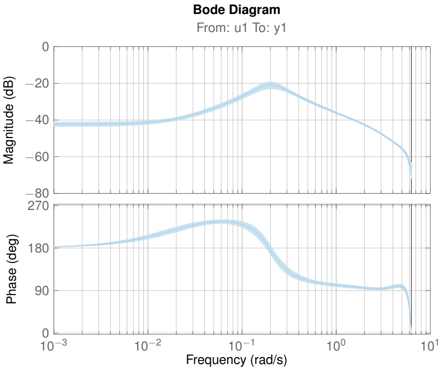
— Place requirements directly on one power plant.





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 $S(s)$

—

$$G_1(s) = G_J(s)S(s) \tag{17}$$

Estimating $S(s)$

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$$G_J(s) = \frac{1}{2Hs + K_d} \tag{18}$$

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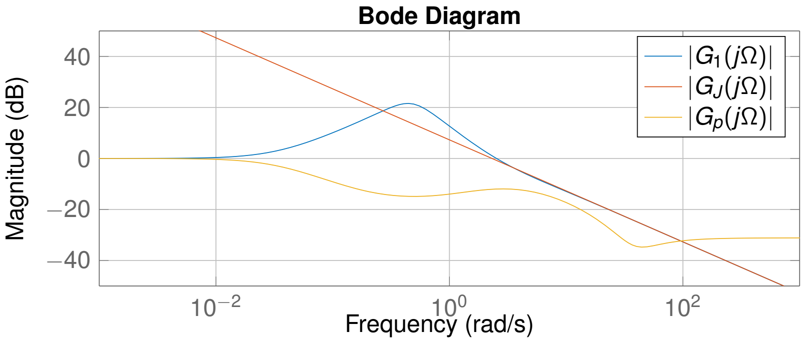
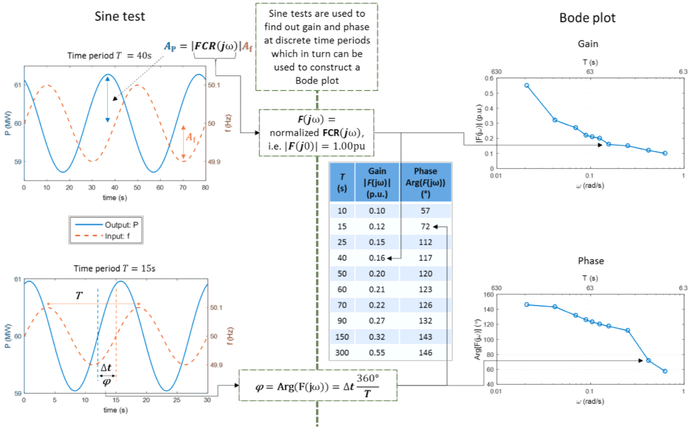
— Need to estimate H

Estimating H



Dataset from Statkraft

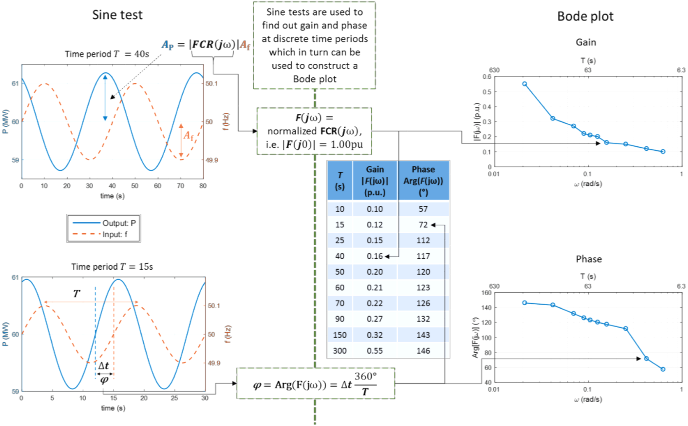
— Norway's biggest power producers.



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

- Norway's biggest power producers.
- They performed the tests from the draft requirements



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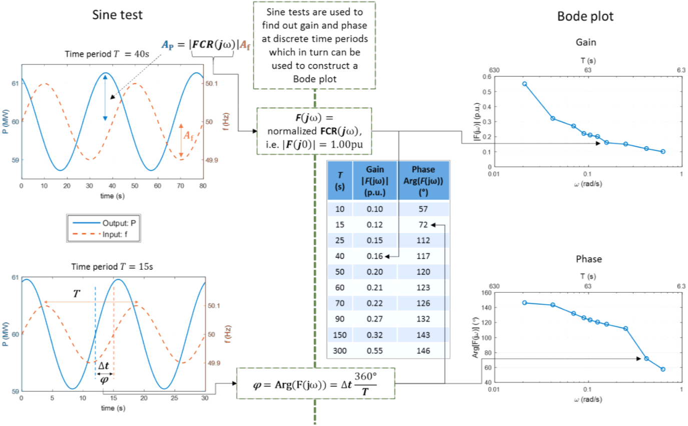
Dataset from Statkraft

- 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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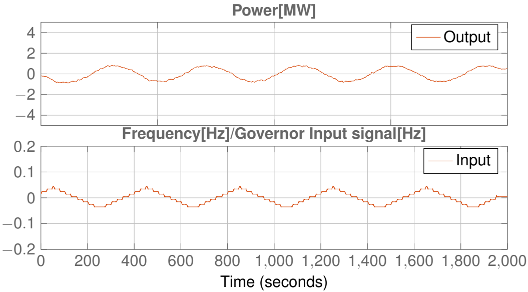
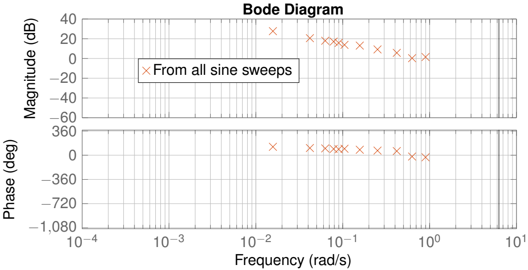
Can the industry proposed tests be done easier?





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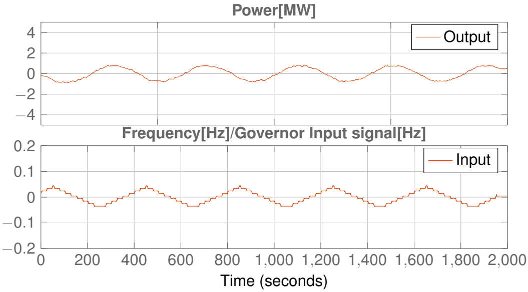
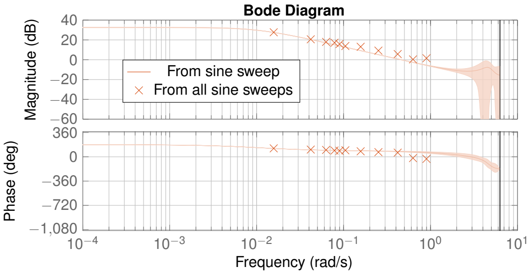
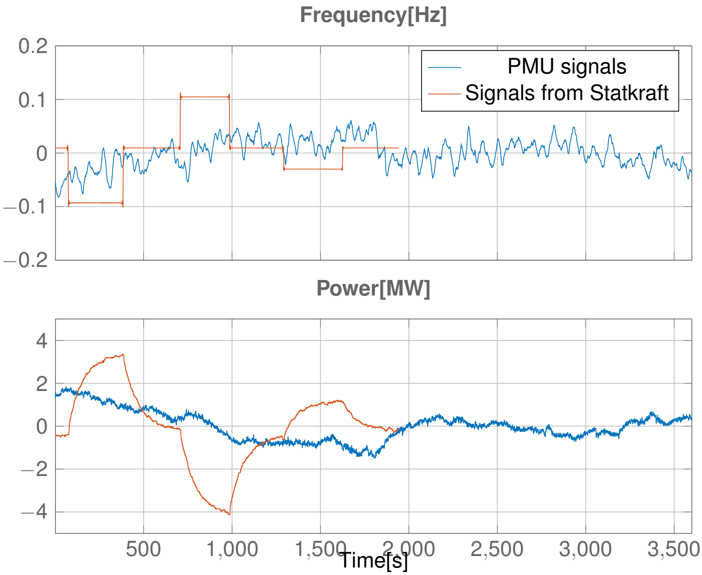
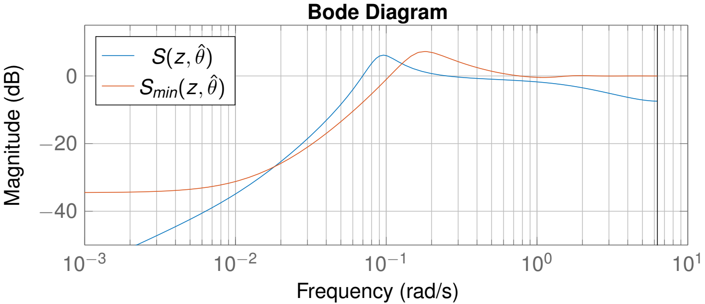




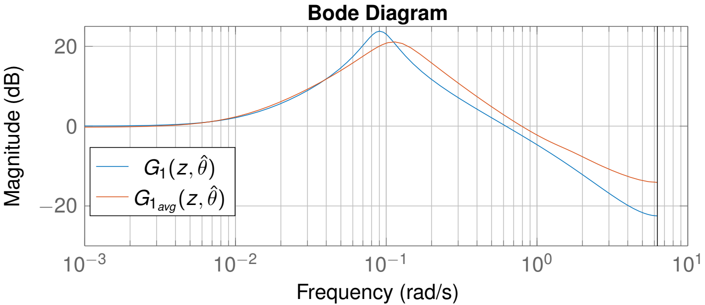
Datasets used



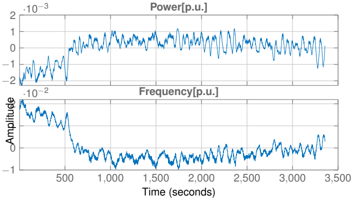
Estimated sensitivity functions

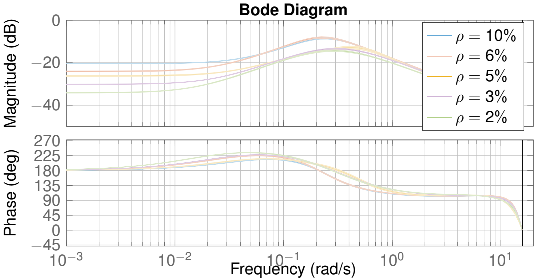


Estimated $G_1(s)$



Control system data in closed loop





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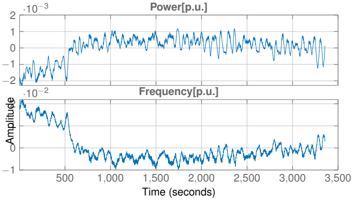

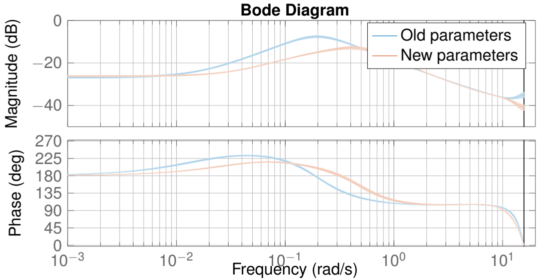

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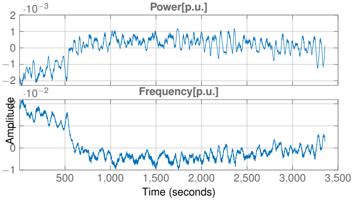
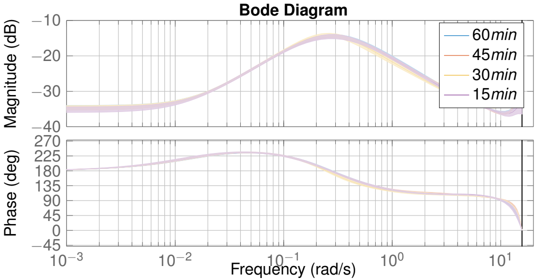
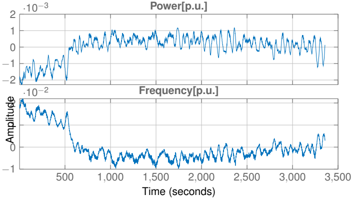




Control system data in closed loop



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.

Outline

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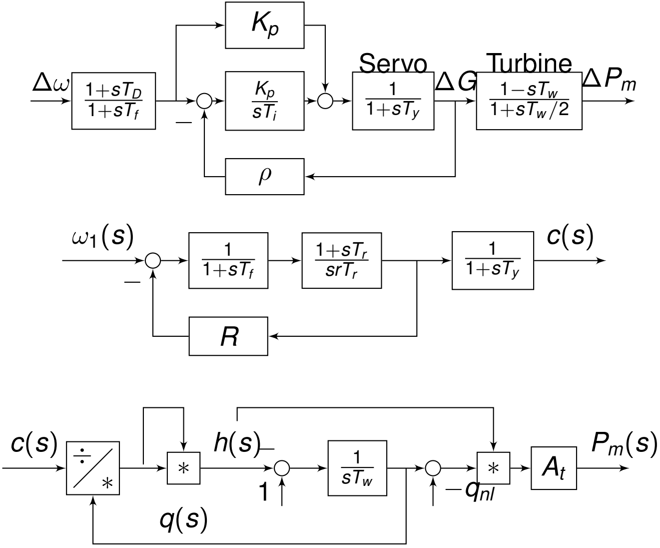
Conclusions and further work

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

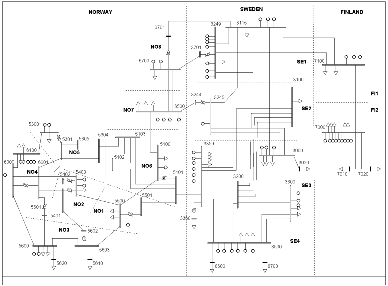
— Added the frequency divider formula to the simple test system.

$$\omega_l = \mathbf{1} + \mathbf{D}(\omega_e - \mathbf{1}) \qquad (21)$$

where

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

More detailed power system model

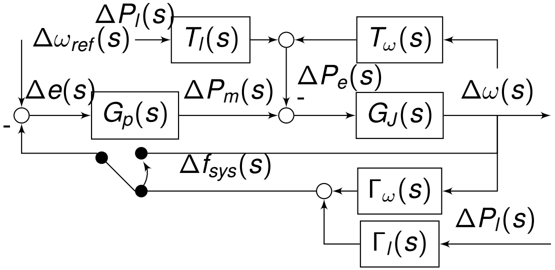


— Added the frequency divider formula to the simple test system.

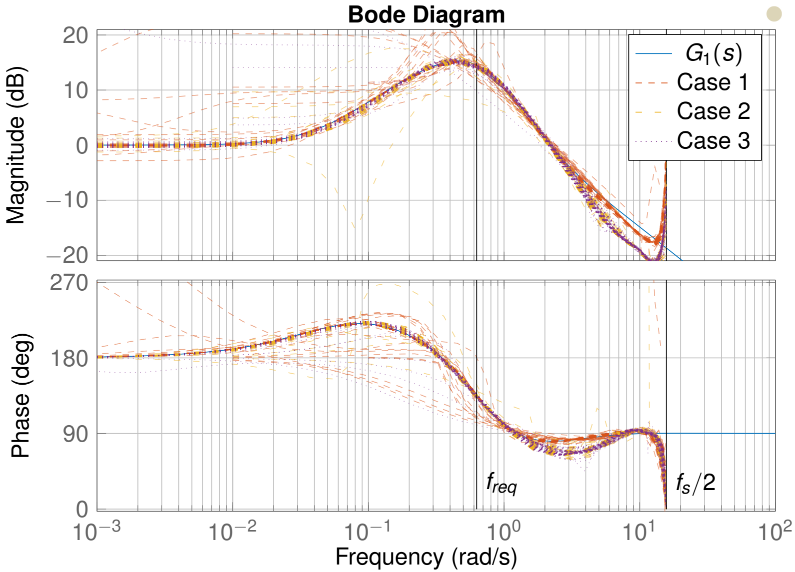
— Used the Nordic 44 test system in PSS/E.

Identification cases

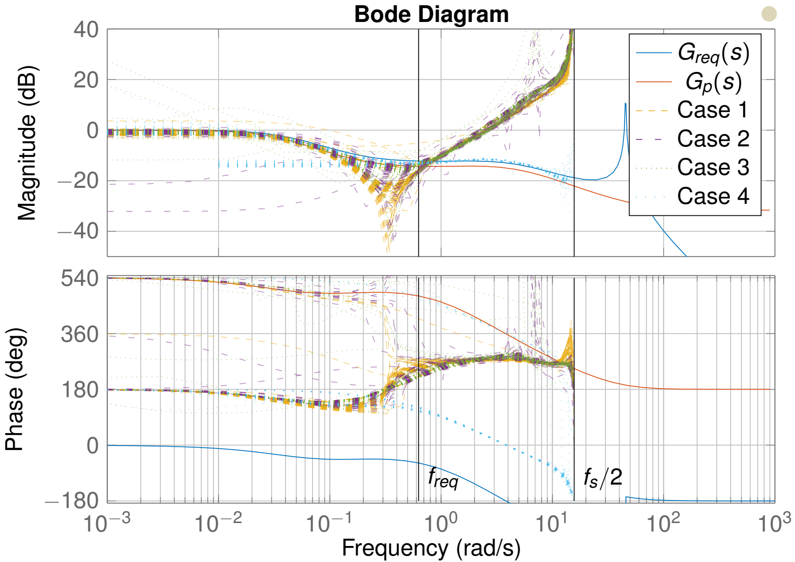
1. **Case 1** Normal operation and speed feedback.
2. **Case 2** Normal operation, speed feedback and PMU.
3. **Case 3** Normal operation, frequency feedback and PMU.
4. **Case 4** Open loop operation.



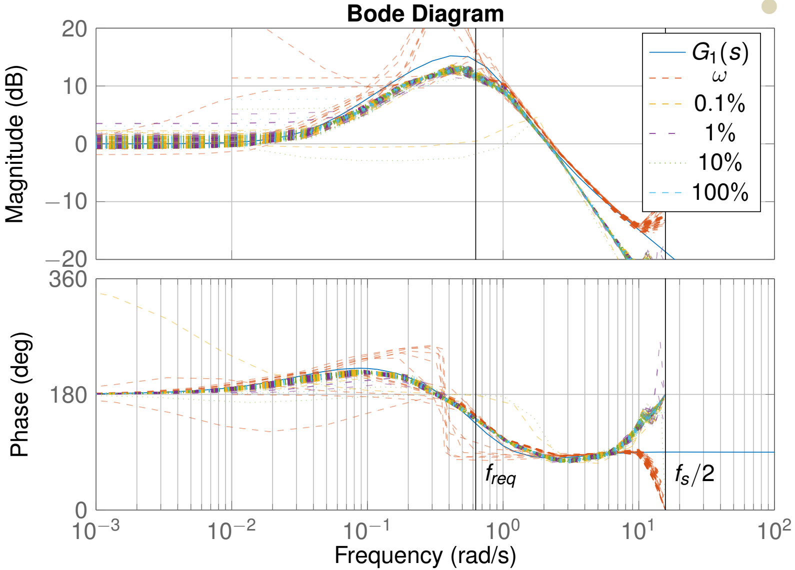
Test the different cases



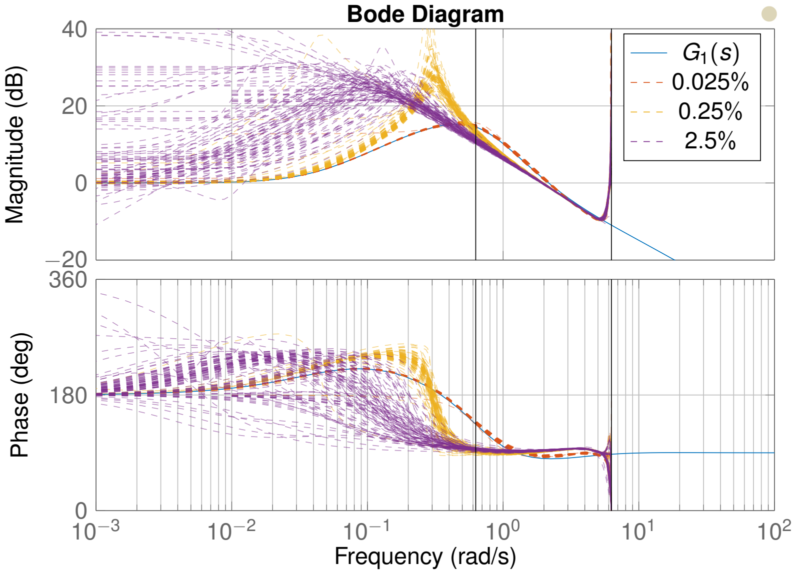
Test the different cases



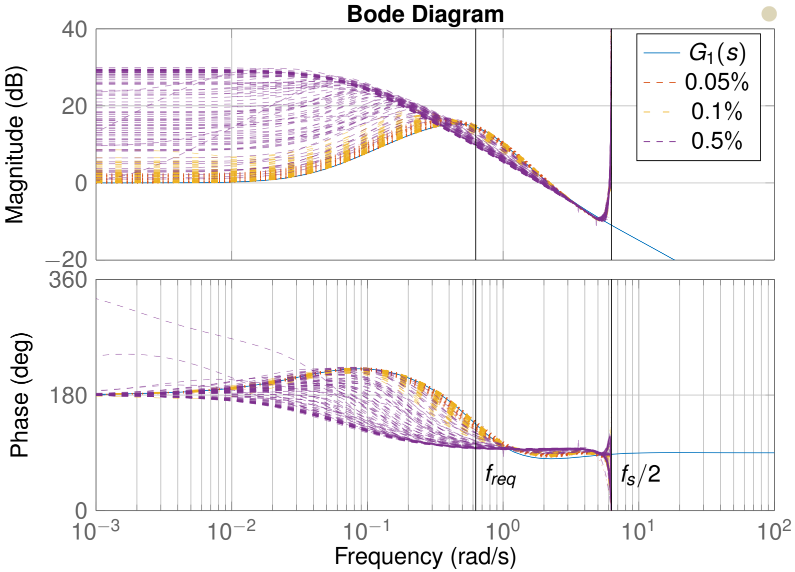
Test frequency assumption



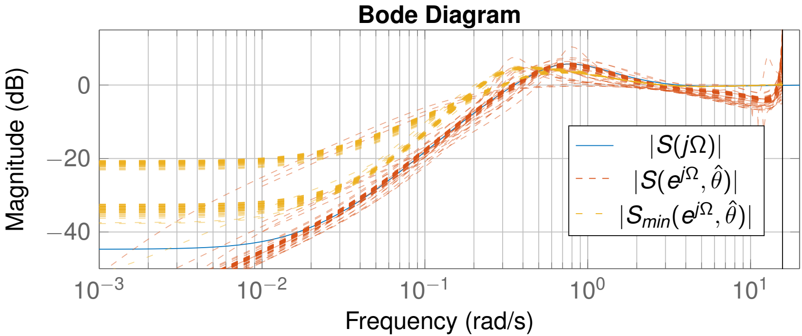
Test backlash



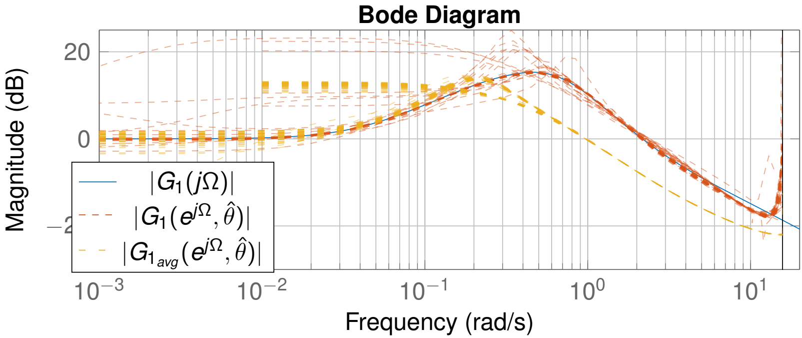
Test deadband



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

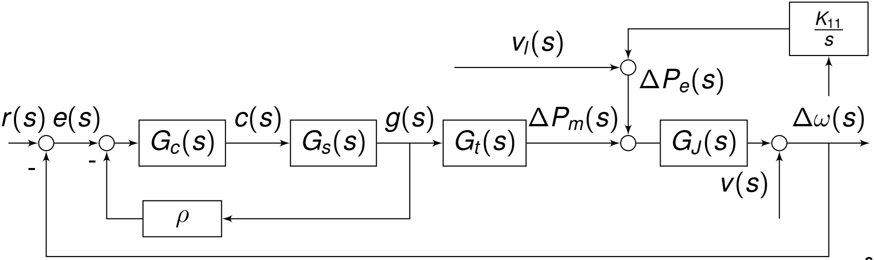
— How to best identify hydro power plant dynamics given access to control system data.

Systems to be identified

$$e(s) = G_1(s)\Delta P_{e1}(s) + S(s)r(s) \tag{23}$$

$$\Delta\omega_1(s) = G_s(s)G_t(s)G_J(s)c(s) - G_J(s)\Delta P_{e1}(s) \tag{24}$$

$$G_p(s) = \frac{G_c(s)G_s(s)G_t(s)G_J(s)}{G_J(s)(1+\rho G_c(s)G_s(s))} \tag{25}$$



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— Two approaches.

Systems to be identified

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— Two approaches.

— Extra excitation is needed.

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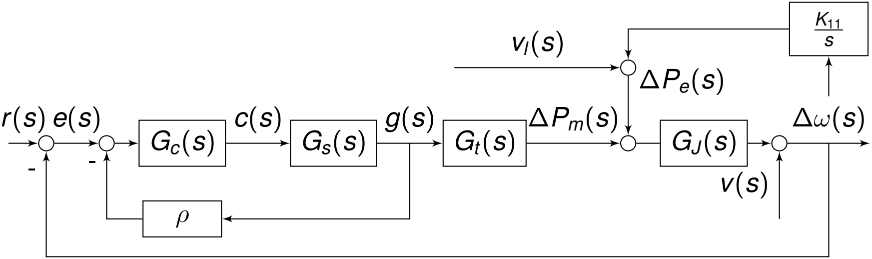
— Two approaches.

— Extra excitation is needed.

— PMU approach is a special case without extra excitation.

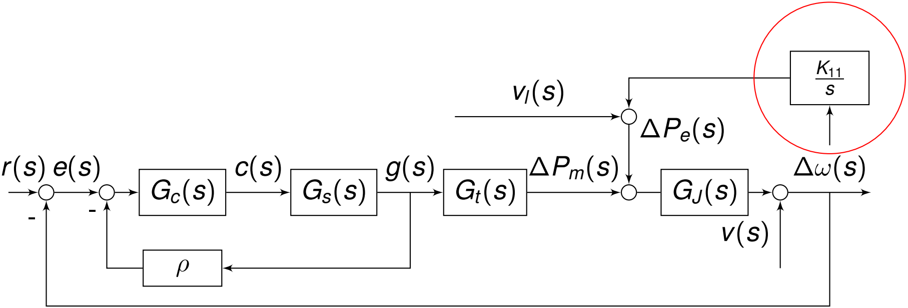
Identifiability

— The systems can be identified



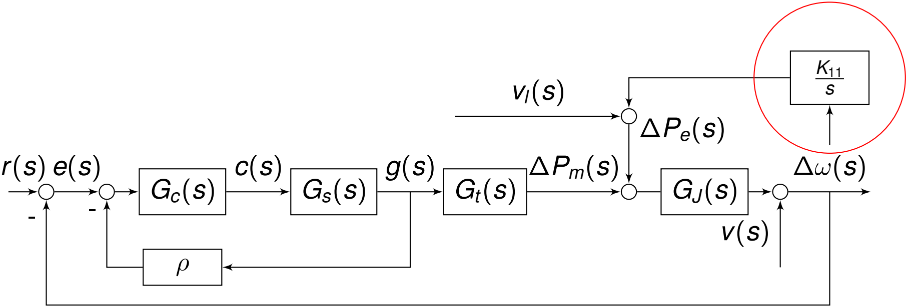
Identifiability

- 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 $G_J(s)$

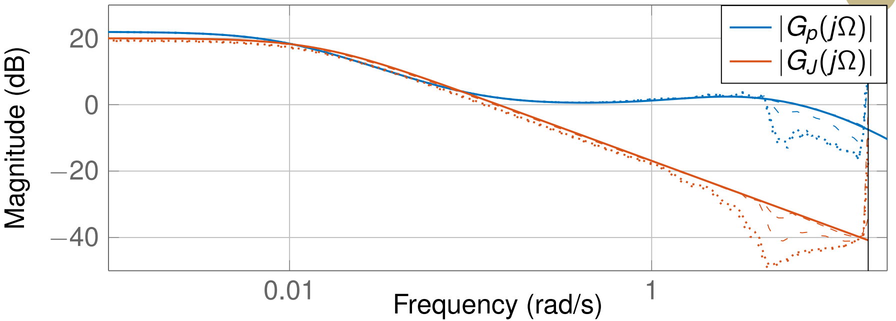


Figure: The mean value of $|G_p(e^{j\Omega}, \hat{\theta}_N)|$ and $|G_J(e^{j\Omega}, \hat{\theta}_N)|$ calculated from the MCS. The solid lines are the analytical calculated versions and the dashed loosely dashed dotted and loosely dotted lines represent an SNR of $50dB$, $26dB$, $6dB$, and $3dB$ respectively

Identifying $S(s)$

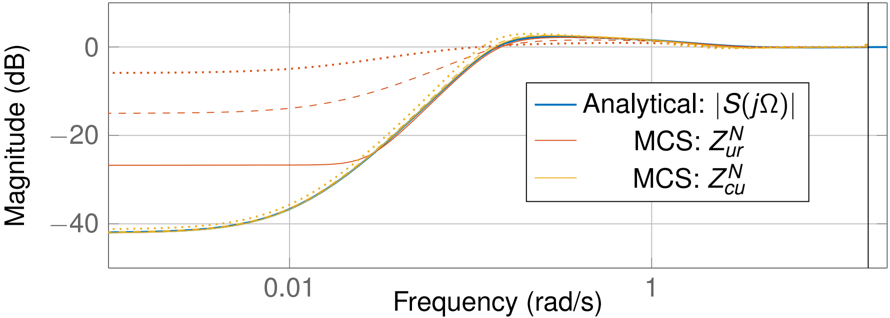


Figure: The mean value of $|S(e^{j\Omega}, \hat{\theta}_N)|$ calculated analytical and from the MCS. The solid, dashed and dotted lines represent an SNR of 50dB, 26dB, and 6dB respectively

Identifying $G_1(s)$

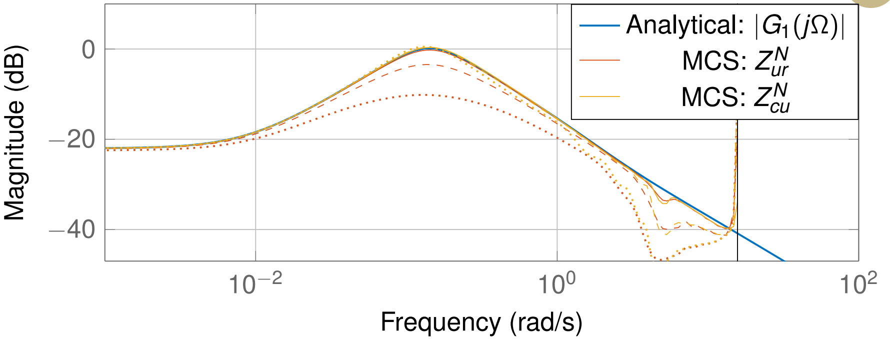


Figure: The mean value of $|G_1(e^{j\Omega}, \hat{\theta}_N)|$ calculated analytical and from the MCS. The solid, dashed and dotted lines represent an SNR of $50dB$, $26dB$, and $6dB$ respectively

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

Methodology Paper I

Simple test system Paper II

Theoretical validation Paper III

Tests at Statkraft's power plants Paper IV

Simulation studies Paper V

The best way to do the identification Paper VI

Conclusions and further work

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.