NTNU
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Frequency control and stability requirements on hydro power plants

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Outline

Problem

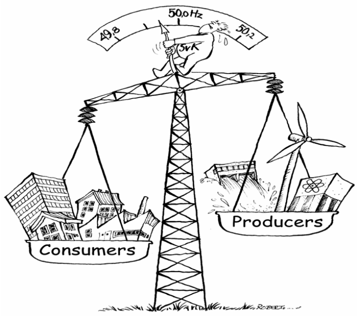
Methodology Paper I

Simple test system Paper II

Conclusions and further work

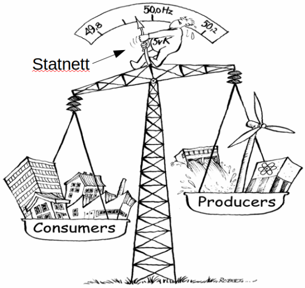
Load and production balancing

— 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

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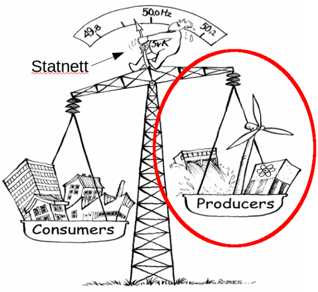
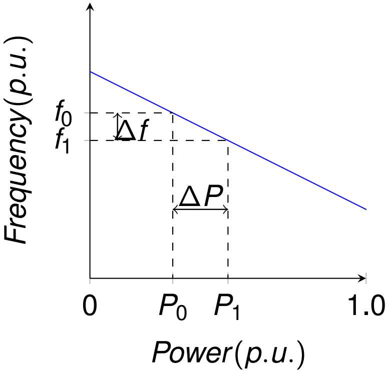
- However, it is the power plant owners who can control the frequency.

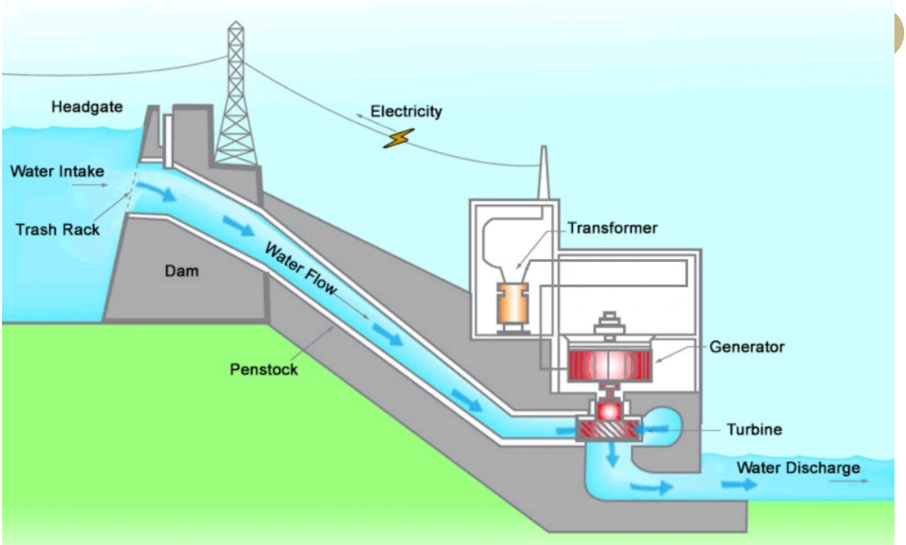


Load and production balancing

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

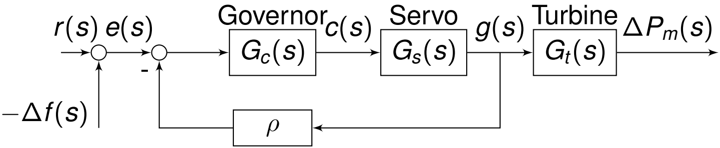


Hydro power plant



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



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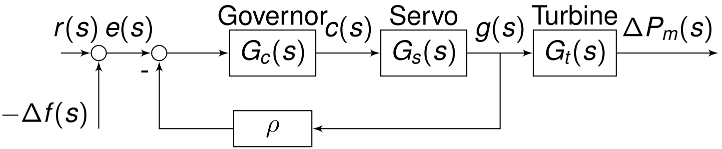
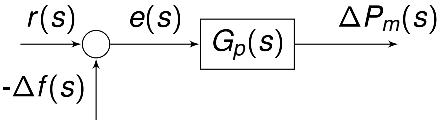
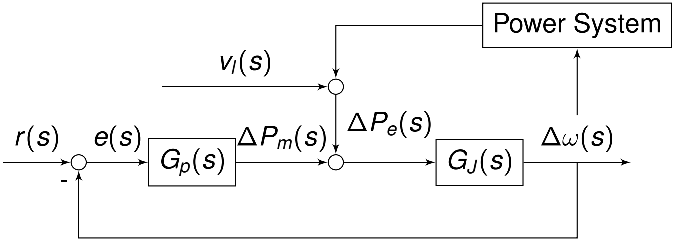




The frequency containment process $G_p(s)$ in the power system

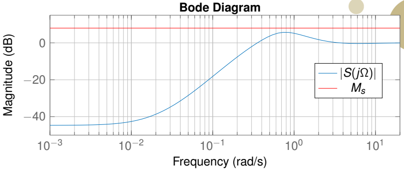
- $G_J(s)$ represents the swing dynamics of the power plant.
- $v_l(s)$ represents stochastic load.



Stability requirements for frequency control

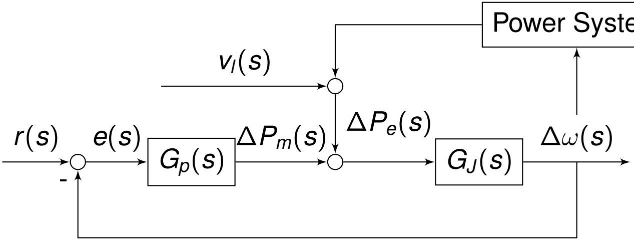
— Stability margin from control theory:

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



— where:

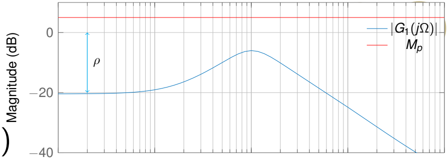
$$S(s) = \frac{1}{1 + G_p(s)G_J(s)} \qquad (2)$$



Performance requirements for frequency control

— We want to contain frequency deviations.

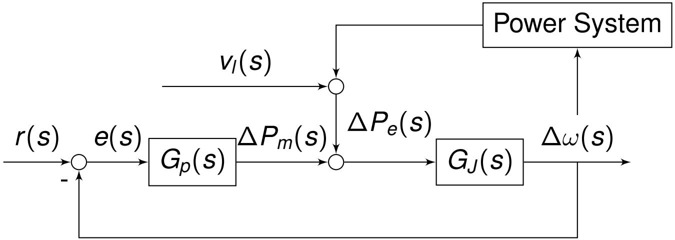
$$\Delta\omega(s) = \frac{G_J}{1 + G_p(s)G_J(s)}\Delta P_e(s) \quad (3)$$



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

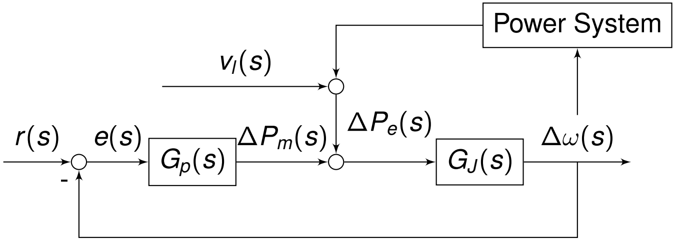
— Define

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



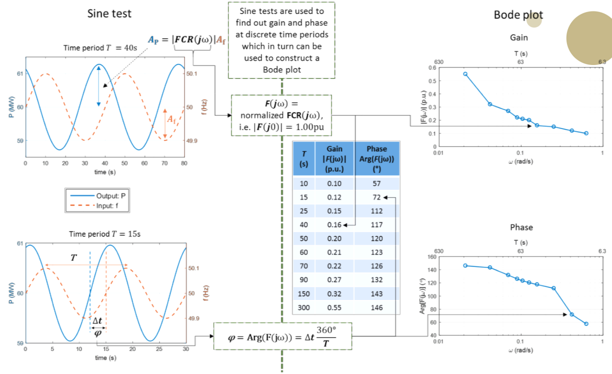
Future of frequency control

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

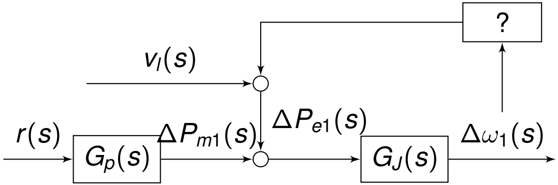


Industry proposed tests

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



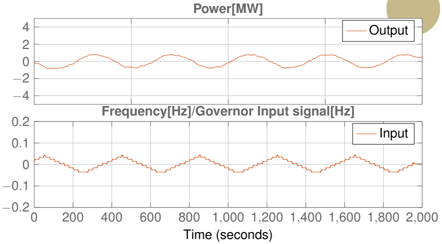
T (s)	Gain $\lvert F(j\omega)\rvert$ (p.u.)	Phase Arg($F(j\omega)$) (°)
10	0.10	57
15	0.12	72
25	0.15	112
40	0.16	117
50	0.20	120
60	0.21	123
70	0.22	126
90	0.27	132
150	0.32	143
300	0.55	146

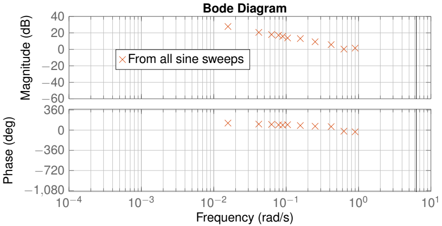


Example from real tests

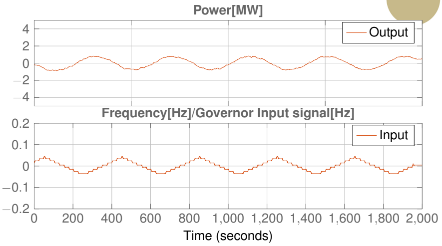
— The power plant needs to be disconnected

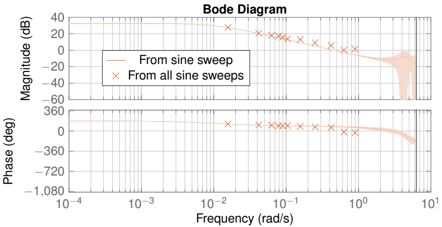
— Takes up to 20 hours.





Example from real tests





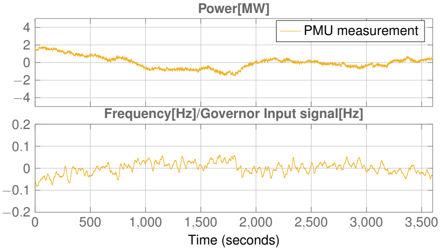
- The power plant needs to be disconnected
- Takes up to 20 hours.
- Only one sine test needed with system identification.

Motivation

— Can we do the tests easier?

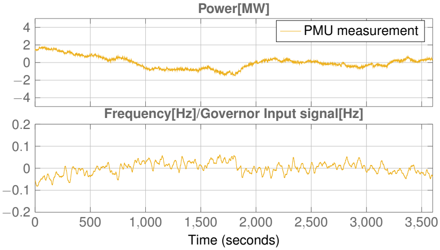
Motivation

- 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?



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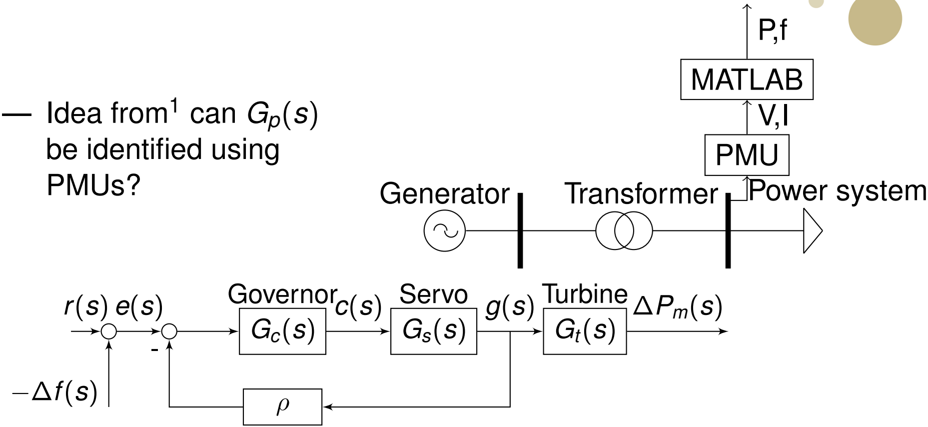
Background

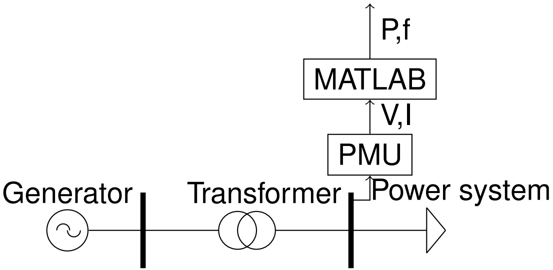
— Idea from[1] can $G_p(s)$ be identified using PMUs?



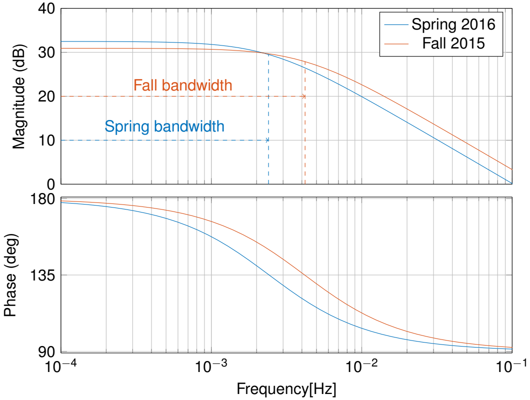
[1] Dinh Thuc Duong et al. "Estimation of Hydro Turbine-Governor's Transfer Function from PMU Measurements". In: IEEE PES General Meeting. Boston: IEEE, July 2016

Methodology

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



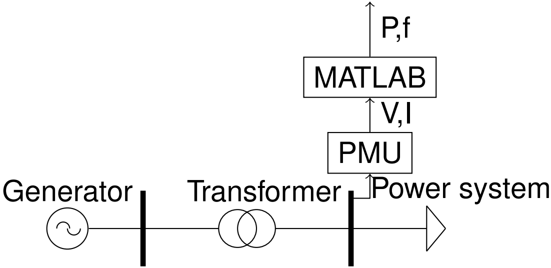
Estimated droop and bandwidth



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

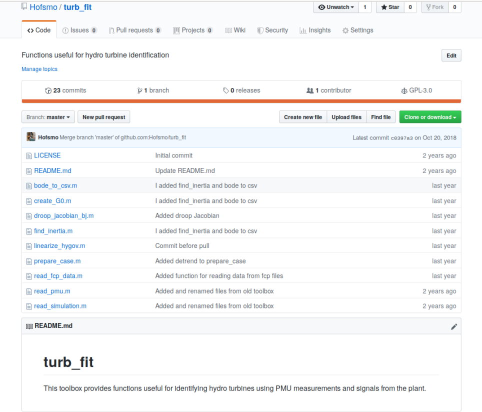
Main contributions to the research questions

— 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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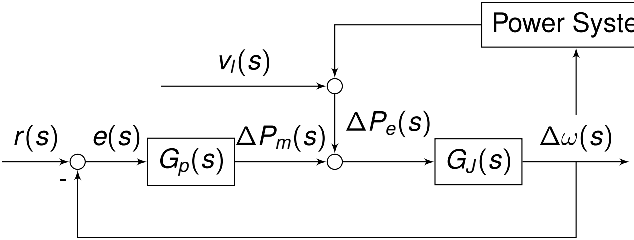
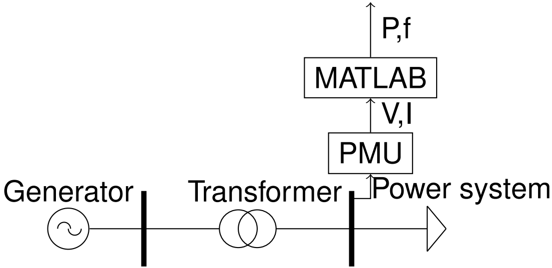
Motivation

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



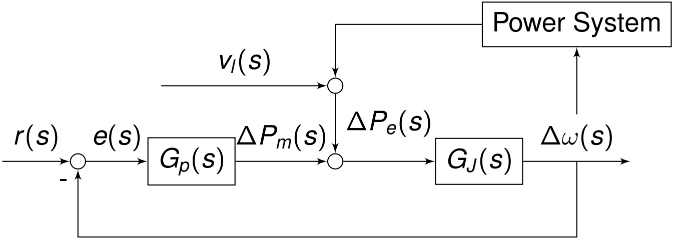
What do we need to model?

— From the PMU we get



What do we need to model?

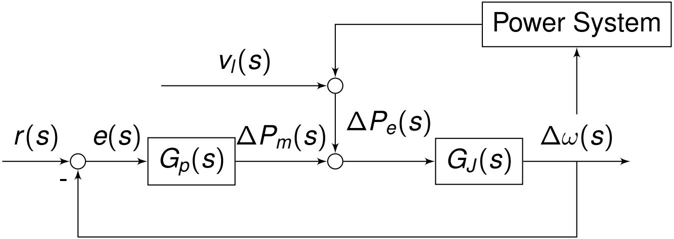
— From the PMU we get
  - Power: $\Delta P_e(s)$.



What do we need to model?

— From the PMU we get

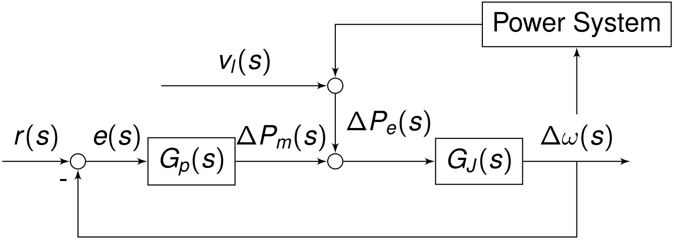
- Power: $\Delta P_e(s)$.
- Frequency: $\Delta f(s) \approx 2\pi \Delta\omega(s)$.



What do we need to model?

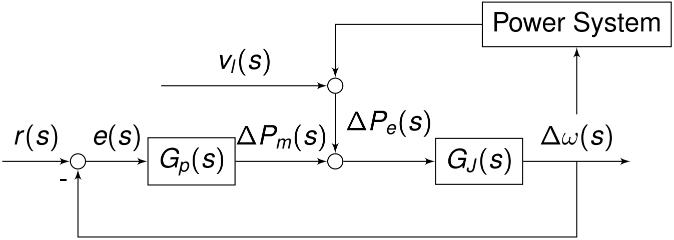
— From the PMU we get
  - Power: $\Delta P_e(s)$.
  - Frequency: $\Delta f(s) \approx 2\pi \Delta\omega(s)$.

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



What do we need to model?

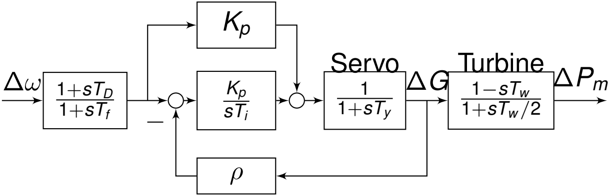
- From the PMU we get
  - Power: $\Delta P_e(s)$.
  - Frequency: $\Delta f(s) \approx 2\pi\Delta\omega(s)$.
- We need to model how $\Delta P_e(s)$ and $\Delta f(s)$ is related through the power system.
- We also need to model the power plant consisting of $G_p(s)$ and $G_J(s)$.



Power plant model

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

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



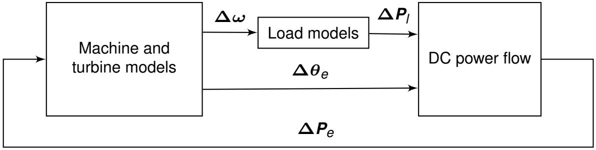
Power system model

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

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

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

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



Test system

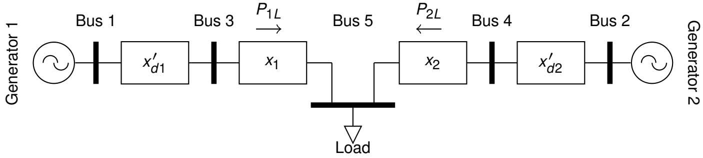
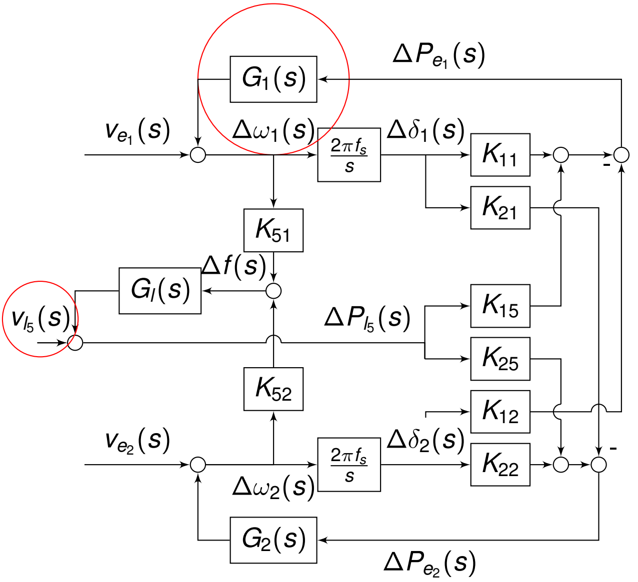


Figure: Single line diagram

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

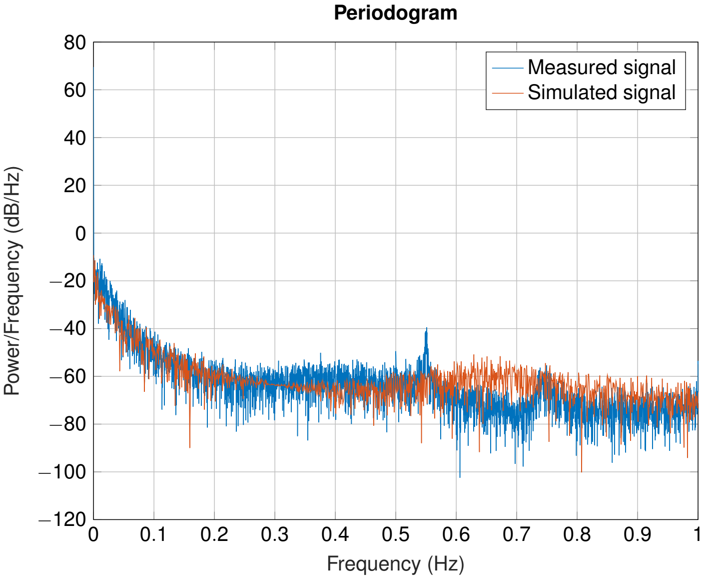


Figure: Power spectrum density of measured and simulated frequency

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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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.