NTNU
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Frequency control and stability requirements on hydro power plants

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Outline

Problem

Methodology Paper I

Simple test system Paper II

Theoretical validation Paper III

Tests at Statkraft's power plants Paper IV

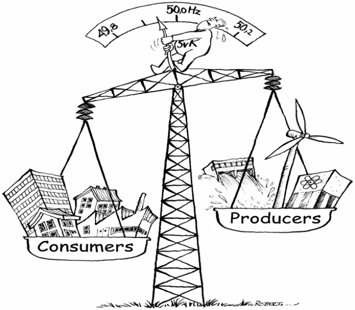
Simulation studies Paper V

The best way to do the identification Paper VI

Conclusions and further work

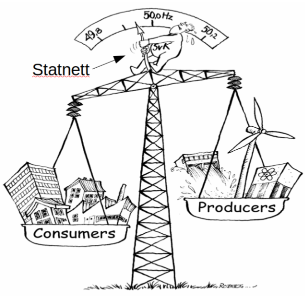
Load and production balancing

- 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 the TSOs to control the frequency.



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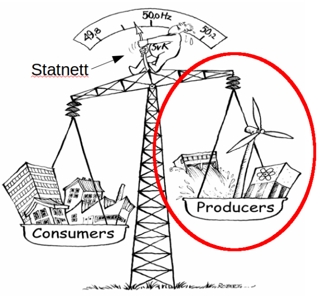
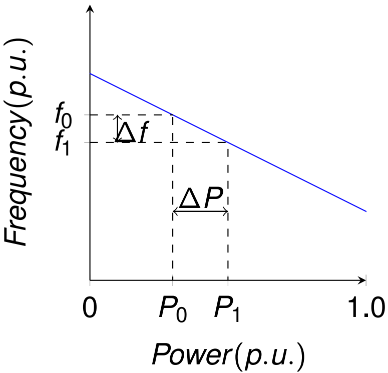
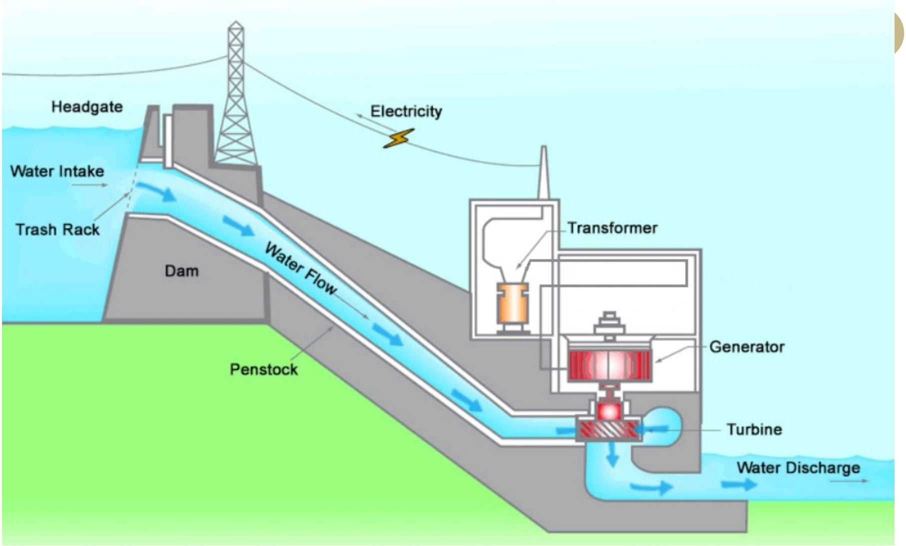


Load and production balancing

- The power system frequency measures the power balance.
- It is the responsibility of the TSOs to control the frequency.
- However, it is the power plant owners who can control the frequency.
- The TSOs pay all power plant owners above a certain size to provide frequency control.(droop $\rho = \Delta f / \Delta P$)

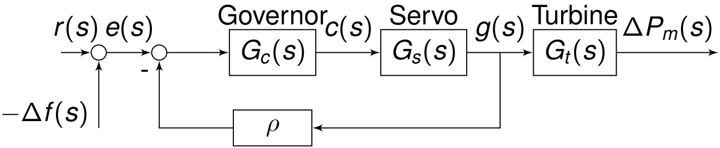


Hydro power plant



Implementation of the frequency containment process

- $r(s)$ Reference frequency
- $e(s)$ Control error
- $f(s)$ Frequency
- $c(s)$ Control signal
- $g(s)$ Guide vane opening
- $\Delta P_m(s)$ Mechanical power



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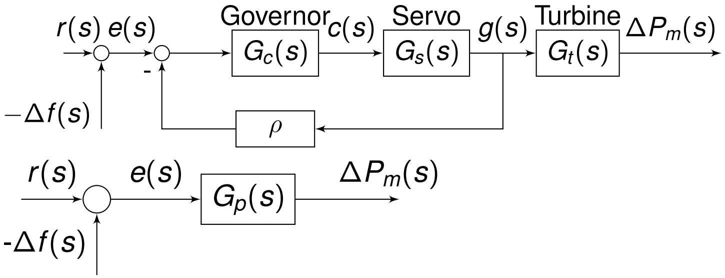
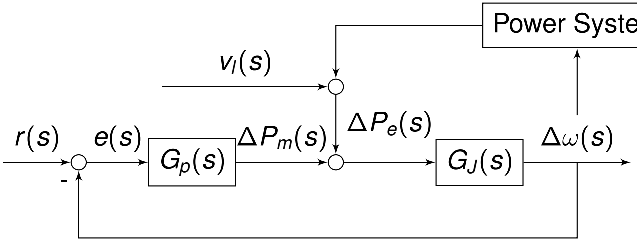


The frequency containment process $G_p(s)$ in the power system

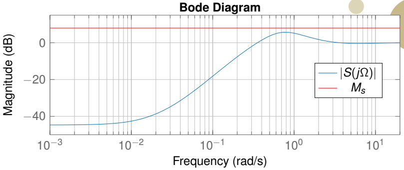
- $G_J(s)$ represents the swing dynamics of the power plant.
- $v_l(s)$ represents stochastic load.



Stability requirements for frequency control

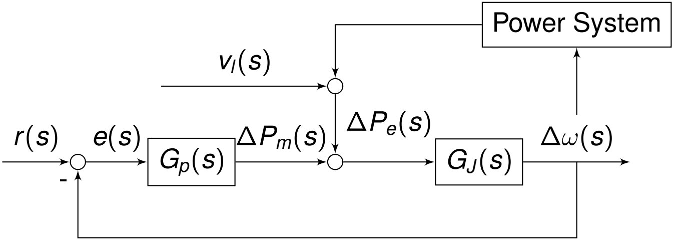
- Stability margin from control theory:

$$\max |S(j\Omega)| < M_s \qquad (1)$$



- where:

$$S(s) = \frac{1}{1 + G_p(s)G_J(s)} \qquad (2)$$



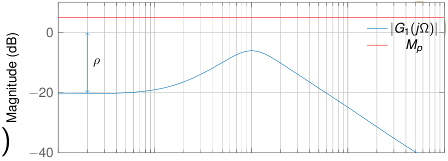
Performance requirements for frequency control

— We want to contain frequency deviations.

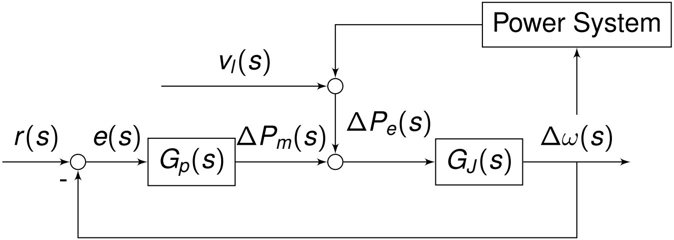
$$\Delta\omega(s) = \frac{G_J}{1 + G_p(s)G_J(s)}\Delta P_e(s) \tag{3}$$

— Define

$$G_1(s) = \frac{G_J}{1 + G_p(s)G_J(s)} \tag{4}$$

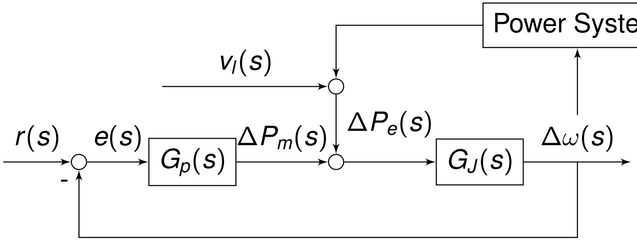


$$|G_1(j\Omega)| < M_p \tag{5}$$



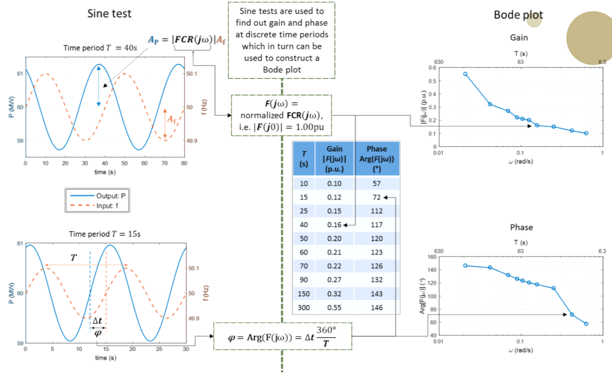
Future of frequency control

- Power plants have to show that they fulfill:
  - Stability requirement $|S(j\Omega)| < M_s$
  - Performance requirement $|G_1(j\Omega)| < M_p$
- To do this they need models of:
  - $G_p(s)$
  - and $G_J(s)$

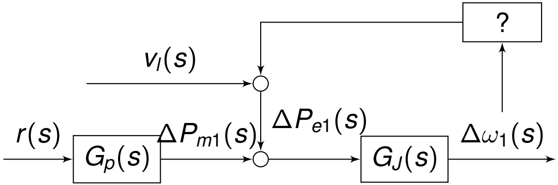


Industry proposed tests

- Time consuming.
- Use system estimate for $G_J(s)$.
- Input $r(s)$
- Output $\Delta P_e(s)$

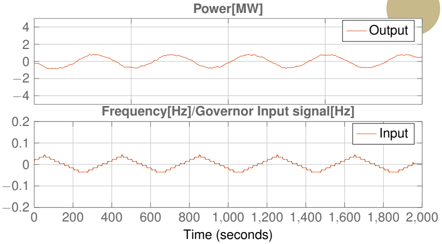


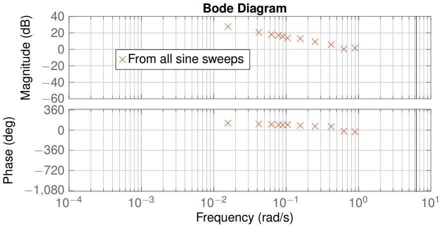
T (s)	Gain $\lvert F(j\omega)\rvert$ (p.u.)	Phase $\mathrm{Arg}(F(j\omega))$ (°)
10	0.10	57
15	0.12	72
25	0.15	112
40	0.16	117
50	0.20	120
60	0.21	123
70	0.22	126
90	0.27	132
150	0.32	143
300	0.55	146



Example from real tests

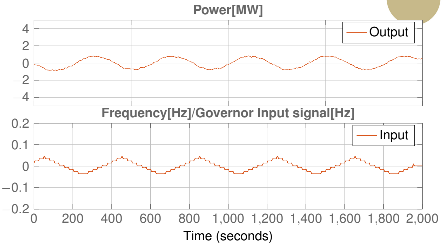
- The power plant needs to be disconnected
- Takes up to 20 hours.

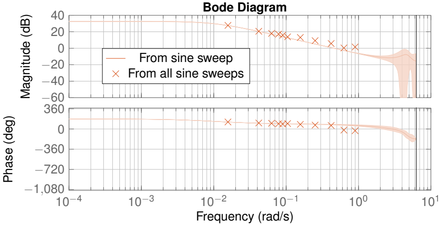




Example from real tests

- The power plant needs to be disconnected
- Takes up to 20 hours.
- Only one sine test needed with system identification.





Motivation

— Can we do the tests easier?

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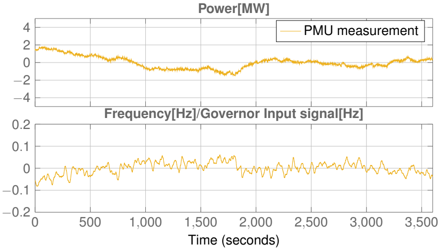
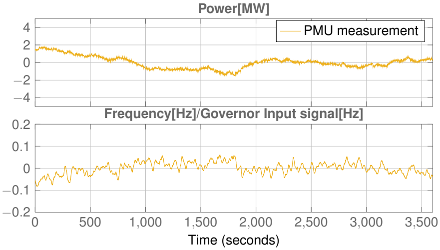
— The power system is never really in steady state.



Motivation

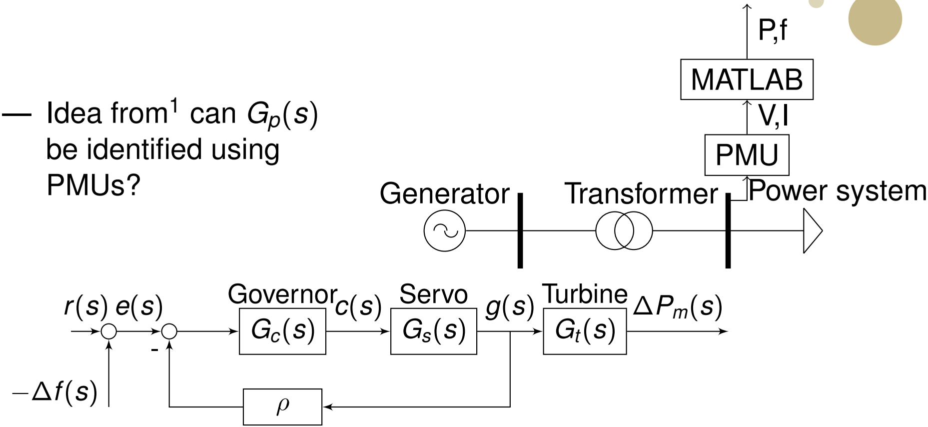
- Can we do the tests easier?
- The power system is never really in steady state.
- Can the power plant dynamics be identified from normal operation measurements?



Outline

Background

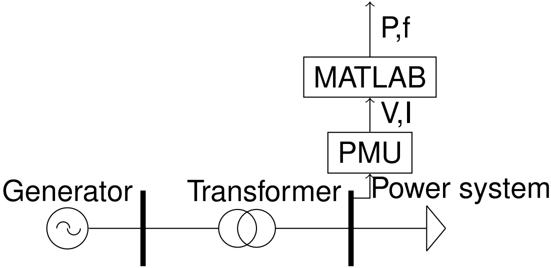
- Idea from[1] can $G_p(s)$ be identified using PMUs?



[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

Methodology

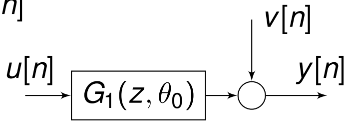
- Collect data from PMUs.
- Preprocess data.
- Calculate power and frequency from the measurements.
- Identify models.
- Validate models.



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

$$\mathcal{S} : y[n] = G_1(z, \theta_1) u[n] + H_1(z, \theta_1) e[n] \tag{6}$$

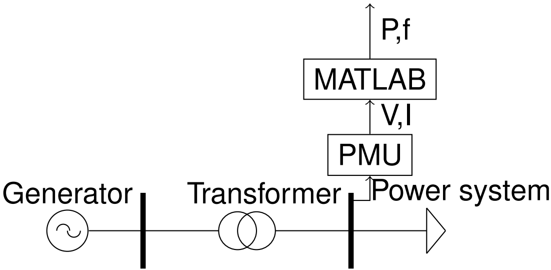


- Using the data set Z^N we want to find the parameter vector θ^N minimizing

$$\hat{\theta}_N = \arg\min_{\theta} \frac{1}{N} \sum_{n=1}^{N} [H_1^{-1}(z, \theta)(y[n] - G_1(z, \theta) u[n])]^2 \tag{7}$$

Main contributions

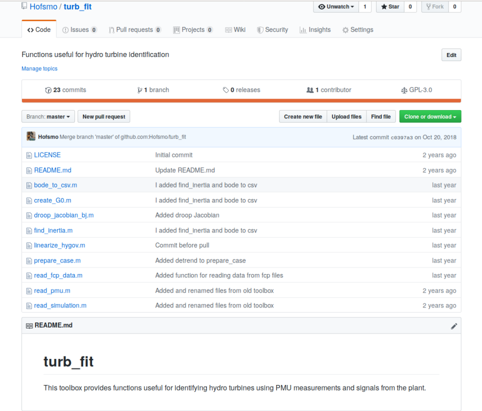
— Promising results for 19 datasets.



Main contributions

— Promising results for 19 datasets.

— Developed code for interfacing with the PMU data.



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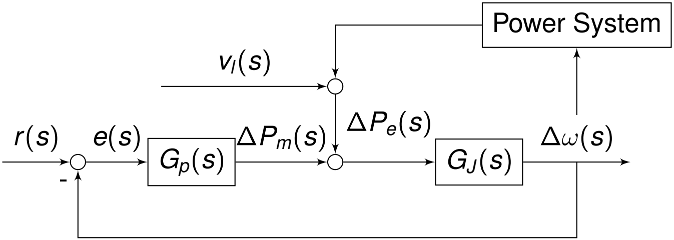
Conclusions and further work

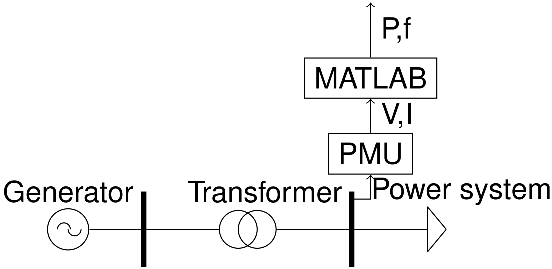
Motivation

— Create a model for analysing the identifiability of hydro power plant dynamics.



What do we need to model?

— From the PMU we get
  - Power: $\Delta P_e(s)$.
  - Frequency: $\Delta f(s) \approx 2\pi\Delta\omega(s)$.



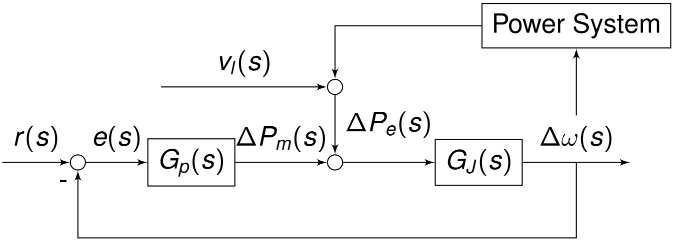
What do we need to model?

— From the PMU we get
  - Power: $\Delta P_e(s)$.
  - Frequency: $\Delta f(s) \approx 2\pi \Delta\omega(s)$.

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

— We need to model the external perturbation.

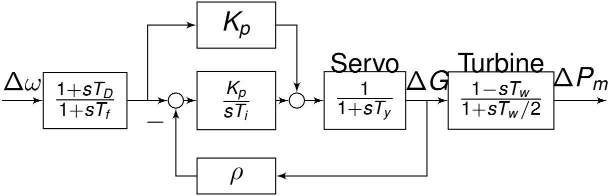
— We also need to model the power plant consisting of $G_p(s)$ and $G_J(s)$.



Power plant model

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

$$G_J(s) = \frac{1}{2Hs + K_d} \tag{8}$$



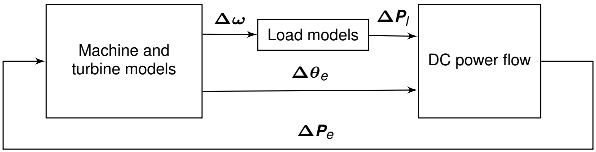
Power system model

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

$$\Delta\theta(s) = \frac{2\pi f_s}{s} f(s) \qquad (9)$$

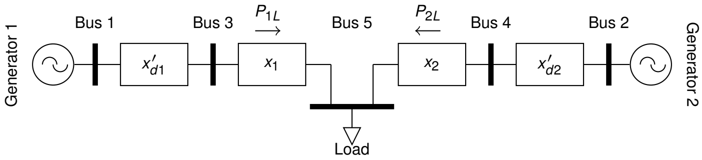
$$P_k \approx \sum_{m \in \Omega_k} x_{km}^{-1} \theta_{km} \qquad (10)$$

$$\mathbf{P} = \mathbf{Y}\theta \qquad (11)$$

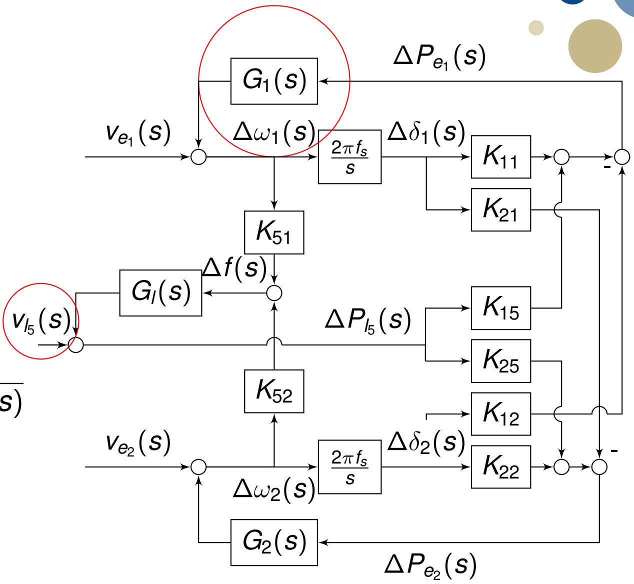


Single line diagram of test system

- Generator 1 is the plant we study.
- Generator 2 represents the rest of the power system.
- The load represents the stochastic behaviour of all loads.
- x_1 and x_2 are line reactances.
- x'_{d1} and x'_{d2} are generator reactances.



Block diagram of test system



— $G_1(s)$ the plant we investigate.

— $v_{l5}(s)$ external perturbation.

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

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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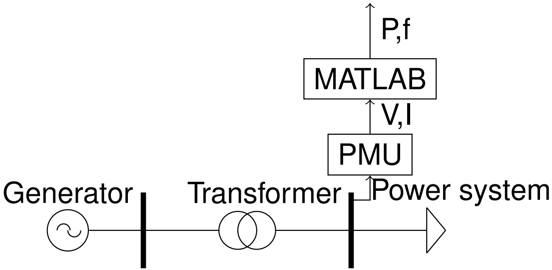
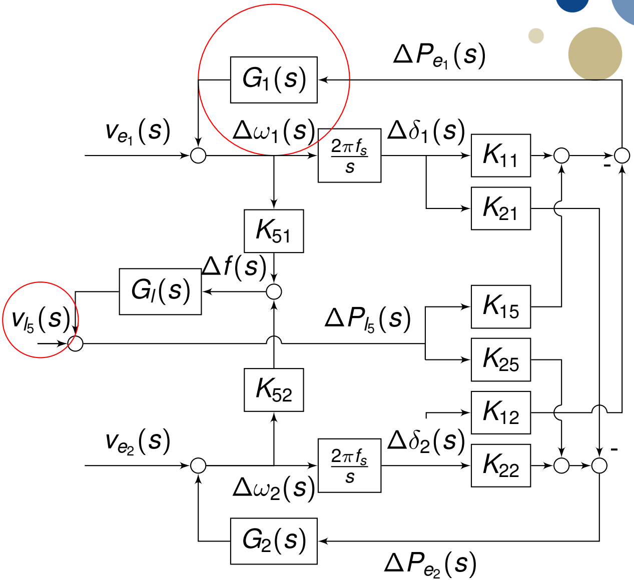
Background

— To validate the PMU method analytically.



Modelled used for the validation

- The system we want to identify is $G_1(s)$.
- The external perturbation to the system is $v_l(s)$.



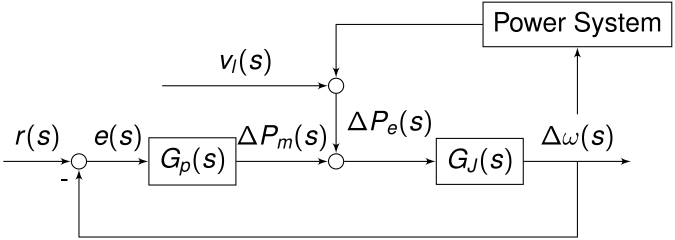
What can we identify using a PMU

— $\Delta\omega(s)$ is related to $\Delta P_e(s)$ by:

$$\Delta\omega(s) = \frac{G_J}{1 + G_p(s)G_J(s)}\Delta P_e(s)$$

— This means that we can identify:

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



Assumptions for the theoretical validation

- 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.

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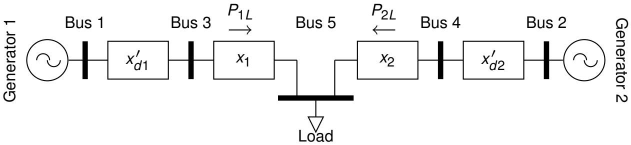
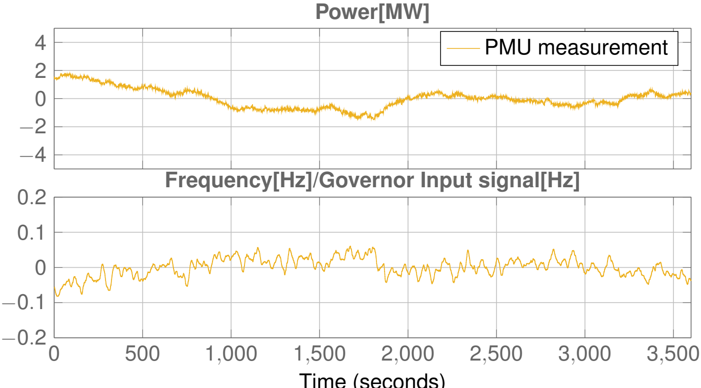
The system is excited by a load acting as a filtered white noise process

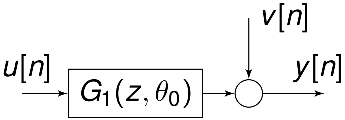


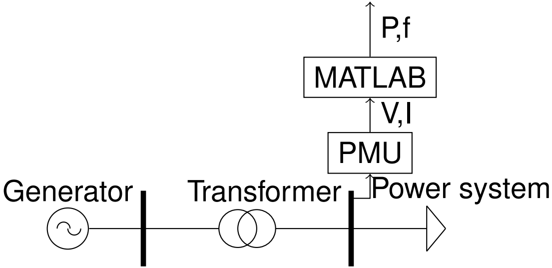


Assumptions for the theoretical validation

The measurement error of the electrical power is negligible

- $u[n] = P[n]$
- $y[n] = f[n]$

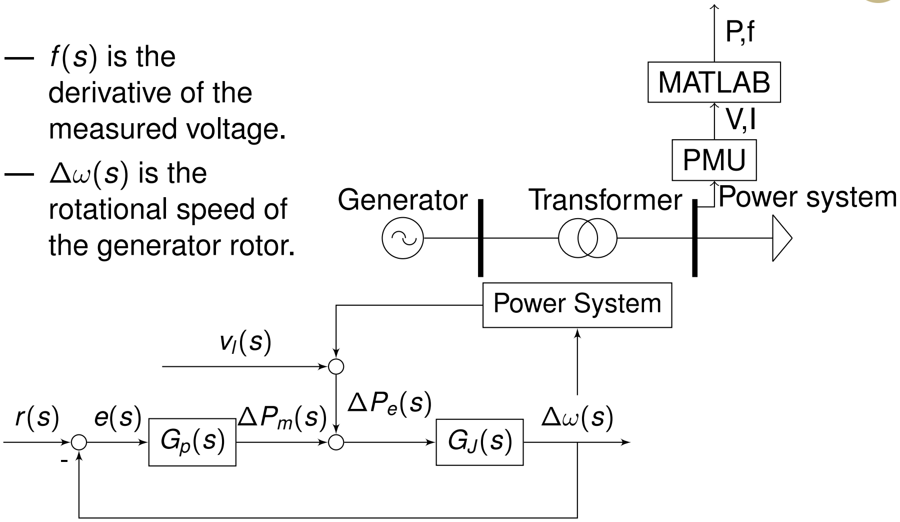




Assumptions for the theoretical validation

The measured frequency is a good estimate of the generator speed

- $f(s)$ is the derivative of the measured voltage.
- $\Delta\omega(s)$ is the rotational speed of the generator rotor.

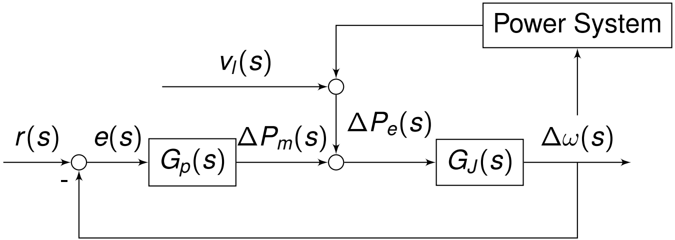


Results from the theoretical validation

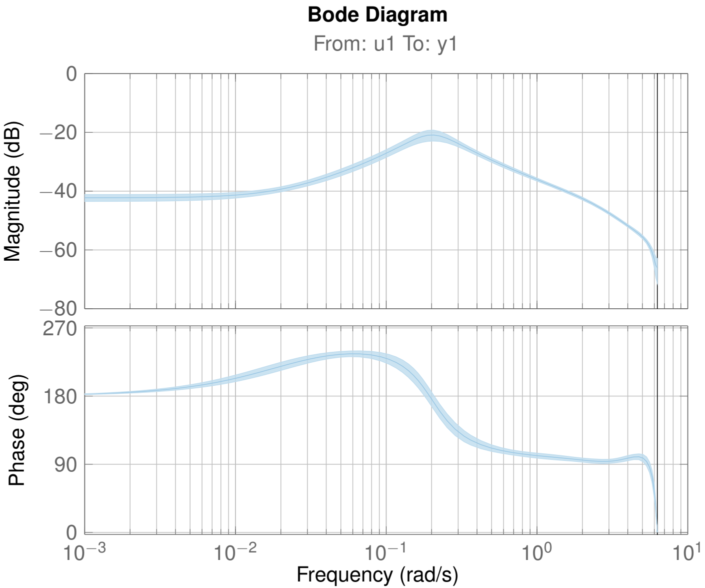
— A consistent estimate of $G_1(s)$ can be obtained by using:

- Measured PMU frequency as the output $u[n]$
- Measured PMU power as the input $y[n]$
- If there is a delay between $\Delta\omega(s)$ and $\Delta P_e(s)$.

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



Model obtained using PMU data



Main contributions

— To show that the transfer function that can be identified using a 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 a real dataset.

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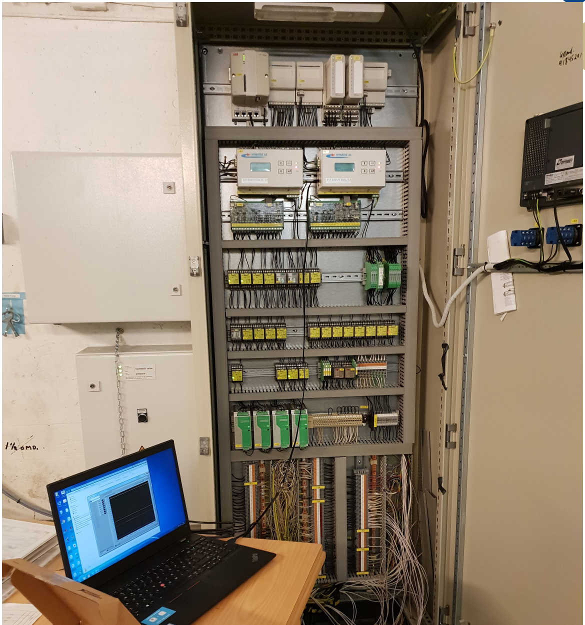
Motivation

— 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.

Power plant location

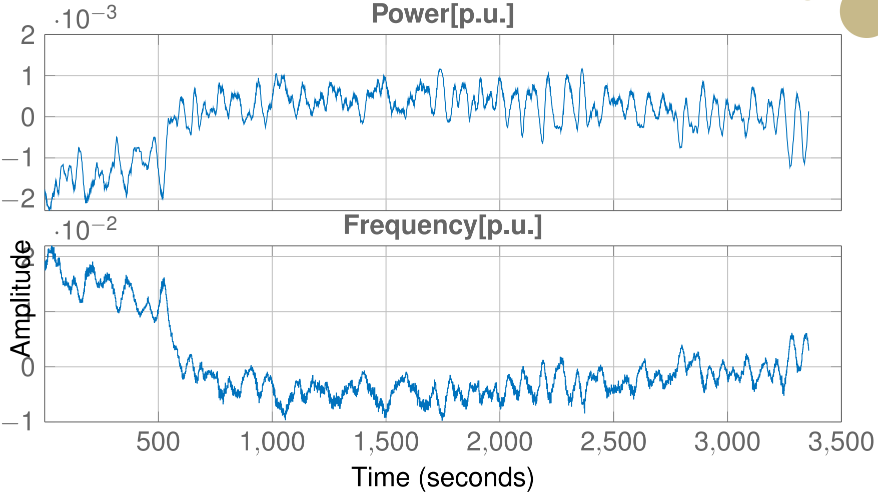
Getting data from the control system

- Collected Electric power ΔP_e
- and power system frequency f.

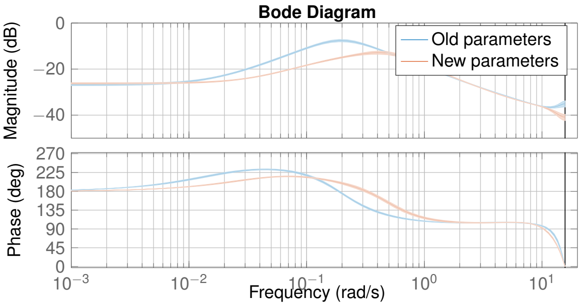


Measurement transformer

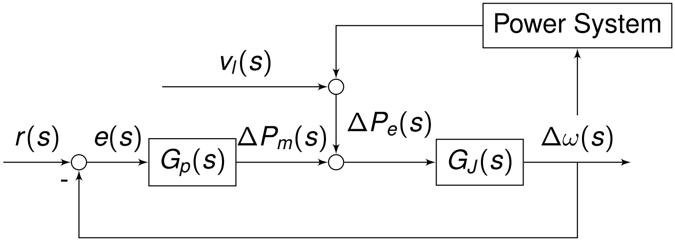
Example of dataset



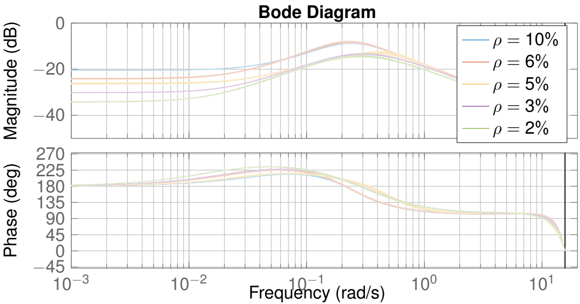
Detecting a new tuning



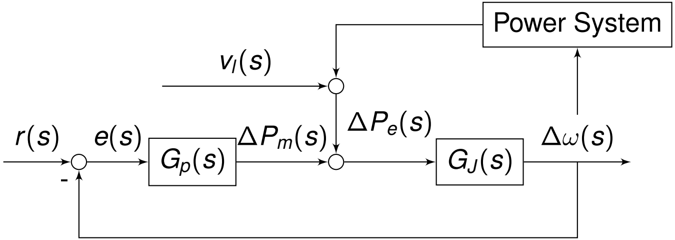
$$G_1(s) = \frac{G_J}{1 + G_p(s)G_J(s)}$$



Detecting droop changes



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



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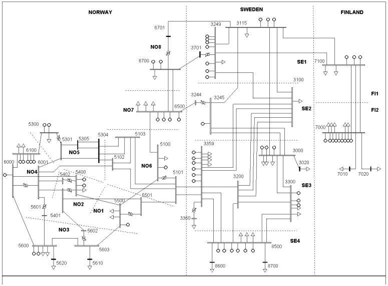
— Test with a more detailed power plant model.
— Test with a more detailed power system model.
— Investigate some of the assumptions from previous papers.

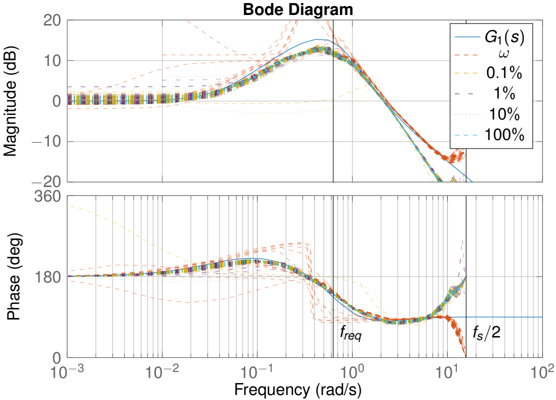
More detailed power system model

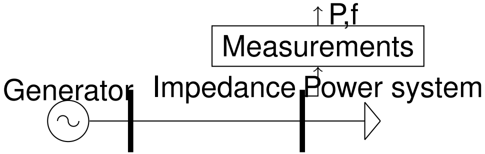
— Used the Nordic 44 test system in PSS/E.



Test frequency assumption

- $f(s)$ is the derivative of the measured voltage.
- $\Delta\omega(s)$ is the rotational speed of the generator rotor.
- Increased the impedance between the generator and PMU.
- 100 simulations for each impedance





Main 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.

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

Motivation

— How to best check the requirements given access to control system data.

What do we want to check

— Stability requirement $|S(j\Omega)| < M_s$

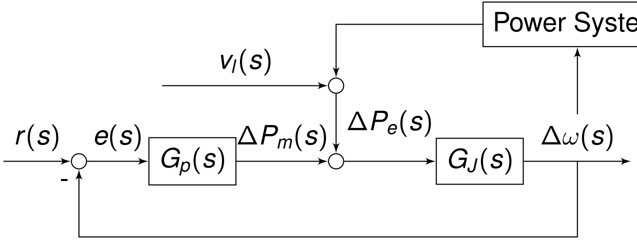
— Performance requirement $|G_1(j\Omega)| < M_p$

— In the requirements this is done by identifying.

- $G_p(s)$ in open loop
- and $G_J(s)$ from the system

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

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

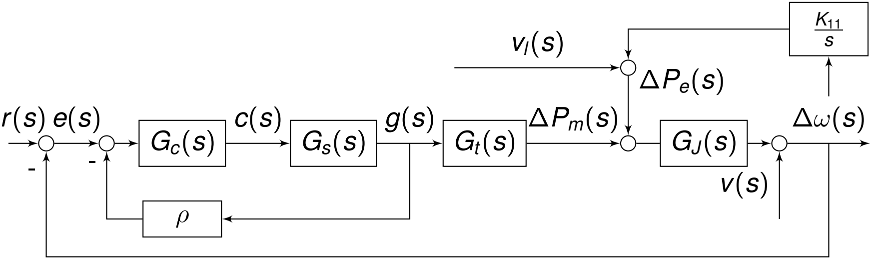


Identify $G_p(s)$ and $G_J(s)$ in closed loop

$$\Delta\omega_1(s) = G_s(s)G_t(s)G_J(s)c(s) - G_J(s)\Delta P_{e1}(s) \tag{12}$$

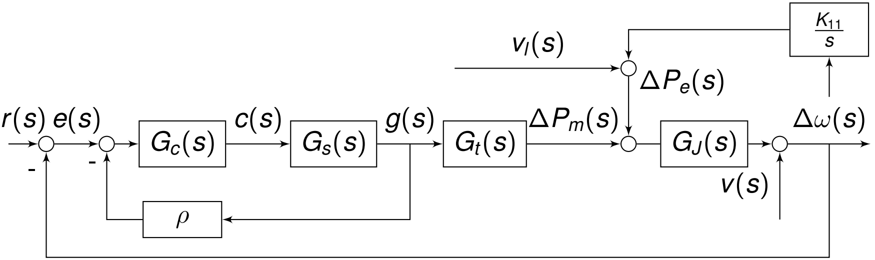
— Assume $G_c(s)$ to be known.

$$G_p(s) = \frac{G_c(s)G_s(s)G_t(s)G_J(s)}{G_J(s)(1+\rho G_c(s)G_s(s))} \tag{13}$$



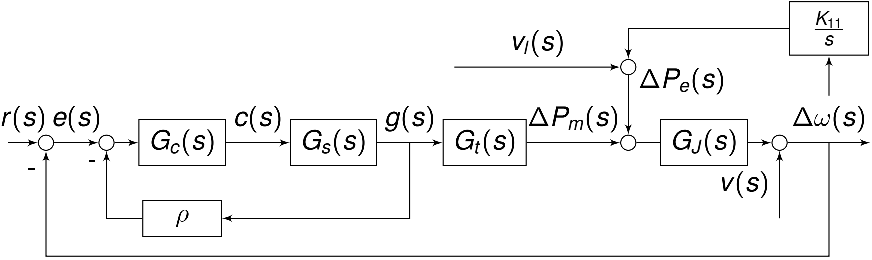
Identify $G_s(s)$ and $S(s)$ directly in closed loop

$$e(s) = G_1(s)\Delta P_{e1}(s) + S(s)r(s) \tag{14}$$



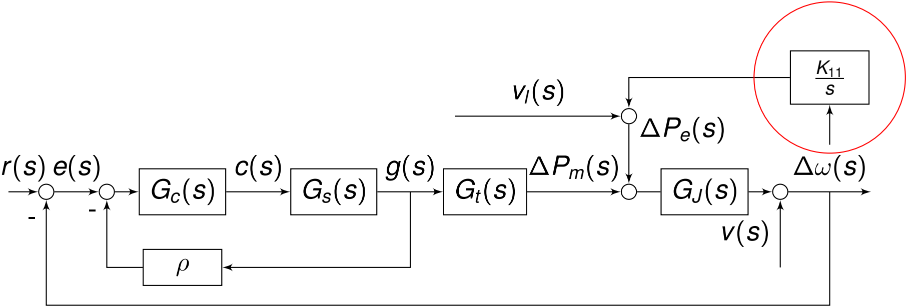
Identifiability

— The systems can be identified



Identifiability

- The systems can be identified
- However, there is a lack of delay
- This is no problem if the effect of $v(s)$ in $\Delta P_e(s)$ is small to the effect of $v_l(s)$.



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

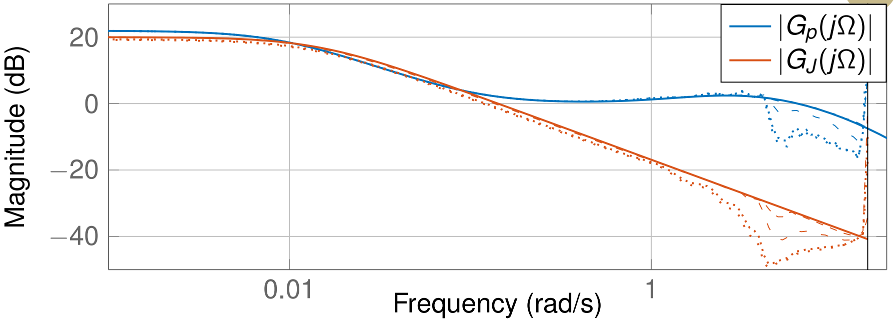


Figure: The mean value of $|G_p(e^{j\Omega}, \hat{\theta}_N)|$ and $|G_J(e^{j\Omega}, \hat{\theta}_N)|$ calculated from the MCS. The solid lines are the analytical calculated versions and the dashed loosely dashed dotted and loosely dotted lines represent an SNR of $50dB$, $26dB$, $6dB$, and $3dB$ respectively

Identifying $S(s)$

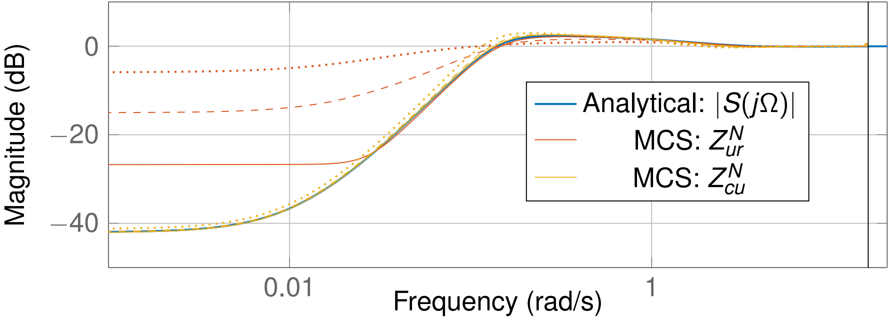


Figure: The mean value of $|S(e^{j\Omega}, \hat{\theta}_N)|$ calculated analytical and from the MCS. The solid, dashed and dotted lines represent an SNR of 50dB, 26dB, and 6dB respectively

Identifying $G_1(s)$

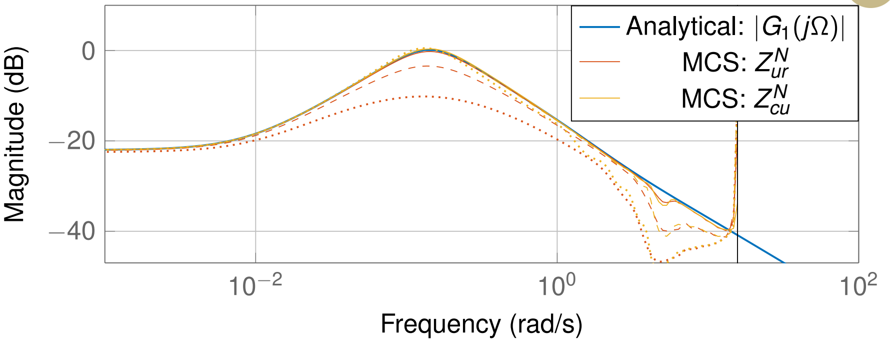


Figure: The mean value of $|G_1(e^{j\Omega}, \hat{\theta}_N)|$ calculated analytical and from the MCS. The solid, dashed and dotted lines represent an SNR of $50dB$, $26dB$, and $6dB$ respectively

Main contributions

- Demonstrated two methods for finding transfer functions for checking the requirements in closed loop.
- The best method for finding the transfer functions is to first identify $G_p(s)$ and $G_J(s)$.
- Analytical validation of the demonstrated methods.
- Discussed the delay condition introduced in Paper II.

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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.