Norwegian University of Science and Technology

Frequency control and stability requirements on hydro power plants

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Department of electrical engineering

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Outline

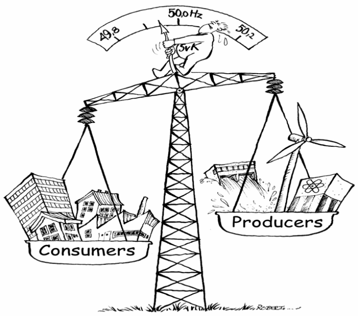
Problem

Paper I

Paper II

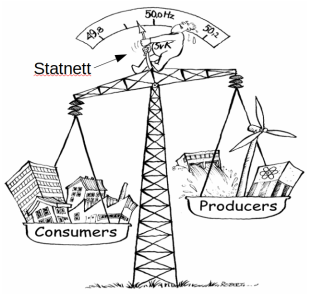
Load and production balancing

— The power system frequency measures the power balance.



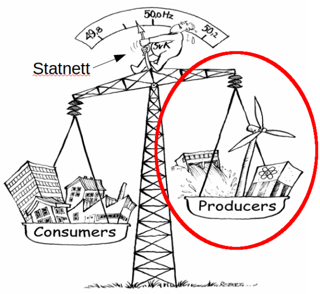
Load and production balancing

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



Load and production balancing

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



Buying frequency control

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

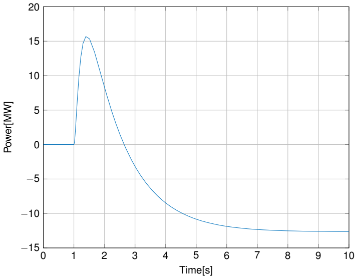


Figure: Frequency control response to step change in frequency

Buying frequency control

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

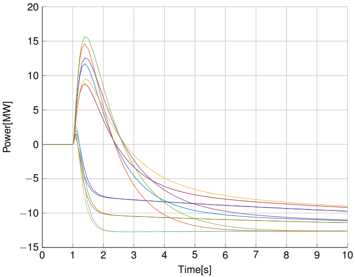


Figure: Frequency control response to step change in frequency

Buying frequency control

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

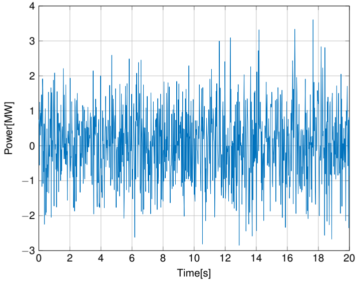


Figure: Frequency control response to step change in frequency

Future of frequency control

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

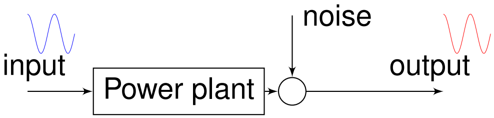
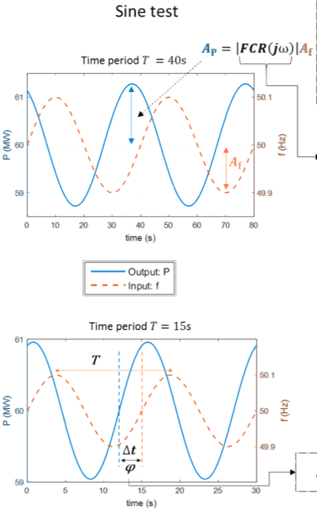


Figure: Test of power plant

Tests proposed by the industry



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

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

T (s)	Gain $\lvert F(j\omega)\rvert$ (p.u.)	Phase Arg(F(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

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

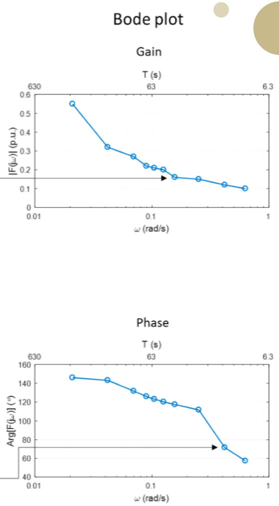
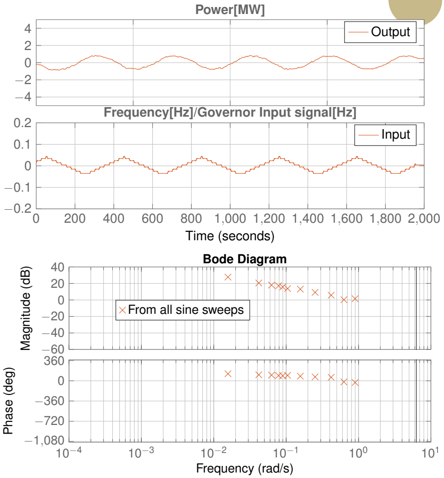


Figure: Testing procedure [source:ENTSO-E]

Example from real tests

— The power plant needs to be disconnected

— Takes up to 20 hours.

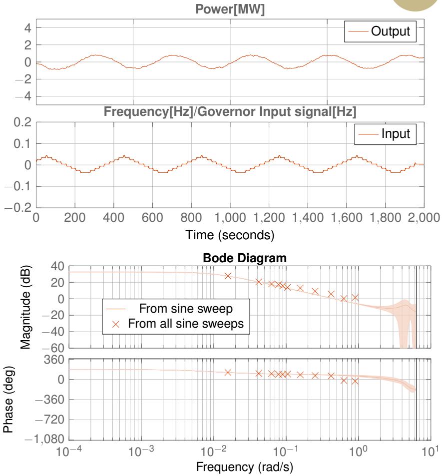


Example from real tests

— The power plant needs to be disconnected

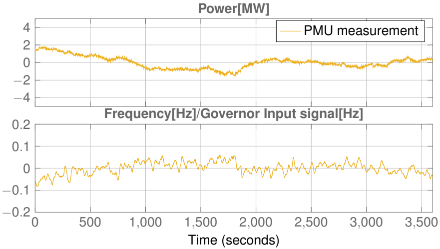
— Takes up to 20 hours.

— Only one sine test needed with model learning.



Motivation

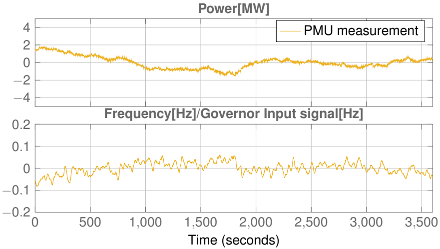
— The power system is never really in steady state.



Motivation

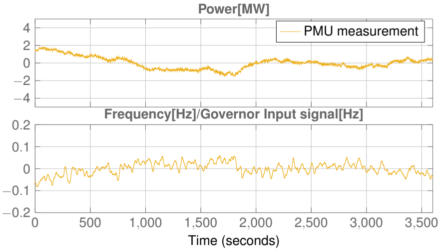
— The power system is never really in steady state.

— Can the power plant dynamics be identified from normal operation measurements?



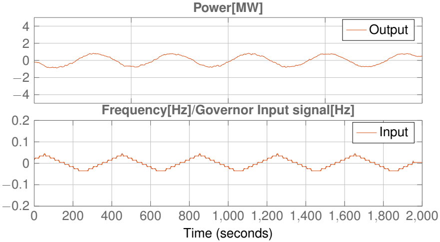
Research questions

— Can power plant dynamics be identified using a PMU?



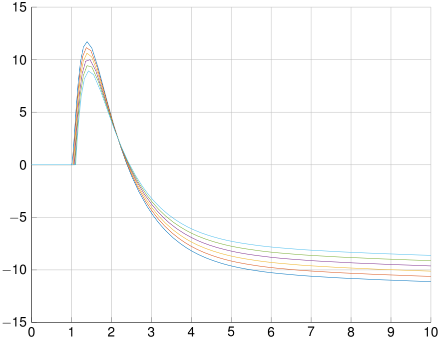
Research questions

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



Research questions

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



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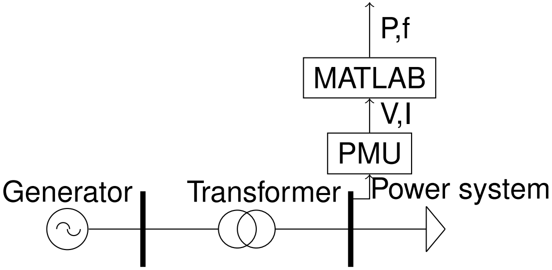
Background

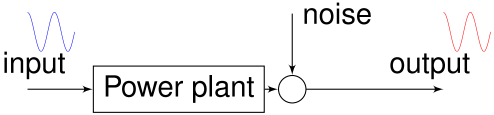
— Idea from[1] can the power plant dynamics be identified using PMUs



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

Background

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



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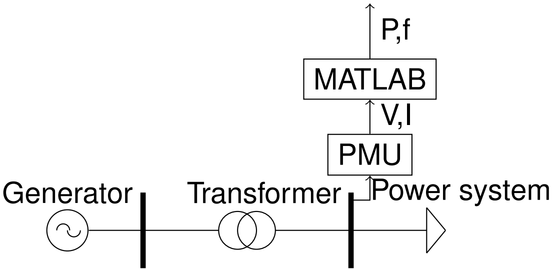
Methodology

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



Vector fitting basics

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

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- It assumes the system to have the following structure.

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

Vector fitting basics

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

- 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.

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

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

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

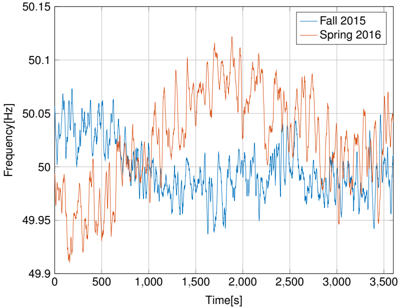
$$y_i = \int_0^t e^{\tilde{p}_i(t-\tau)} y_i(\tau) d\tau \tag{5}$$

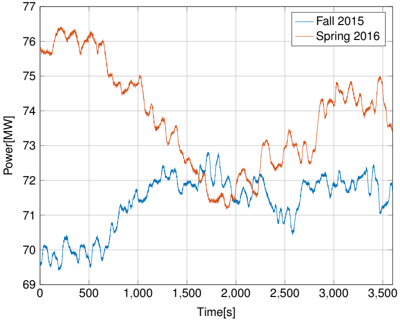
Vector fitting basics ctd.

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

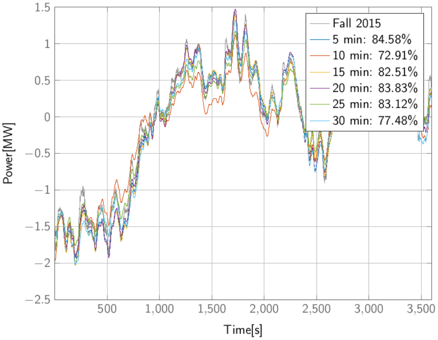
$$y(t) - (\tilde{d}x(t) + \sum_{i=1}^{n_p} \tilde{r}_i x_i - \sum_{i=1}^{n_p} \tilde{k}_i y_i) \tag{6}$$

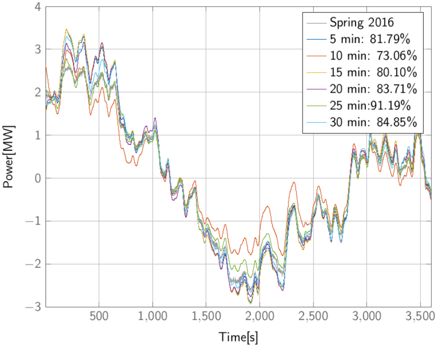
Cross validation using distant data sets



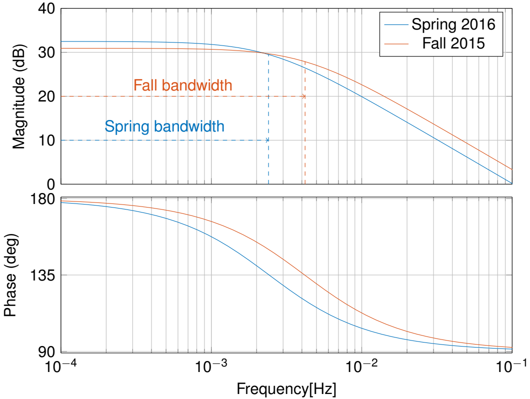


Cross validation using distant data sets





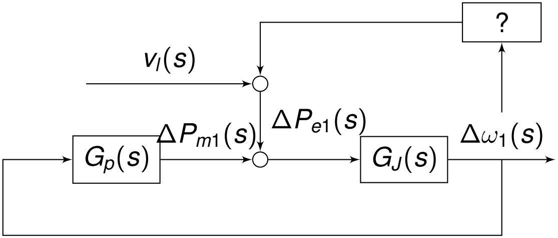
Estimated droop and bandwidth



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

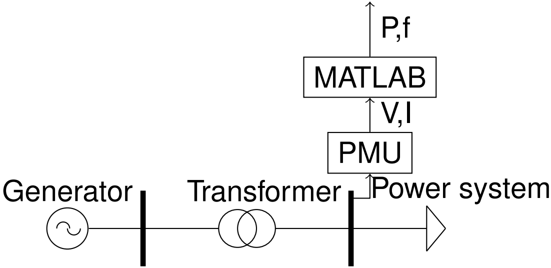
Shortcoming with the paper

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



Main contributions to the research questions

— Promising results for 19 datasets.



Main contributions to the research questions

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

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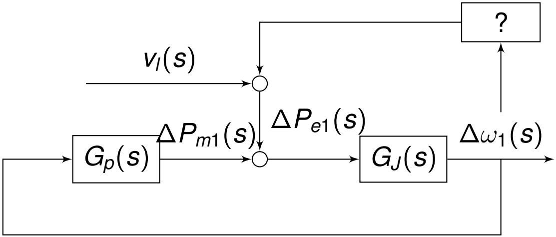
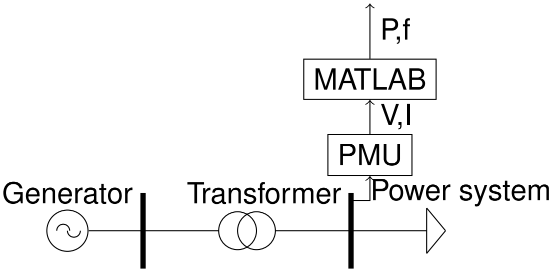
Motivation

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



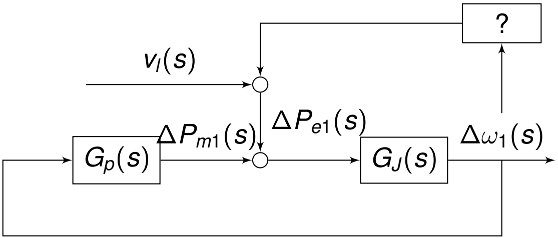
What do we need to model?

— From the PMU we get



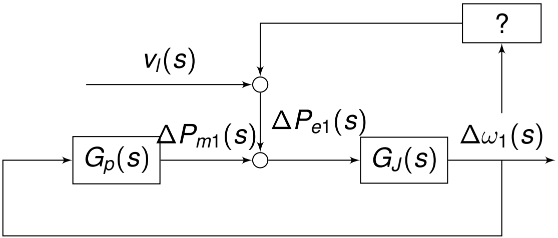
What do we need to model?

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



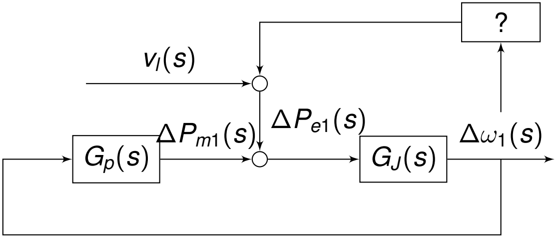
What do we need to model?

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



What do we need to model?

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



Idea behind the test system

— The frequency and power system angle is related.

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

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

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

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

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