NTNU
Norwegian University of
Science and Technology

Identification of turbine dynamics using PMUs

Sigurd Hofsmo Jakobsen
Department of electrical engineering

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Outline

- Background
- Previous work
- Theoretical validation
- Results
- Conclusions and further work

Background

Power Systems

- Large interconnected system

Figure: Nordic power system[ENTSO-e]

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Power Systems

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- Large interconnected system
- Balancing challenge

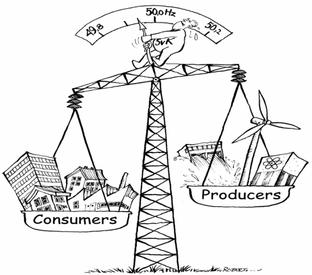


Figure: Balancing challenge[Statnett]

Background

The power system is dynamic

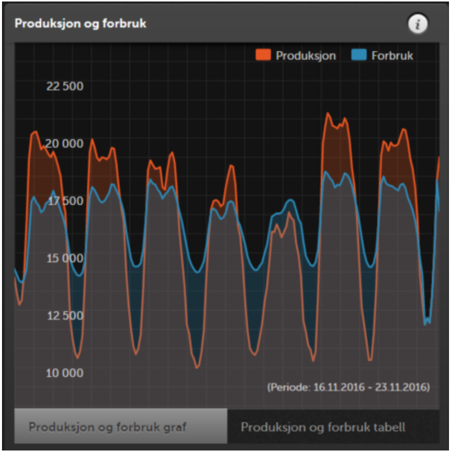
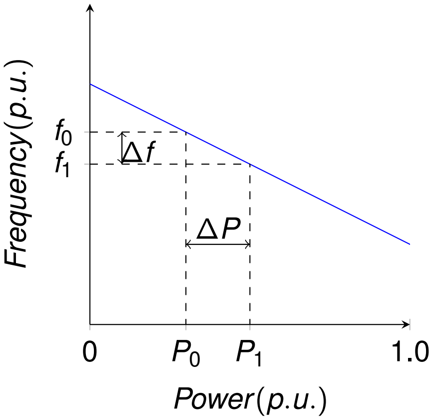


Figure: Production and consumption [statnett.no]

Background

Frequency containment reserves (FCR)

- Power balance/frequency containment control (FCC) is mainly determined by governor response.
- Activation of primary reserves is determined by the governor droop settings.



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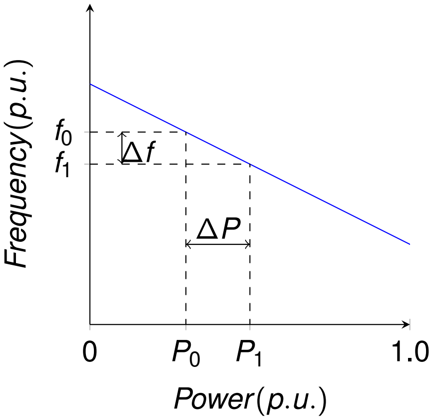
- Power balance/frequency containment control (FCC) is mainly determined by governor response.
- Activation of primary reserves is determined by the governor droop settings.
- In steady state



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Challenges in operation

- Towards 100% renewable electricity generation
  - Larger variability
  - More uncertainty
  - Increasing complexity

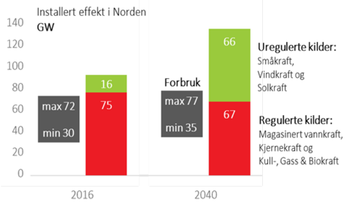

Figure: Present and future energy mix[Statnett]

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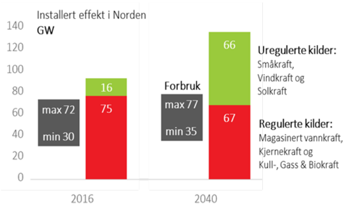

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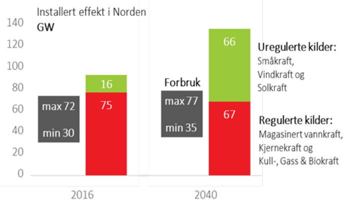

Figure: Present and future energy mix[Statnett]

Background
Challenges in operation

- Towards 100% renewable electricity generation
    - Larger variability
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    - Increasing complexity
- More dynamics
- Less time for actions
- **Hydropower** is the main resource for balancing

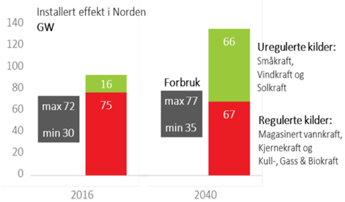
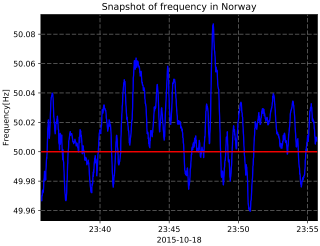


Figure: Present and future energy mix[Statnett]

Background

Frequency quality in the Nordics

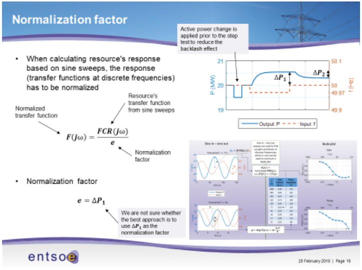
- From 2008 the time the frequency has been outside its allowed band has increased
- The performance of hydro turbine governors play an important role



Background

New requirements on FCR

- Nordic TSOs are developing new requirements on FCR
- This includes offline testing and verification of performance



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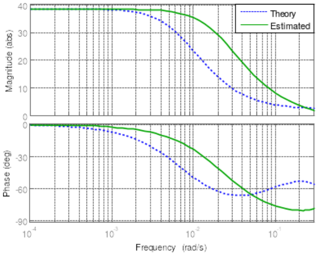
2. What is the best way to do the tests?
3. Is there anything to gain from combining traditional tests at the plant with PMU measurements?

Previous work

- Governor dynamics were identified using the ARX model structure



Previous work

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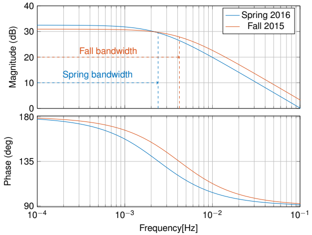
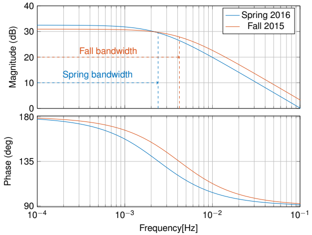
- Governor dynamics were identified using time domain vector fitting



Previous work

- Governor dynamics were identified using the ARX model structure
- Governor dynamics were identified using time domain vector fitting
- However, no theoretical validation was made.



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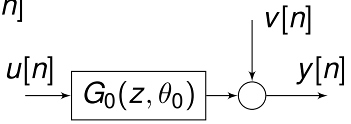
- Ongoing work:
    - Investigation of assumptions made in the validation.
    - Investigation of least costly experiment for validation.

Theoretical validation

System identification basic

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

$$\mathcal{S} : y[n] = G_0(z, \theta_0)u[n] + H_0(z, \theta_0)e[n] \tag{1}$$



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

$$\hat{\theta}_N = \arg\min_{\theta} \frac{1}{N} \sum_{n=1}^{N} \epsilon^2(n, \theta) \tag{2}$$

Theoretical validation
Consistency

- A consistent estimate means that the true parameter vector θ_0 is the unique solution to the asymptotic prediction error criterion.

$$\theta^* = \arg\min_{\theta} \bar{E}\epsilon^2(n,\theta) \tag{3}$$

with

$$\bar{E}\epsilon^2(n,\theta) = \lim_{N\to\infty} \frac{1}{N}\sum_{t=1}^{N} E\epsilon^2(n,\theta) \tag{4}$$

and

$$\epsilon(n,\theta) = H_1^{-1}(z,\theta)(y[n] - G_1(z,\theta)u[n]) \tag{5}$$

Theoretical validation
System identification basics take away

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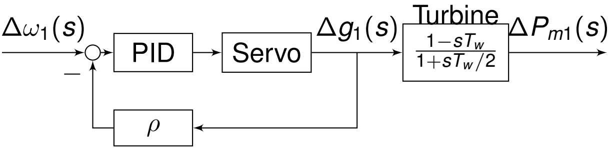
System identification basics take away

- Define what one wants to identify.
- Define the input and outputs of the system.
- Prove that one will obtain a consistent estimate using the selected inputs and outputs.
- *The input and output have to be modeled to do this*

Definition of identification problem

Choice of input and output to the identification problem



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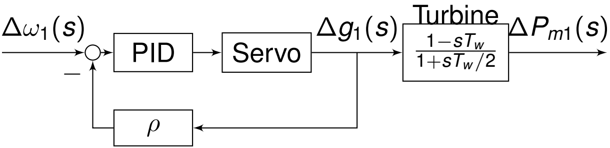

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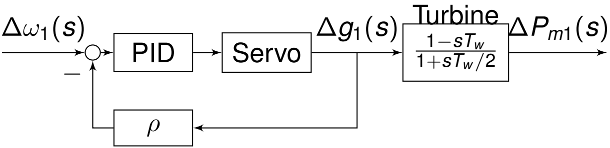

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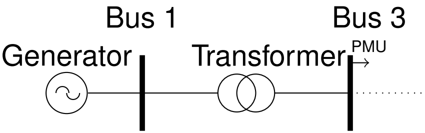

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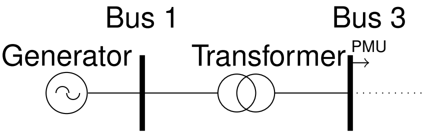

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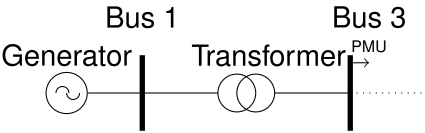

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  - $\Delta\omega_3[n]$ and,
  - $\Delta P_{e3}[n]$.

Definition of identification problem

Assumptions regarding input and output

- We assume that the PMU is situated sufficiently close to the generator such that:
  - $\Delta\omega_1[n] \approx \Delta\omega_3[n]$ and,
  - $\Delta P_{e1}[n] \approx \Delta P_{e3}[n]$.
- The electrical power is related to the mechanical power by the swing equation:

$$\Delta\omega_1(s) = \frac{\Delta P_{m1}(s) - \Delta P_{e1}(s)}{2\mathcal{H}_1 s + K_{d1}} \tag{6}$$

Definition of identification problem

Transfer function that can be identified using PMUs

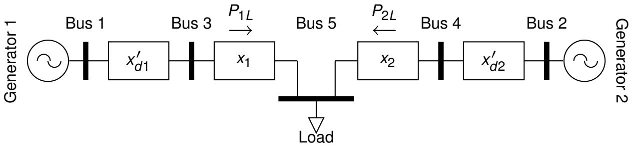
- We now introduce the following transfer functions:
  - The turbine and governor dynamics are described by $G_{t1}(s)$ and,
  - $G_{J1}(s) = 1/(2\mathcal{H}_1 s + K_{d1})$
- We can now write the angular speed as:

$$\Delta\omega_1(s) = -\frac{G_{J1}(s)}{1 + G_{J1}(s)G_{t1}(s)}\Delta P_{e1}(s) + v_1(s) \tag{7}$$

- The transfer function $G_1(s)$ we can identify is therefore:

$$G_1(s) = -\frac{G_{J1}(s)}{1 + G_{t1}(s)G_{J1}(s)} \tag{8}$$

Introduction of test system



- *We need to model relation between $P_{e1}[n]$ and $\Delta\omega_1[n]$.*
- We therefore introduce a small test system consisting of:
  - The plant we want to identify.
  - an aggregated plant,
  - an aggregated load and,
  - the line reactances.

Test system for identification
Model of the load

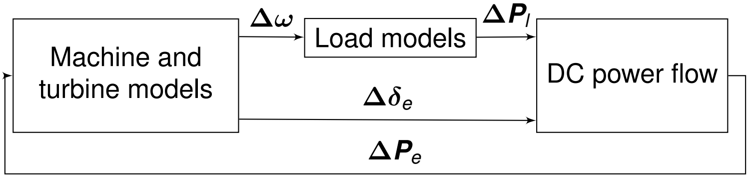
- We assume the following model for the load

$$\Delta P_{load} = \Delta P_f + \Delta P_s \tag{9}$$

where:
  - ΔP_f: is frequency dependent part of the load
  - ΔP_s: is the stochastic part of the load assumed to be filtered white noise.

Test system for identification

Connecting the elements together



- To connect the elements together we will use the dc power flow.
  - It is simple.
  - Strong coupling between active power and frequency.

Test system for identification

DC power flow

- We start by organizing the DC power flow in terms of loads and generators

$$\begin{bmatrix} \Delta \boldsymbol{P}_e \\ \Delta \boldsymbol{P}_l \end{bmatrix} = \begin{bmatrix} \boldsymbol{B}_{11} & \boldsymbol{B}_{12} \\ \boldsymbol{B}_{21} & \boldsymbol{B}_{22} \end{bmatrix} \begin{bmatrix} \Delta \delta_e \\ \Delta \delta_l \end{bmatrix} \tag{10}$$

- The angle of the non generator buses can now be calculated as:

$$\Delta \delta_l = \boldsymbol{B}_{22}^{-1} (\Delta \boldsymbol{P}_l - \boldsymbol{B}_{21} \Delta \delta_e) \tag{11}$$

- The power injections at the generator buses are:

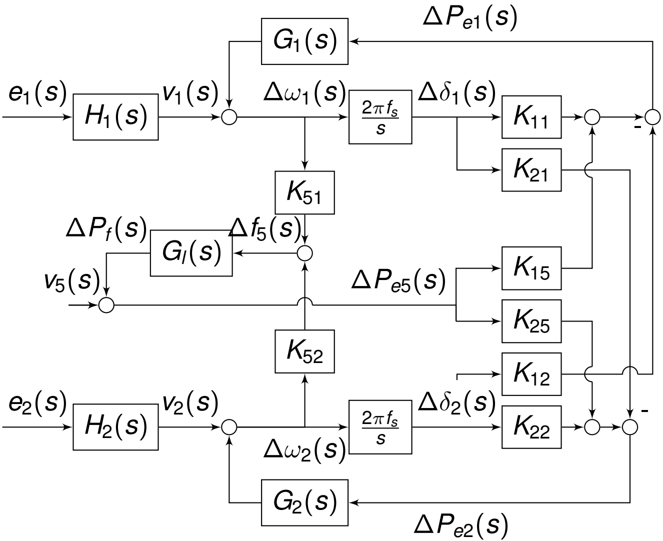
$$\Delta \boldsymbol{P}_e = \boldsymbol{B}_{11} \Delta \delta_e + \boldsymbol{B}_{12} \Delta \delta_l \tag{12}$$

- Finally, we substitute (**??**) into (**??**) and rearrange to obtain.

$$\Delta \boldsymbol{P}_e = \begin{bmatrix} \boldsymbol{B}_{11} - \boldsymbol{B}_{12} \boldsymbol{B}_{22}^{-1} \boldsymbol{B}_{21} & \boldsymbol{B}_{12} \boldsymbol{B}_{22}^{-1} \end{bmatrix} \begin{bmatrix} \Delta \delta_e \\ \Delta \boldsymbol{P}_l \end{bmatrix} \tag{13}$$

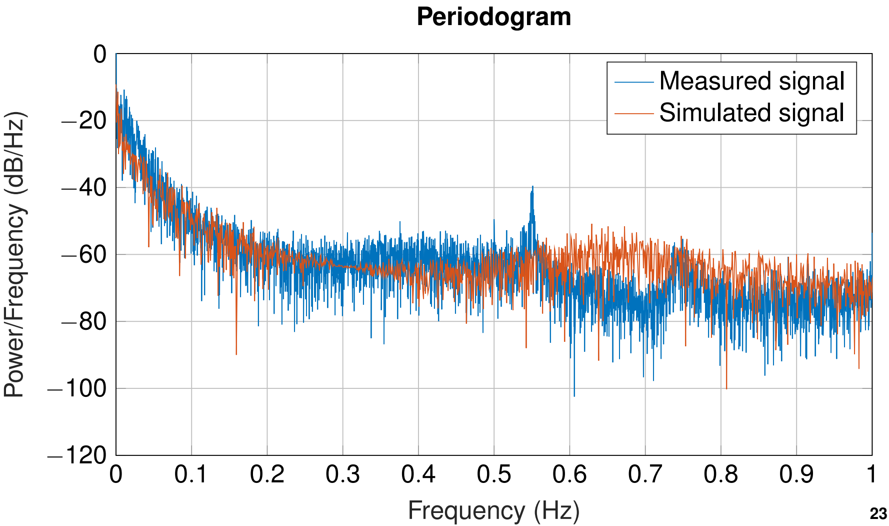
Test system for identification

Putting it all together



Test system for identification

System frequency response



Results

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:

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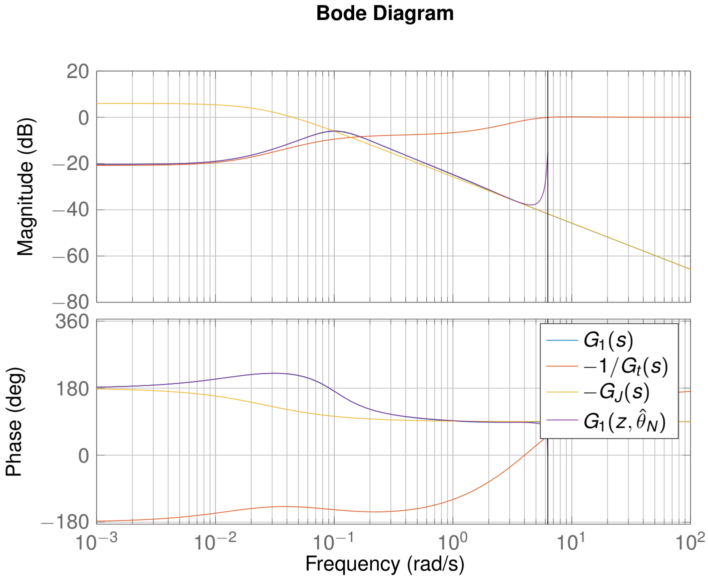
Results

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 white noise process
  - The measurement error of the electrical power is negligible.
  - The measured frequency is a good estimate of the generator speed.

Results

Results from simulations



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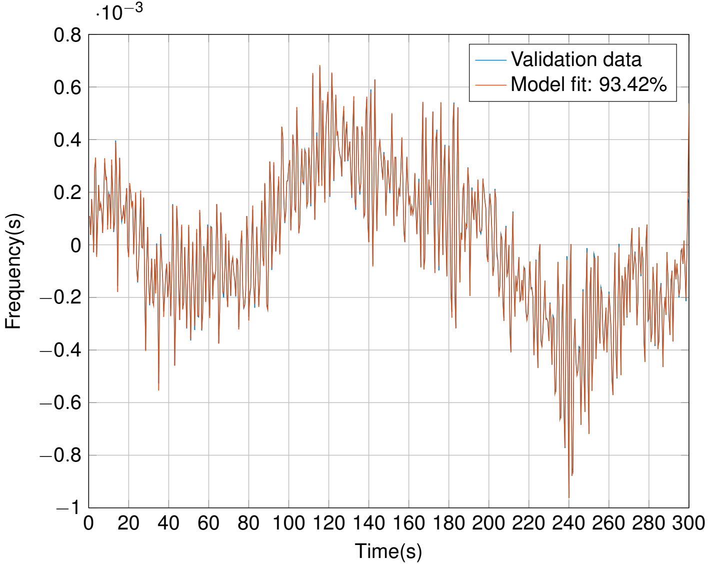

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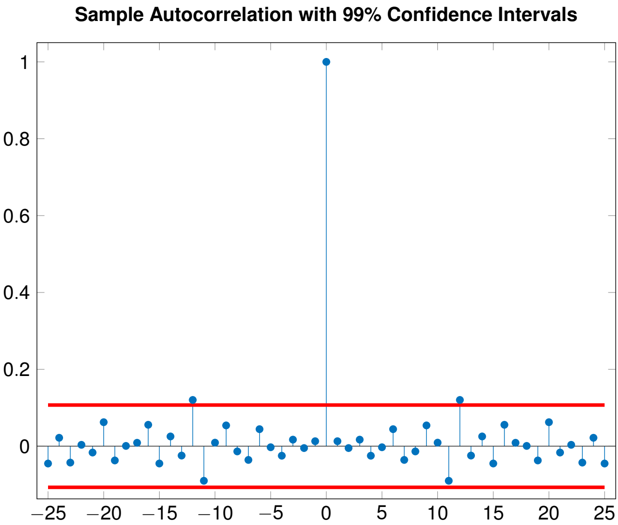
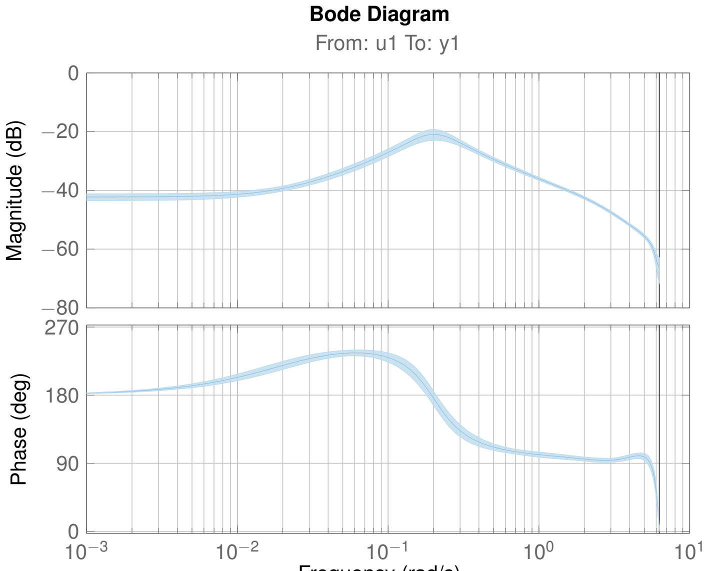


Results

Results from the power system



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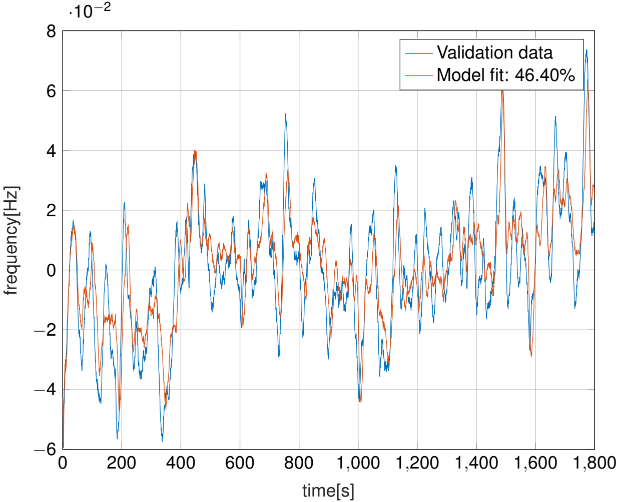

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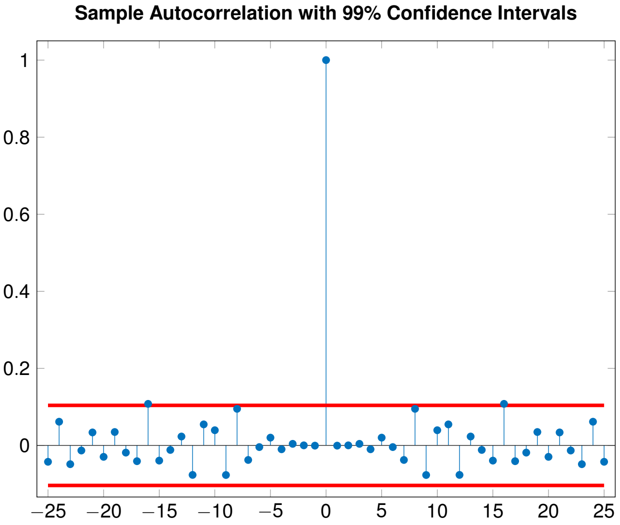


Assumption that $\Delta\omega_1[n] \approx \Delta\omega_3[n]$

- In reality $\Delta\omega_1[n] \approx \Delta\omega_3[n]$ is only valid for a certain frequency range.
- To show this we will develop an expression for $\omega_\epsilon[n] = \omega_1[n] - \omega[n]$.

Assumption that $\Delta\omega_1[n] \approx \Delta\omega_3[n]$

The angular velocity at bus 3

- We need an expression for the angular velocity at bus 3.
- The two standard options would be:
  - The time derivative of the voltage angle at the bus.
  - The centre of inertia equation.
- We will instead use the frequency divider(FD) formula (Milano 2017).

Assumption that $\Delta\omega_1[n] \approx \Delta\omega_3[n]$

Derivation of the FD formula

- Start by the DC power flow assumption assuming the load changes to be negligible.

$$\begin{bmatrix} \boldsymbol{\Delta P_e} \\ \mathbf{0} \end{bmatrix} = \begin{bmatrix} \boldsymbol{B}_{11} & \boldsymbol{B}_{12} \\ \boldsymbol{B}_{21} & \boldsymbol{B}_{22} \end{bmatrix} \begin{bmatrix} \boldsymbol{\Delta\delta_e} \\ \boldsymbol{\Delta\delta_l} \end{bmatrix} \tag{14}$$

- Then we rearrange

$$\boldsymbol{\Delta\delta_l} = -\boldsymbol{B}_{22}^{-1}\boldsymbol{B}_{21}\boldsymbol{\Delta\delta_e} \tag{15}$$

- We now take the time derivative to obtain.

$$\boldsymbol{\Delta\omega_l} = -\boldsymbol{B}_{22}^{-1}\boldsymbol{B}_{21}\boldsymbol{\Delta\omega_e} \tag{16}$$

Assumption that $\Delta\omega_1[n] \approx \Delta\omega_3[n]$

FD example

$$
\boldsymbol{B} = \left[\begin{array}{cc:ccc}
b'_{d1} & 0 & -b'_{d1} & 0 & 0 \\
0 & b'_{d2} & 0 & -b'_{d2} & 0 \\
\hdashline
-b'_{d1} & 0 & b'_{d1} + b_1 & 0 & -b_1 \\
0 & -b'_{d2} & 0 & b'_{d2} + b_2 & -b_2 \\
0 & 0 & -b_1 & -b_2 & b_1 + b_2
\end{array}\right] \tag{17}
$$

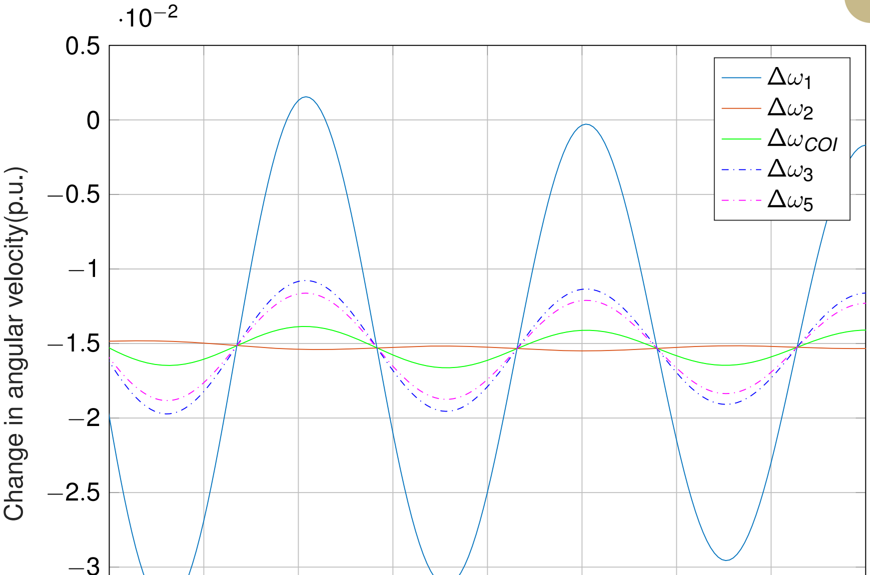
$$
\Delta\omega_3 = \frac{(b_1 b_{d2} + b_1 b_2 + b_2 b_{d2}) b_{d1}}{|\boldsymbol{B}_{22}|} \Delta\omega_1 + \frac{b_1 b_2 b_{d2}}{|\boldsymbol{B}_{22}|} \Delta\omega_2 \tag{18}
$$

$$
\Delta\omega_5 = \frac{b_1 b'_{d1} (b'_{d2} + b_2)}{|\boldsymbol{B}_{22}|} \Delta\omega_1 + \frac{b_2 b'_{d2} (b'_{d1} + b_1)}{|\boldsymbol{B}_{22}|} \Delta\omega_2 \tag{19}
$$

$$
\Delta\omega_{COI} = \frac{1}{\mathcal{H}_1 + \mathcal{H}_2} (\mathcal{H}_1 \Delta\omega_1 + \mathcal{H}_2 \Delta\omega_2) \tag{20}
$$

Assumption that $\Delta\omega_1[n] \approx \Delta\omega_3[n]$

FD example



Assumption that $\Delta\omega_1[n] \approx \Delta\omega_3[n]$

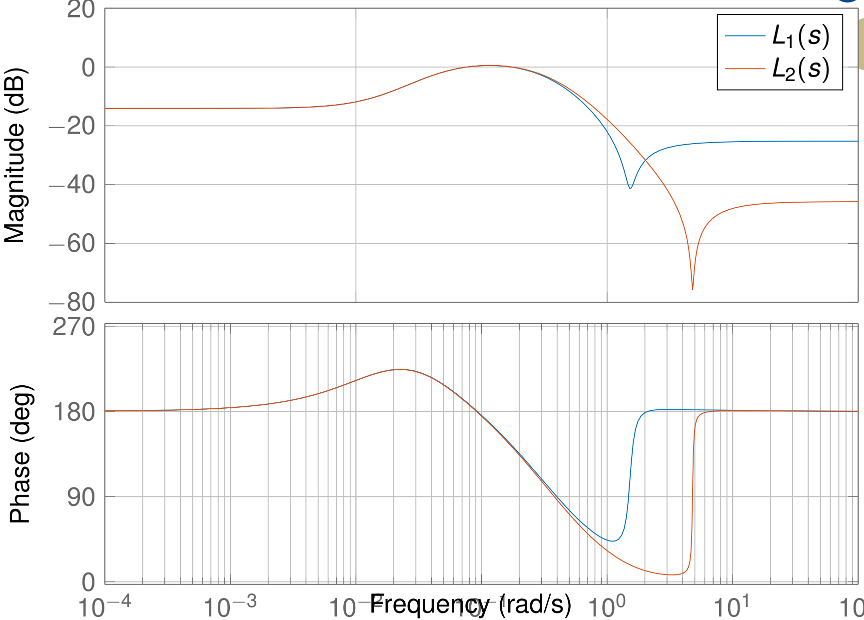
Difference between angular speeds at bus 1 and 3

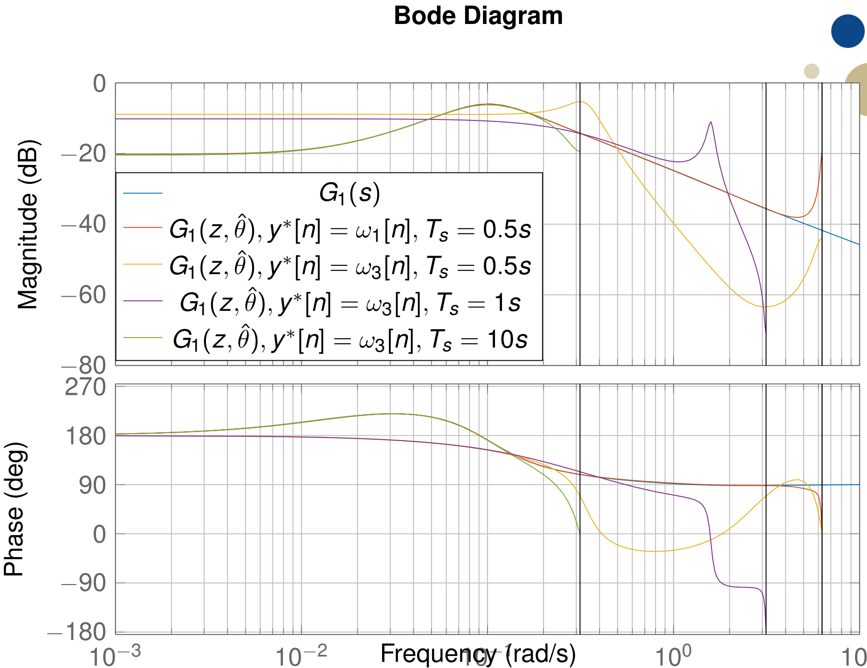
- We can write the difference as

$$\omega_\Delta(s) = \frac{L_1(s)(1 - K_{f1}) - K_{f2}L_2(s)}{M(s)} \Delta P_l(s) \tag{21}$$

- $\omega_\Delta(s)$ is zero under two different conditions.
  1. $b_1 >> b_2$
  2. $L_1(s) = L_2(s)$

Bode Diagram




Bode Diagram
Magnitude (dB)
0
−20
−40
−60
−80
$G_1(s)$
$G_1(z,\hat{\theta}), y^*[n] = \omega_1[n], T_s = 0.5s$
$G_1(z,\hat{\theta}), y^*[n] = \omega_3[n], T_s = 0.5s$
$G_1(z,\hat{\theta}), y^*[n] = \omega_3[n], T_s = 1s$
$G_1(z,\hat{\theta}), y^*[n] = \omega_3[n], T_s = 10s$
Phase (deg)
270
180
90
0
−90
−180
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Frequency (rad/s)

Conclusions and further work

- Conclusions:
  - It is indeed possible to identify the turbine dynamics(closed loop with electromechanical dynamics) using PMU measurements.
  - However, only low the low frequency dynamics
- Future work:
  - Look into how to best do the identification of turbine dynamics.
  - Look into control solutions using identified models.