NTNU
Norwegian University of
Science and Technology

Frequency control and stability requirements on hydro power plants

Sigurd Hofsmo Jakobsen
Department of Electric Power Engineering

October 31, 2019

Outline

Background and research questions

Methodology

Simple test system

Theoretical validation

Tests at Statkraft's power plant

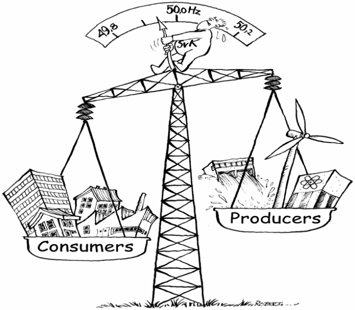
More detailed simulations

The best way to do the identification

Conclusions and further work

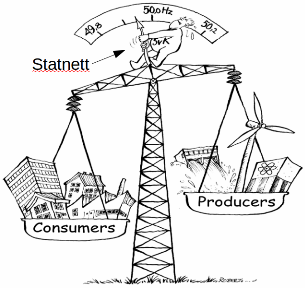
Load and production balancing

- 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.

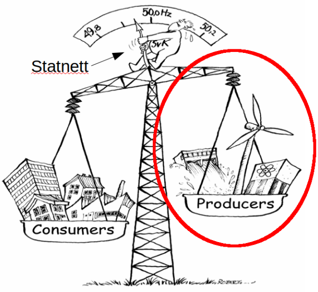


Load and production balancing

— The power system frequency measures the power balance.

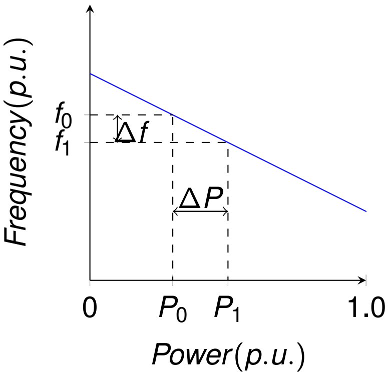
— It is the responsibility of the TSOs to control the frequency.

— However, it is the power plant owners who can control the frequency.

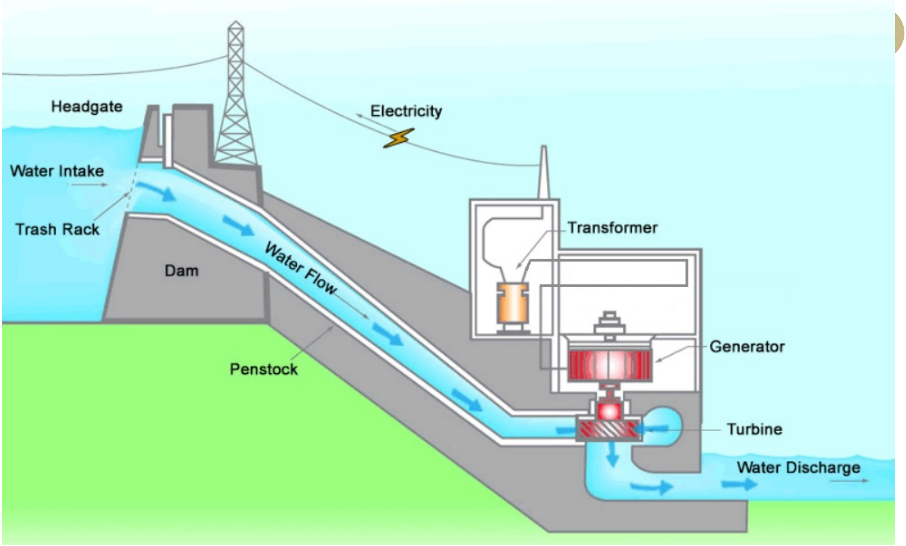


Load and production balancing

- 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 $\rho = \Delta f / \Delta P$)

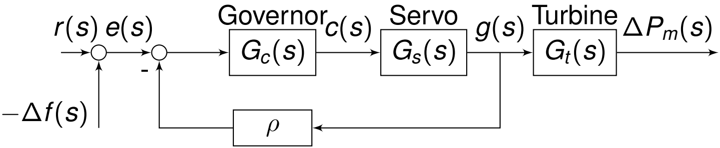


Hydro power plant



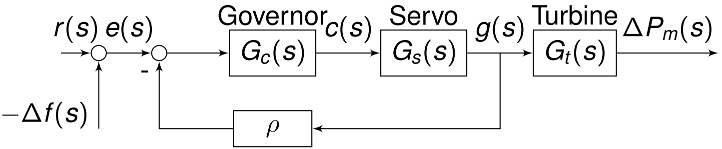
Implementation of the frequency containment process

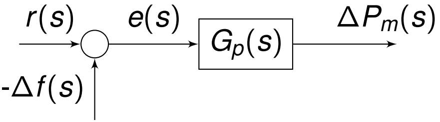
- $r(s)$ Reference frequency
- $e(s)$ Control error
- $f(s)$ Frequency
- $c(s)$ Control signal
- $g(s)$ Guide vane opening
- $\Delta P_m(s)$ Mechanical power



Implementation of the frequency containment process

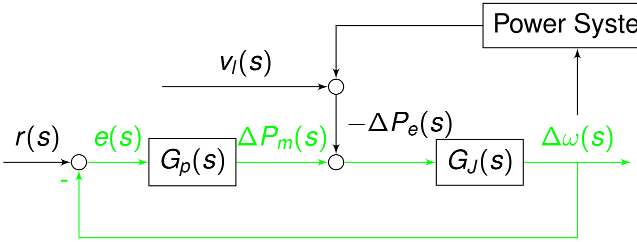
- $r(s)$ Reference frequency
- $e(s)$ Control error
- $f(s)$ Frequency
- $c(s)$ Control signal
- $g(s)$ Guide vane opening
- $\Delta P_m(s)$ Mechanical power





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

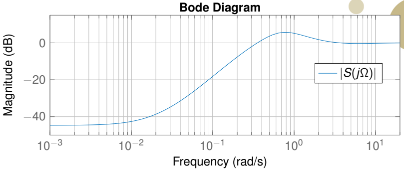
- $G_J(s)$ represents the swing dynamics of the power plant.
- $v_l(s)$ represents stochastic load.



Stability requirements for frequency control

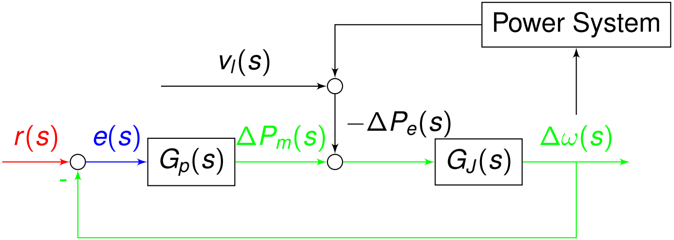
— Stability margin from control theory:

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



— where:

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



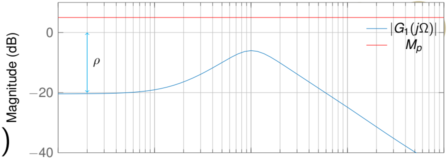
Performance requirements for frequency control

- We want to contain frequency deviations.

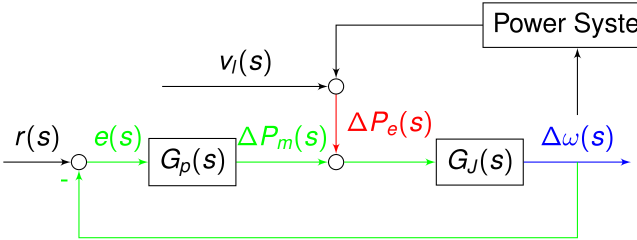
$$\Delta\omega(s) = \frac{G_J}{1 + G_p(s)G_J(s)}\Delta P_e(s) \quad (3)$$

- Define

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

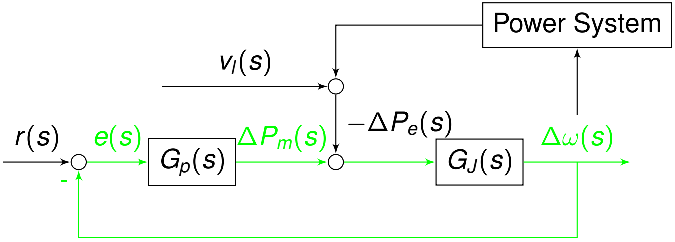


$$|G_1(j\Omega)| < M_p \quad (5)$$



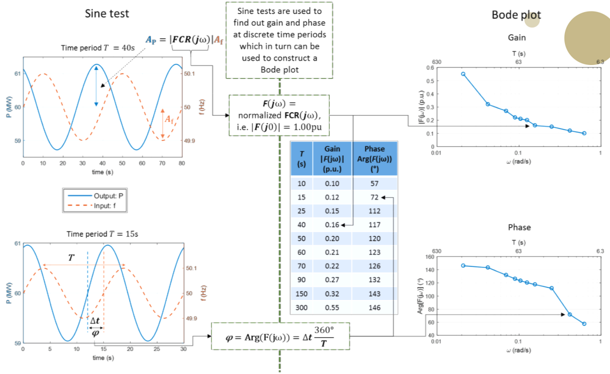
Future of frequency control

- 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 $G_J(s)$

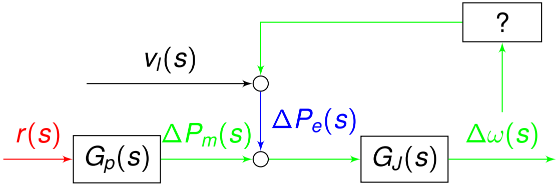


Industry proposed tests

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

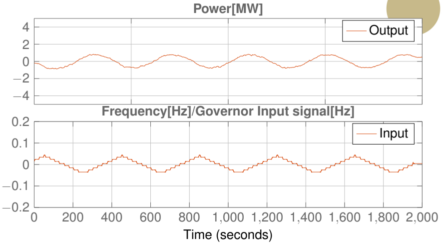


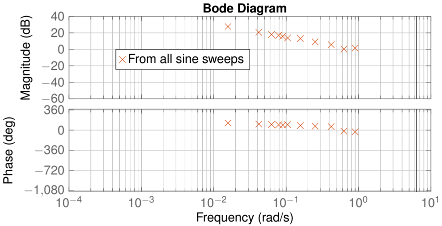
T (s)	Gain $\lvert F(j\omega)\rvert$ (p.u.)	Phase $\mathrm{Arg}(F(j\omega))$ (°)
10	0.10	57
15	0.12	72
25	0.15	112
40	0.16	117
50	0.20	120
60	0.21	123
70	0.22	126
90	0.27	132
150	0.32	143
300	0.55	146



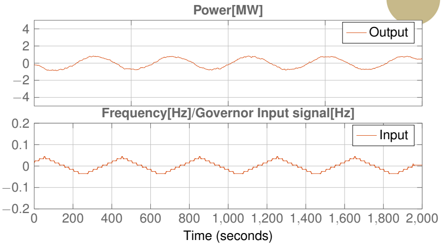
Example from real tests

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

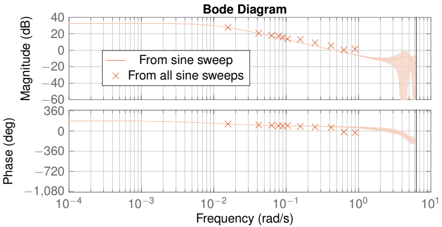




Example from real tests



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

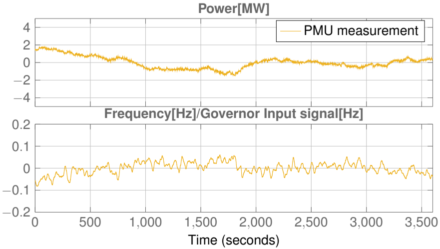


Motivation

— Can we do the tests easier?

Motivation

- Can we do the tests easier?
- The power system is never really in steady state.

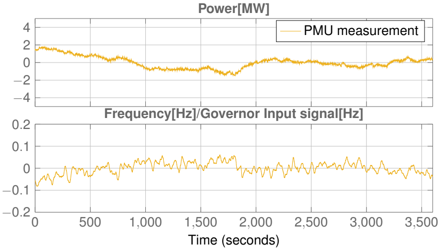


Motivation

— 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?



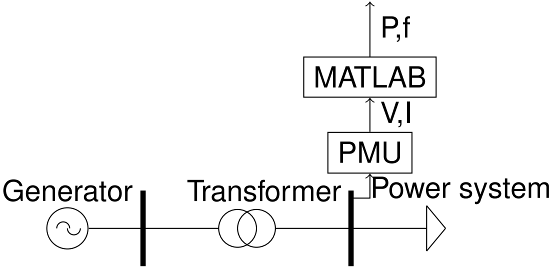
Research questions

- 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?

Outline

Methodology

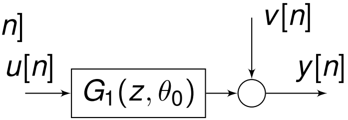
- Collect data from PMU or control system.
- Preprocess data.
- Calculate power and frequency from the measurements.
- Identify models.
- Validate models.



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

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



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

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

Outline

Background and research questions

Methodology

Simple test system

Theoretical validation

Tests at Statkraft's power plant

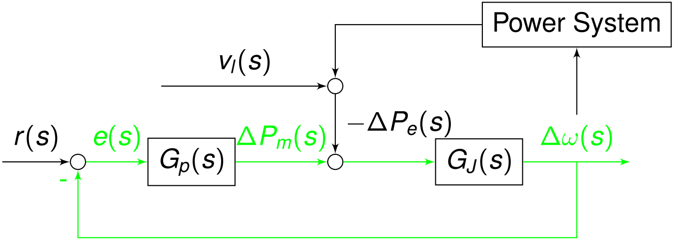
More detailed simulations

The best way to do the identification

Conclusions and further work

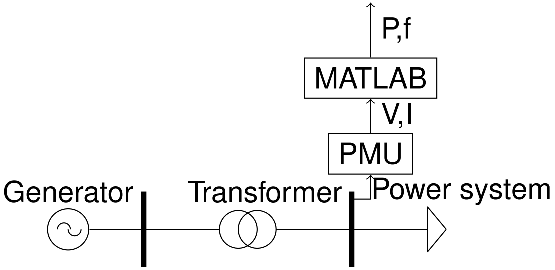
Motivation

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



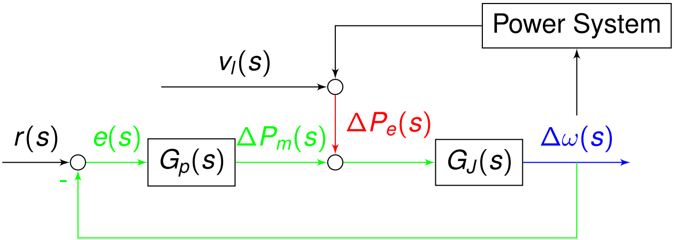
What do we need to model?

— 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?

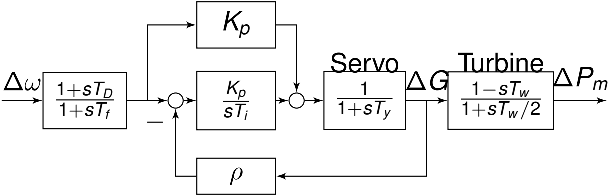
- From the PMU we get
  - Power: $\Delta P_e(s)$.
  - Frequency: $\Delta f(s) \approx 2\pi\Delta\omega(s)$.
- We need to model how $\Delta P_e(s)$ and $\Delta f(s)$ is related through the power system.
- We need to model the external perturbation.
- We also need to model the power plant consisting of $G_p(s)$ and $G_J(s)$.



Power plant model

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

$$G_J(s) = \frac{1}{2Hs + K_d} \tag{6}$$



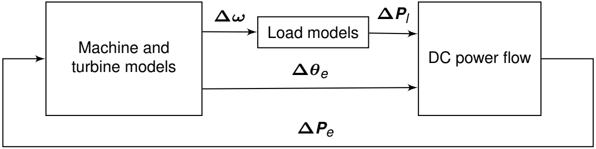
Power system model

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

$$\Delta\theta(s) = \frac{2\pi f_s}{s} f(s) \quad (7)$$

$$P_k \approx \sum_{m \in \Omega_k} x_{km}^{-1} \theta_{km} \quad (8)$$

$$\mathbf{P} = \mathbf{Y}\theta \quad (9)$$



Single line diagram of test system

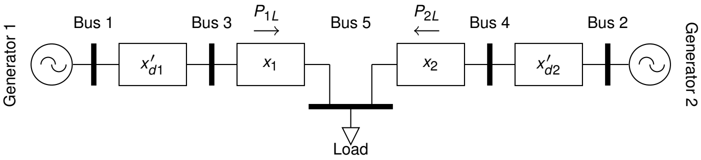
— Generator 1 is the plant we study.

— 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.

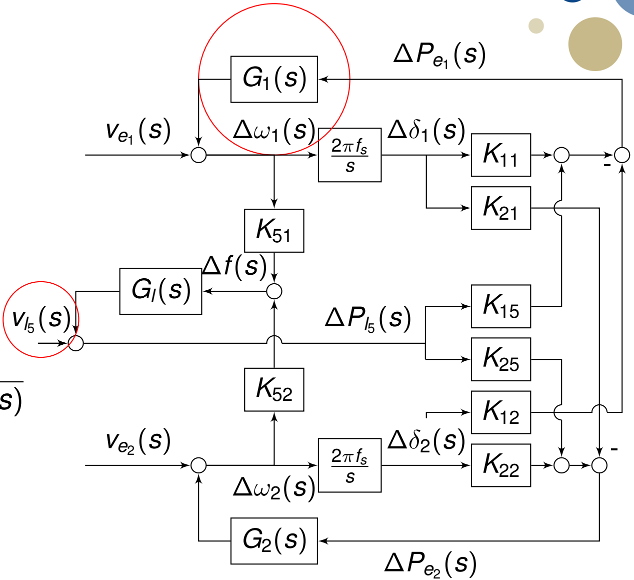


Block diagram of test system

— $G_1(s)$ the plant we investigate.

— $v_{l5}(s)$ external perturbation.

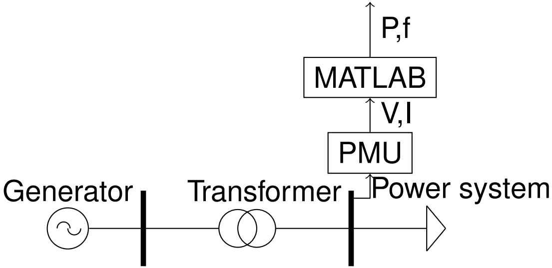
$$G_1(s) = \frac{G_J}{1 + G_p(s)G_J(s)}$$



Outline

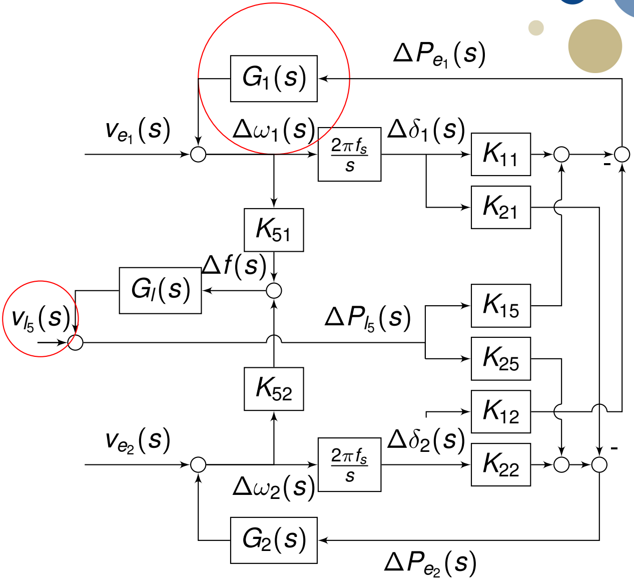
Motivation

— To validate the PMU method analytically.



Modelling used for the validation

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



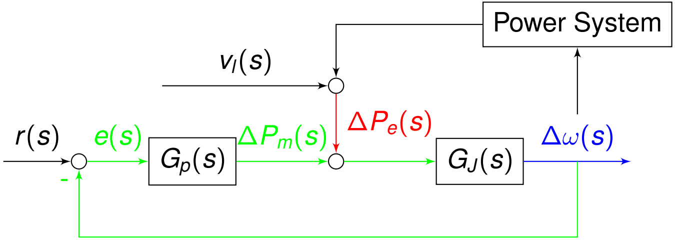
What can we identify using a PMU

— $\Delta\omega(s)$ 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:

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

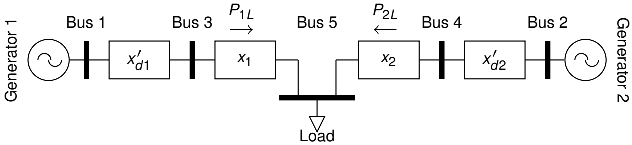


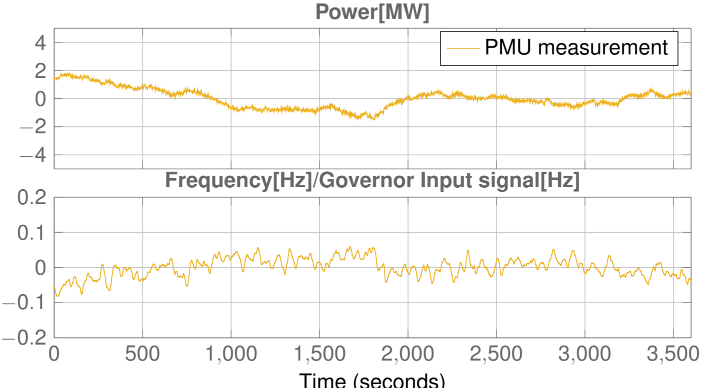
Assumptions for the theoretical validation

— 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.

Assumptions for the theoretical validation

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

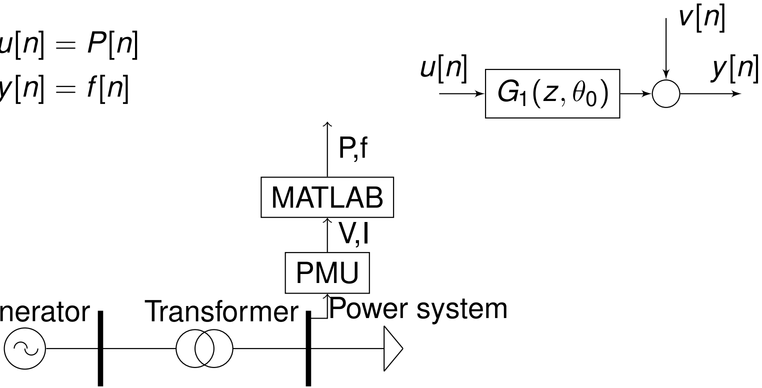




Assumptions for the theoretical validation

The measurement error of the electrical power is negligible

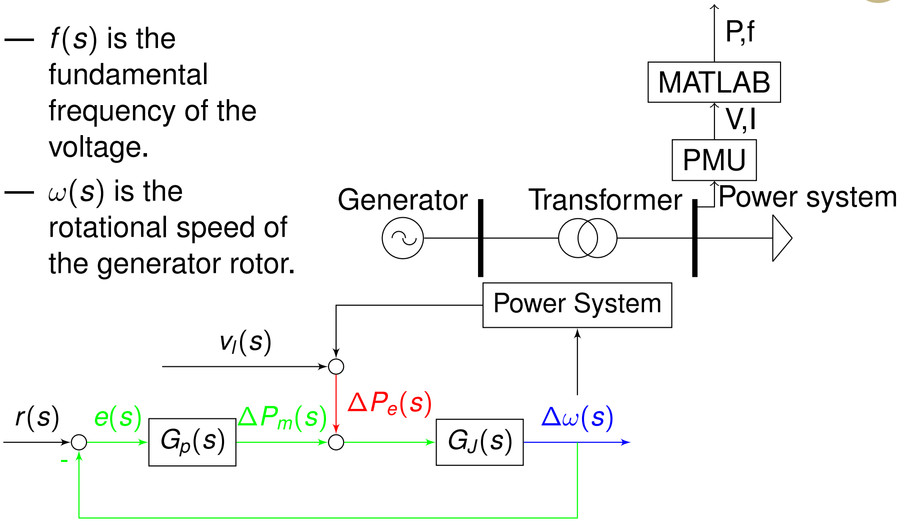
- $u[n] = P[n]$
- $y[n] = f[n]$



Assumptions for the theoretical validation

The measured frequency is a good estimate of the generator speed

- $f(s)$ is the fundamental frequency of the voltage.
- $\omega(s)$ is the rotational speed of the generator rotor.

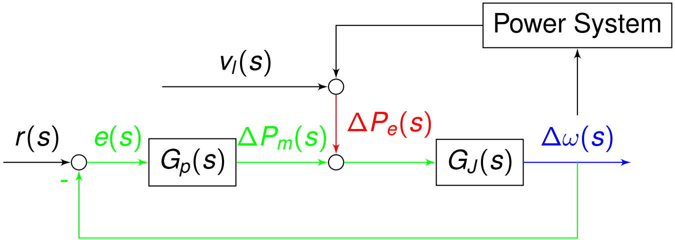


Results from the theoretical validation

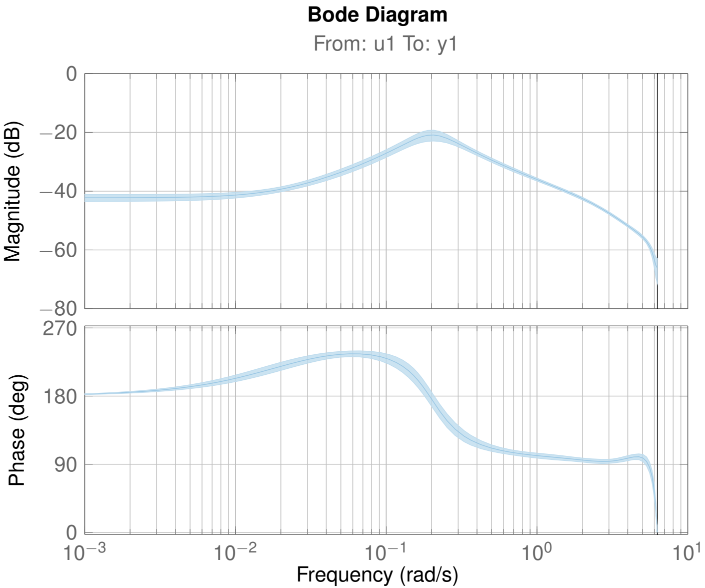
— A consistent estimate of $G_1(s)$ can be obtained by using:

- 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 PMU 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.

Outline

Background and research questions

Methodology

Simple test system

Theoretical validation

Tests at Statkraft's power plant

More detailed simulations

The best way to do the identification

Conclusions and further work

Motivation

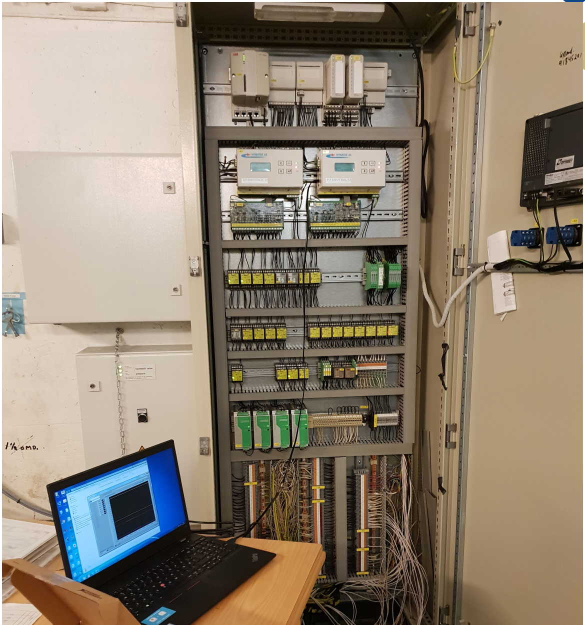
— Test the method on more real datasets.

— Demonstrate that the method can detect parameter changes.

Power plant location

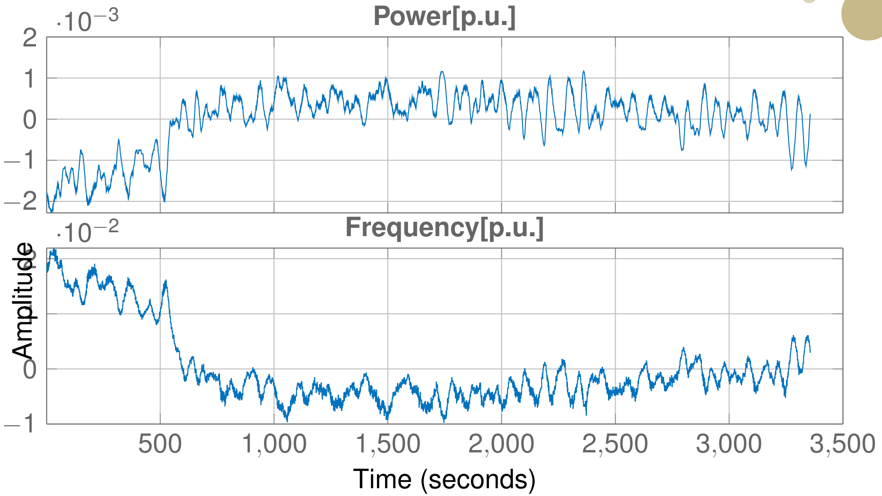
Getting data from the control system

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

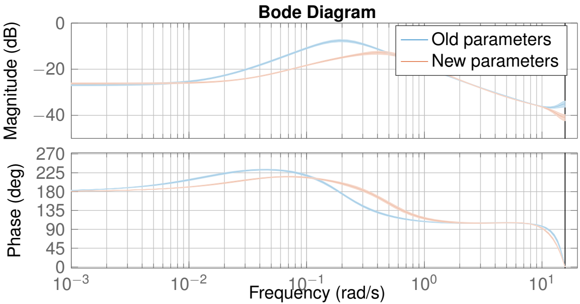


Measurement transformer

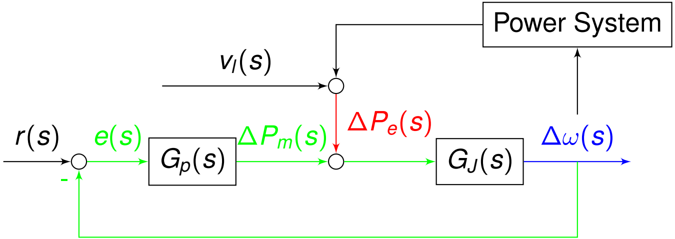
Example of dataset



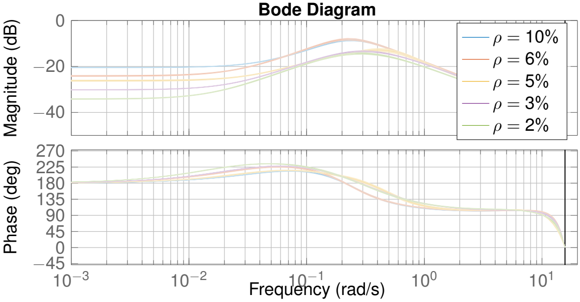
Detecting a new tuning



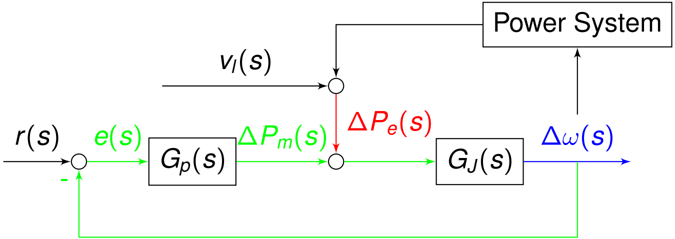
$$G_1(s) = \frac{G_J}{1 + G_p(s)G_J(s)}$$



Detecting droop changes



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



Outline

Background and research questions

Methodology

Simple test system

Theoretical validation

Tests at Statkraft's power plant

More detailed simulations

The best way to do the identification

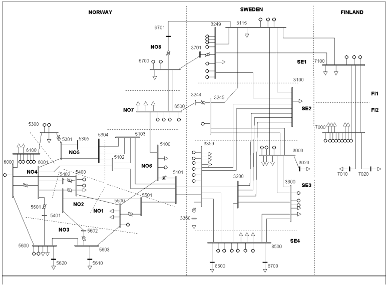
Conclusions and further work

Motivation

- Test with a more detailed power plant model.
- Test with a more detailed power system model.
- Investigate the frequency assumption.

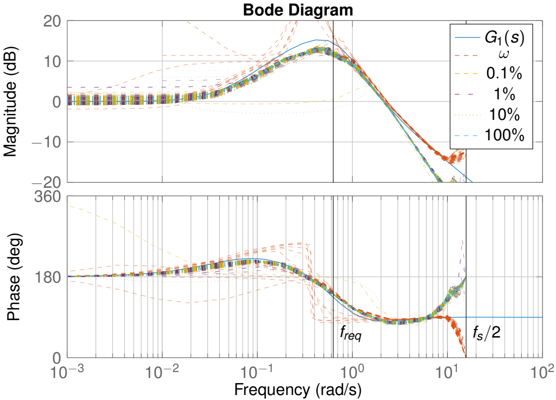
More detailed power system model

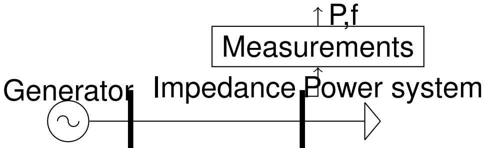
- Used the Nordic 44 test system in PSS/E.



Test frequency assumption

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





Main contribution

— Demonstrated that the results for faster dynamics are biased if the frequency is measured instead of the rotational speed of the rotor.

Outline

Background and research questions

Methodology

Simple test system

Theoretical validation

Tests at Statkraft's power plant

More detailed simulations

The best way to do the identification

Conclusions and further work

Motivation

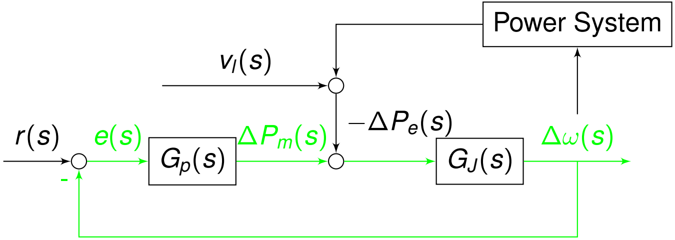
— How to best check the requirements given access to control system data.

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

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

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

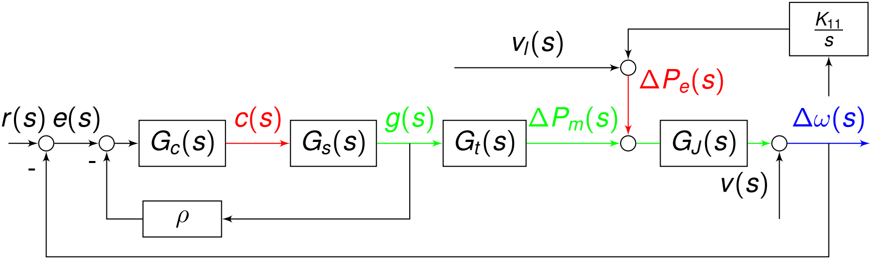


Identify $G_p(s)$ and $G_J(s)$ in closed loop, Method 1

$$\Delta\omega(s) = G_s(s)G_t(s)G_J(s)c(s) - G_J(s)\Delta P_e(s) \tag{10}$$

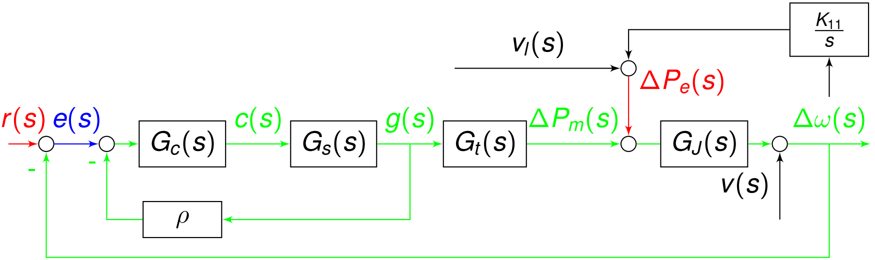
— Assume $G_c(s)$ to be known.

$$G_p(s) = \frac{G_c(s)G_s(s)G_t(s)G_J(s)}{G_J(s)(1 + \rho G_c(s)G_s(s))} \tag{11}$$



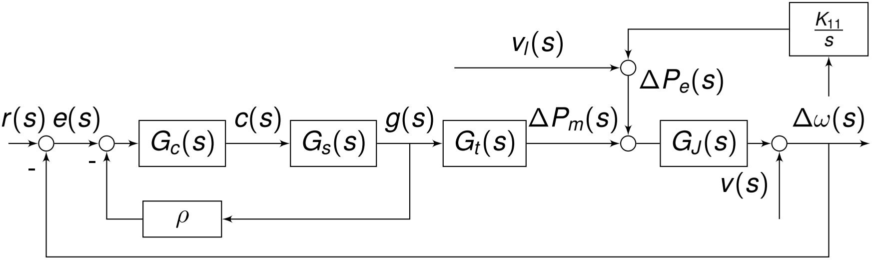
Identify $G_1(s)$ and $S(s)$ directly in closed loop, Method 2

$$e(s) = G_1(s)\Delta P_e(s) + S(s)r(s) \tag{12}$$



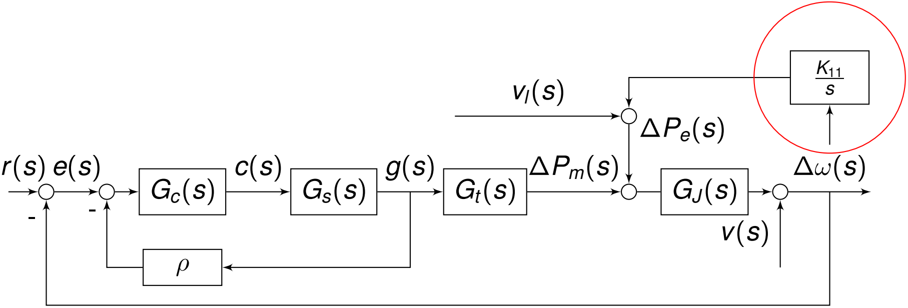
Identifiability

— The systems can be identified



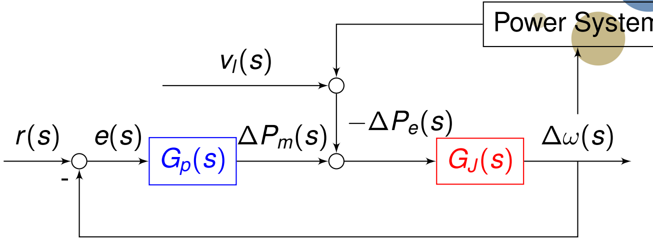
Identifiability

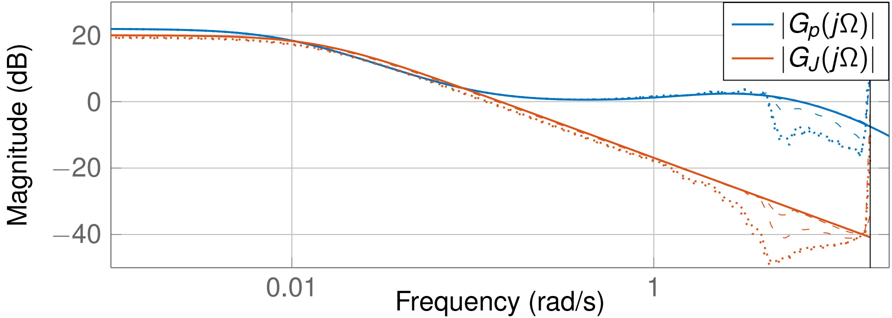
- The systems can be identified
- However, there is a lack of delay
- This is no problem if the effect of $v(s)$ in $\Delta P_e(s)$ is small compared to the effect of $v_l(s)$.



Identifying $G_p(s)$ and $G_J(s)$ with different $v(s)$ amplitudes

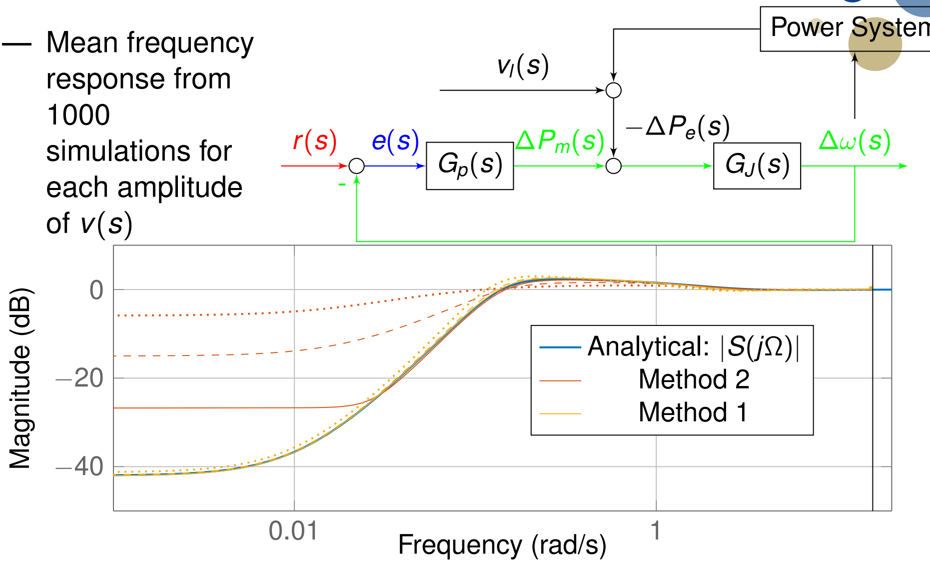
— Mean frequency response from 1000 simulations for each amplitude of $v(s)$





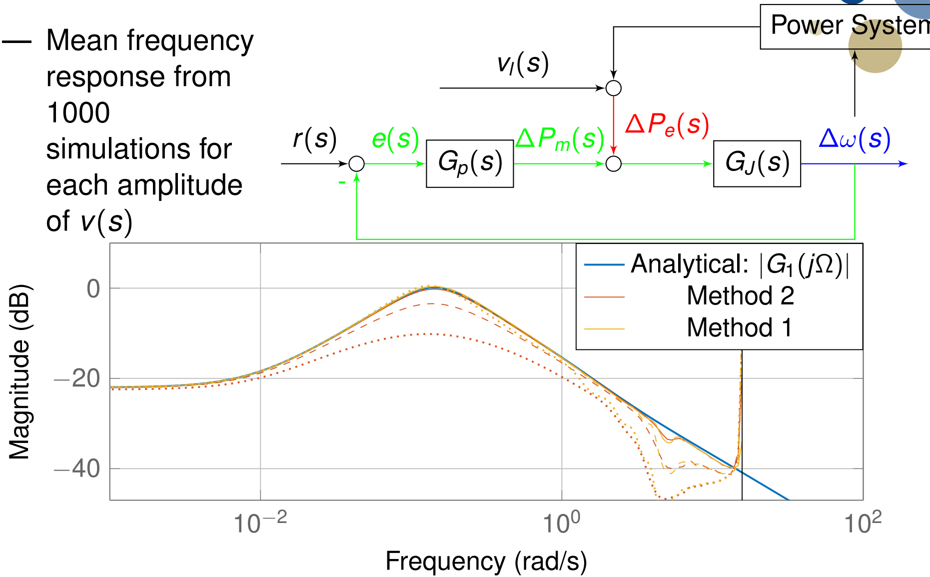
Identifying $S(s)$ with different $v(s)$ amplitudes

- Mean frequency response from 1000 simulations for each amplitude of $v(s)$



Identifying $G_1(s)$ with different $v(s)$ amplitudes

— Mean frequency response from 1000 simulations for each amplitude of $v(s)$



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 earlier.

Outline

Background and research questions

Methodology

Simple test system

Theoretical validation

Tests at Statkraft's power plant

More detailed simulations

The best way to do the identification

Conclusions and further work

Conclusions

— The requirements can be checked using PMU-measurements, however, the results will be biased for faster dynamics, since we are measuring the frequency instead of the rotational speed of the machine.

— The requirements can be checked using control system measurements in normal operation, however, the results may be biased for faster dynamics, because of the delay condition.

— The requirements can be checked using measurement from normal operation with extra excitation. The added excitation will help on potential bias.

Further work

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