Vector fitting for estimation of turbine governor parameters

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Outline

Frequency quality

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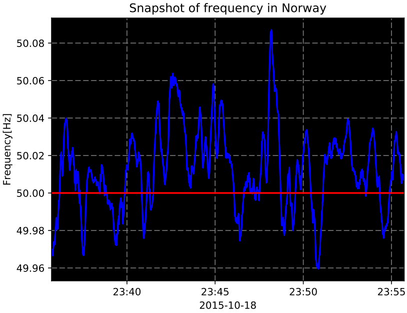

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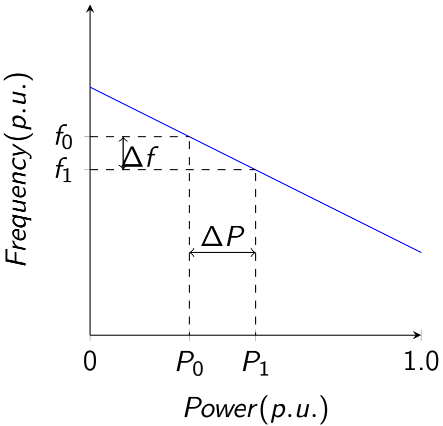

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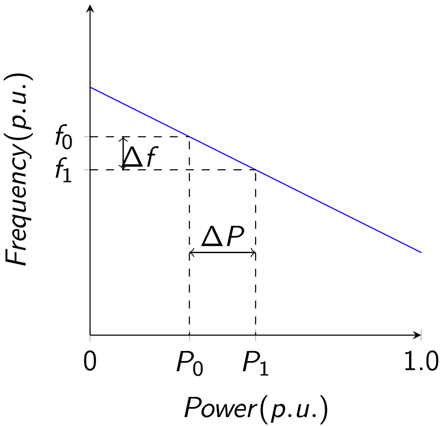

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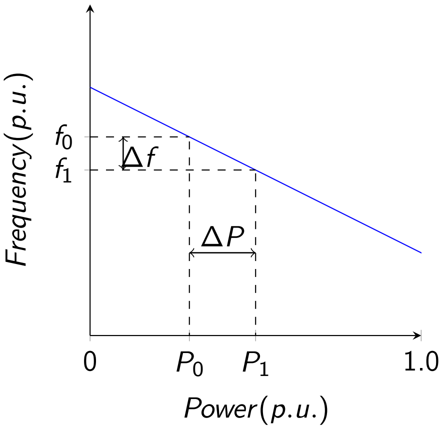

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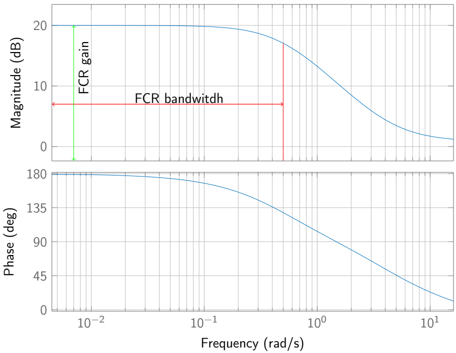
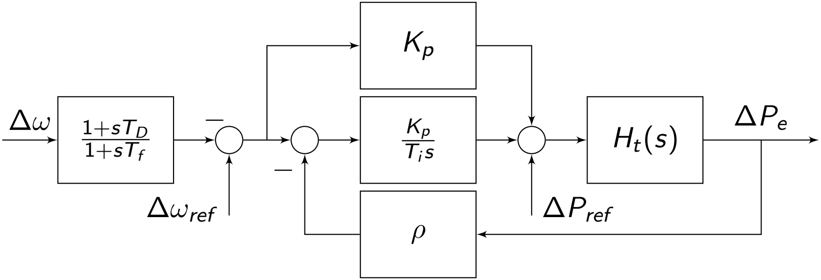
- To prevent large deviations in frequency generators participate in frequency containment control (FCR)
- FCR is sometimes referred to as primary control
- Generators of a certain size have to contribute to this control
- It is of interest to monitor the generators' FCR performance with respect to both gain and bandwidth



Hydro turbine governors

- Typically implemented as a PID controller



$$H = -K_p \frac{1+sT_D}{1+sT_f} \cdot \frac{1+sT_i}{\rho K_p + sT_i} \tag{1}$$

From (1) one can see that the system's poles will be placed at:

$$p_1 = -\frac{1}{T_f}, \;\; p_2 = -\frac{\rho K_p}{T_i} \tag{2}$$

Research questions

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- Can identification of turbine governors be used to analyze the frequency quality?
- Can the identification be done using ambient power system data?
- Is vector fitting a suitable method for doing the identification?

Previous work

- The ARX[1] model structure was used on parts of the same dataset as used in this study in [1]
- The authors of [2] use constrained optimization on disturbance data from the Crete power system.
- and the authors of [3] apply an unscented Kalman filter to the measurements from a trip event in the Midcontinent Independent System.
- Other studies using only simulation data also exist.

[1] Autoregressive exogenous

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Vector fitting basics

- Vector fitting fits a transfer function to measured input and output data

$$Y(s) = H(s) \cdot U(s) \qquad (3)$$

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$$H(s) = d + \sum_{i=1}^{n_p} \frac{r_i}{s - p_i} \tag{4}$$

Vector fitting basics

- Vector fitting fits a transfer function to measured input and output data
- Finding the parameters in (3) is a nonlinear optimization.
- The idea behind vector fitting presented in [4] is to formulate the augmented problem (4) with known poles $\tilde{p}_i$.

$$Y(s) = H(s) \cdot U(s) \tag{3}$$

$$H(s) = d + \sum_{i=1}^{n_p} \frac{r_i}{s - p_i} \tag{4}$$

$$\sigma(s)H(s) = d + \sum_{i=1}^{n_p} \frac{r_i}{s - \tilde{p}_i} \tag{5}$$

Vector fitting basics continued

- How do we choose $\sigma(s)$?

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- First rewrite (3) and (4).

$$H(s) = \frac{\prod_{i=1}^{n_z}(1 - z_i)}{\prod_{i=1}^{n_p}(1 - p_i)} \tag{6}$$

$$\sigma(s)H(s) = \frac{\prod_{i=1}^{n_z}(1 - z_i)}{\prod_{i=1}^{n_p}(1 - \tilde{p}_i)} \tag{7}$$

Vector fitting basics continued

- How do we choose $\sigma(s)$?
- First rewrite (3) and (4).
- We can see that the zeros of $\sigma(s)$ must cancel the poles of (6)

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Vector fitting basics continued

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$$\sigma(s) = 1 + \sum_{i=1}^{n_p} \frac{k_i}{s - \tilde{p}_i} \tag{5}$$

$$d + \sum_{i=1}^{n_p} \frac{r_i}{s - \tilde{p}_i} = (1 + \sum_{i=1}^{n_p} \frac{k_i}{s - \tilde{p}_i})H_{measured}(s) \tag{6}$$

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- In (6) the unknowns are d, r_i, k_i for $\tilde{p}_i$ an initial guess is used.

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- (4) can now be solved by measuring $H(s)$ at multiple frequencies and multiplying with (5) which gives (6)
- In (6) the unknowns are d, r_i, k_i for $\tilde{p}_i$ an initial guess is used.
- The procedure is performed again with the calculated zeros of (4) as the updated starting poles $\tilde{p}_i$

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- Mathematically the criterion is formulated as follows.

$$\| \frac{\tilde{k}_1}{\tilde{p}_1}, \cdots, \frac{\tilde{k}_{n_p}}{\tilde{p}_{n_p}} \| < \epsilon \tag{7}$$

Method for model order reduction

- The order of the obtained models are reduced by discarding residues according to:

$$|\frac{r_i}{p_i},| < \epsilon, i \in n_p \tag{8}$$

Vector fitting in the time domain

- Multiplying the augmented problem (4) by the input and performing Laplace inverse gives vector fitting in the time domain [6]:

$$y(t) \approx \tilde{d}x(t) + \sum_{i=1}^{n_p} \tilde{r}_i x_i - \sum_{i=1}^{n_p} \tilde{k}_i y_i \tag{9}$$

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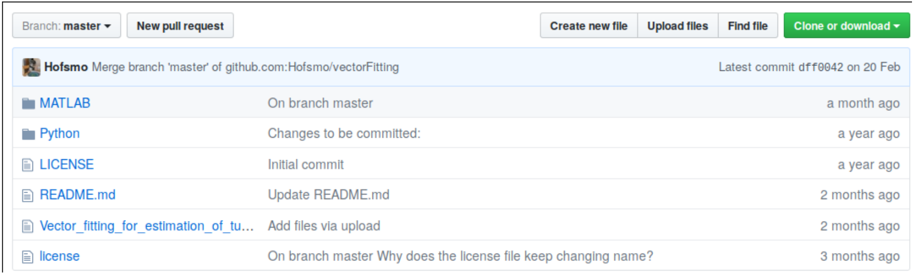
- In (9) x_i and y_i are the solutions of convolution integrals solved numerically using the trapezoidal rule:

$$x_i = \int_0^t e^{\tilde{p}_i(t-\tau)} x_i(\tau) d\tau \tag{10}$$

$$y_i = \int_0^t e^{\tilde{p}_i(t-\tau)} y_i(\tau) d\tau \tag{11}$$

Code for vector fitting

- The vector fitting implementation used in this work is available on GitHub: `https://github.com/Hofsmo/vectorFitting`



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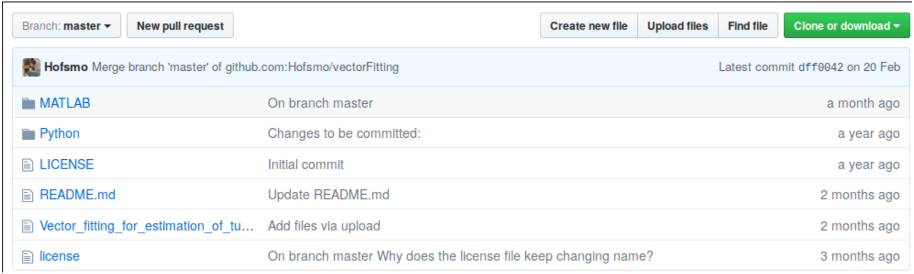
- The original vector fitting implementation in the frequency domain is available on `https://www.sintef.no/projectweb/vectfit/`



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3. Can the results be obtained using a small measurement time window?
4. Is the method fast?

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5. Cross validation and model selection

Data collection

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- Data sets with obvious nonlinearities such as ramping and saturation were discarded.

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- Self validation was not allowed.

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Choice of starting poles

- Starting poles should be chosen in the frequency range of interest.

Minutes	Poles	$[0, 0.5]$	$[0, 0.1]$	$[0, 0.05]$
5	Real	66.66%	66.66%	66.66%
	Complex	73.07%	74.60%	73.53%
	Mixed	74.89%	74.69%	74.42%
10	Real	68.45%	68.45%	68.45%
	Complex	72.49%	73.84%	72.75%
	Mixed	73.49%	72.60%	73.73%
15	Real	66.01%	66.01%	66.01%
	Complex	69.72%	70.40%	70.33%
	Mixed	70.86%	70.43%	70.12%
20	Real	70.73%	70.73%	70.73%
	Complex	72.53%	72.27%	71.16%
	Mixed	71.28%	71.91%	72.38%
25	Real	60.27%	60.27%	60.27%
	Complex	63.45%	62.31%	63.45%
	Mixed	63.14%	63.45%	63.45%
30	Real	68.01%	68.01%	68.01%
	Complex	71.75%	71.45%	72.54%
	Mixed	72.52%	71.44%	72.21%

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- Purely complex starting poles performs more or less the same as mixed poles.
- There is little difference between the length of the time windows.

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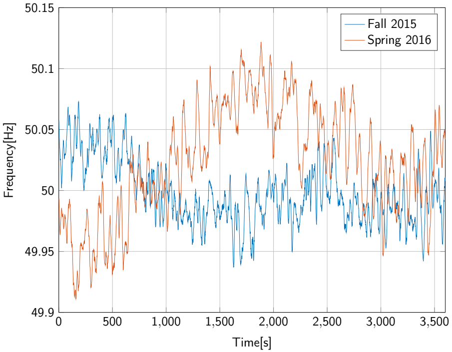
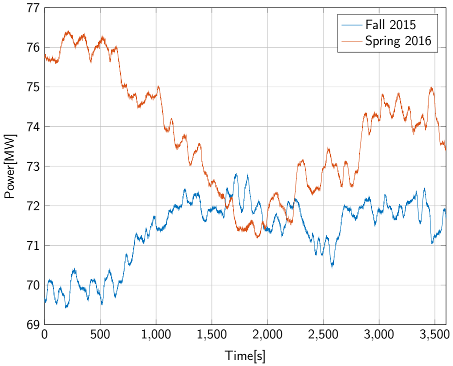
Cross validation using distant data sets





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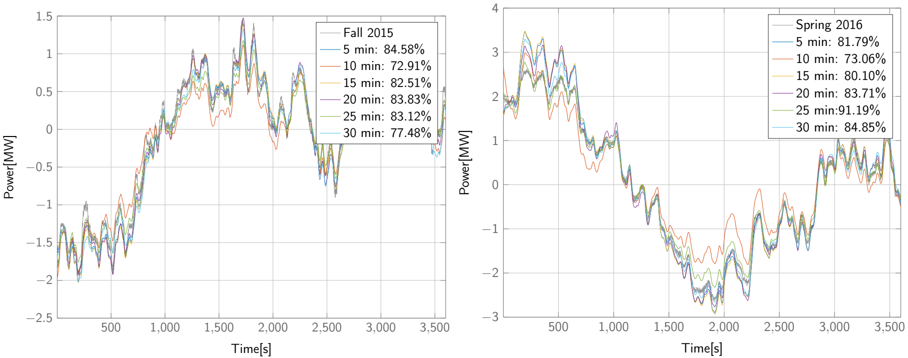
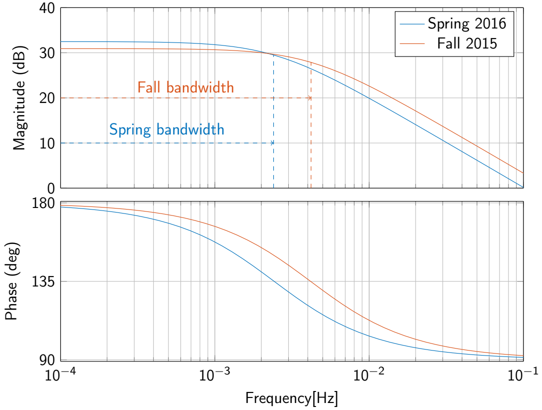


Estimated droop and bandwidth



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

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- It is fast with an execution time around $0.1s$
- It is robust, just filter your data and choose poles in the frequency range of interest and it works.
- Good results were obtained with time windows as short as five minutes.
- One drawback is the lack of uncertainty quantification for identified parameters

Outline

References I

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References III

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