



# Identification of turbine dynamics using PMUs

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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]

# Background

## Power Systems

Figure: Nordic power system[ENTSO-e]

- Large interconnected system
- Balancing challenge

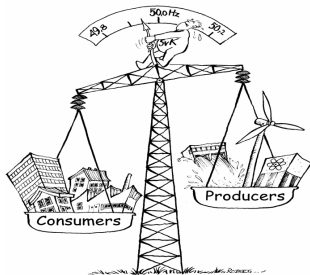


Figure: Balancing challenge[Statnett]

# Background

The power system is dynamic

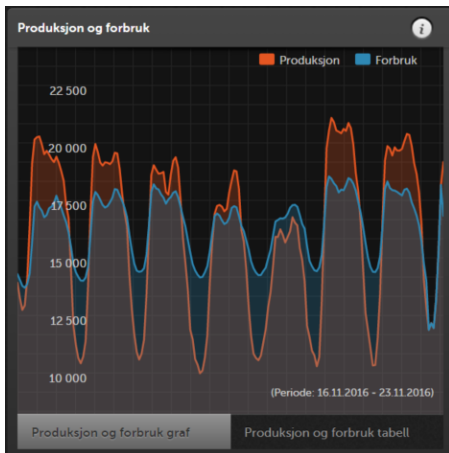
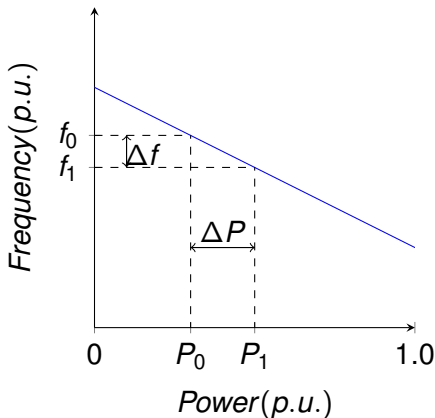


Figure: Production and consumption [statnett.no]

# Background

## Frequency containment reserves (FCR)

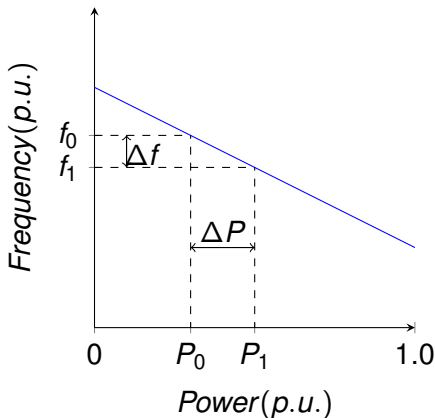
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- Activation of primary reserves is determined by the governor droop settings.



# Background

## Frequency containment reserves (FCR)

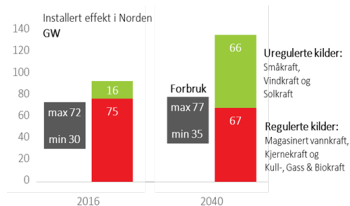
- Power balance/frequency containment control (FCC) is mainly determined by governor response.
- Activation of primary reserves is determined by the governor droop settings.
- In steady state



# Background

## Challenges in operation

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



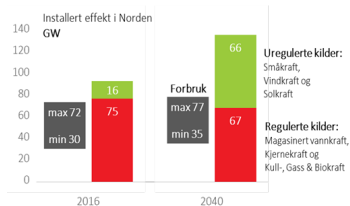
**Figure:** Present and future energy mix[Statnett]



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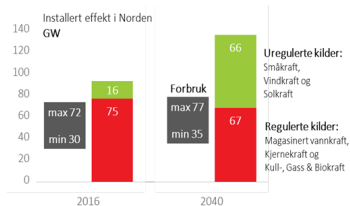


Figure: Present and future energy mix[Statnett]

# Background

## Challenges in operation

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

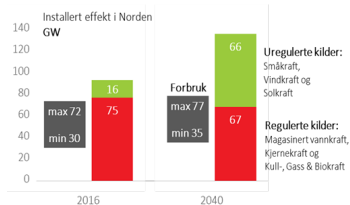
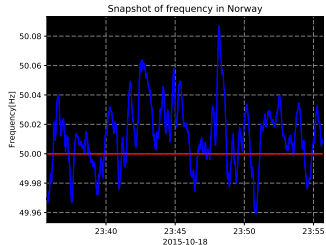


Figure: Present and future energy mix[Statnett]

# Background

## Frequency quality in the Nordics

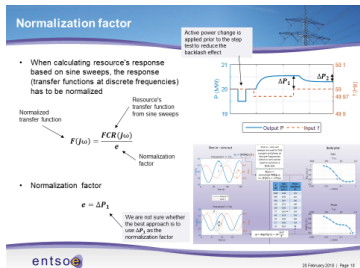
- From 2008 the time the frequency has been outside its allowed band has increased
- The performance of hydro turbine governors play an important role



# Background

## New requirements on FCR

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



## Background

### Research question



1. Do the transmission system operator (TSO) know whether or not the hydropower plants deliver the FCR they are supposed to?

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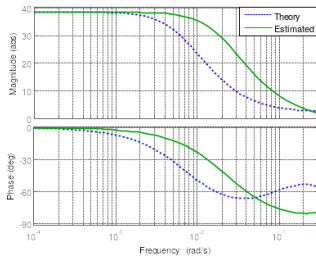
## Research question



1. Do the transmission system operator (TSO) know whether or not the hydropower plants deliver the FCR they are supposed to?
2. Can the measure it online?

# Previous work

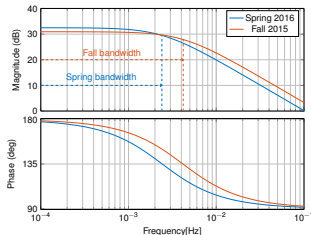
- Governor dynamics were identified using the ARX model structure





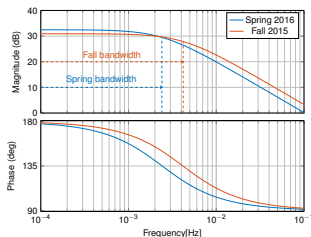
# Previous work

- Governor dynamics were identified using the ARX model structure
- Governor dynamics were identified using time domain vector fitting



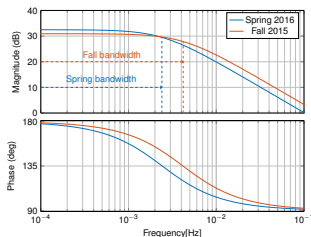
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- Governor dynamics were identified using time domain vector fitting
- However, no theoretical validation was made.
- The theoretical validation was performed in this work.



# Theoretical validation

## System identification basic

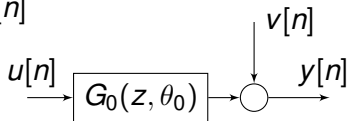


- Assume that a data set  $Z^N = \{u[n], y[n] | n = 1 \dots N\}$  has been collected.
- The dataset  $Z^N$  is assumed generated by

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

- Using the data set  $Z^N$  we want to find the parameter vector  $\theta^N$  minimizing

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



# Theoretical validation

## Consistency



- A consistent estimate means that the true parameter vector  $\theta_0$  is the unique solution to the asymptotic prediction error criterion.

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

with

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

and

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

# Results

## Results from the theoretical validation



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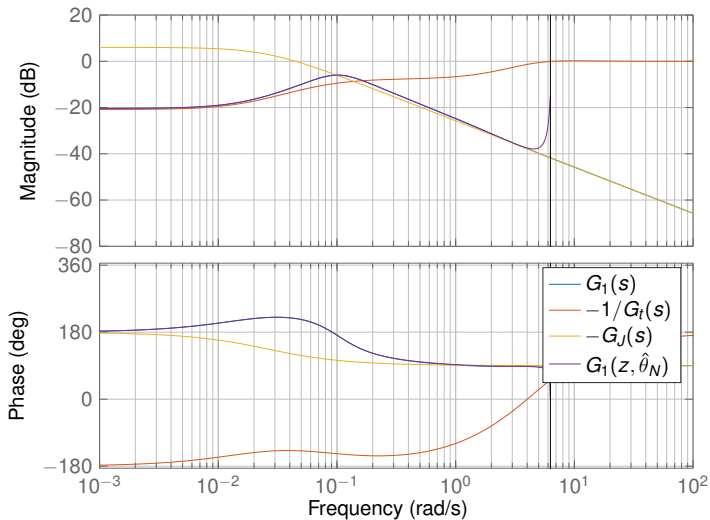


- A consistent estimate of the closed loop transfer function of the turbine and electromechanical dynamics can be obtained by using:
  - Measured PMU frequency as the output  $u[n]$
  - Measured PMU power as the input  $y[n]$
- The proof was done with the following assumptions.
  - The system is excited 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

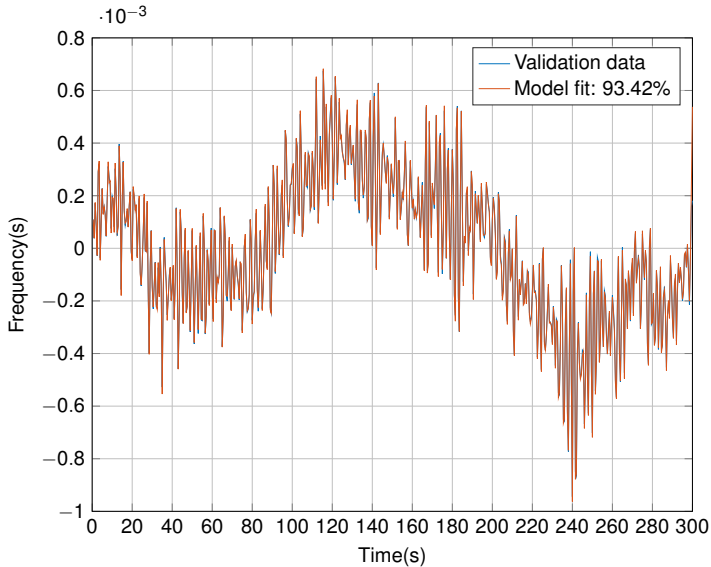
## Results from simulations

Bode Diagram



# Results

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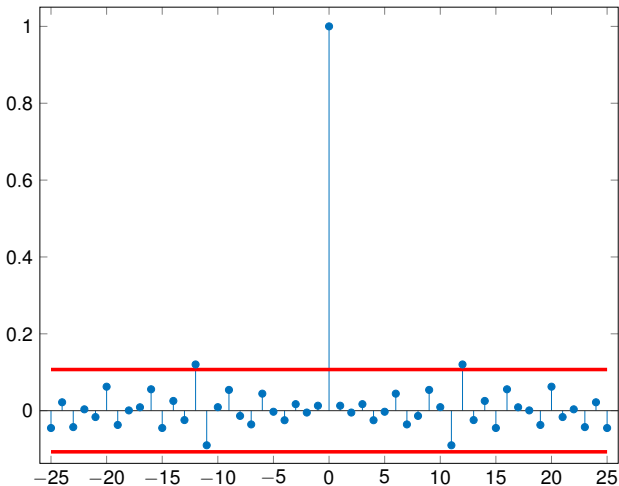


# Results

## Results from simulations



Sample Autocorrelation with 99% Confidence Intervals



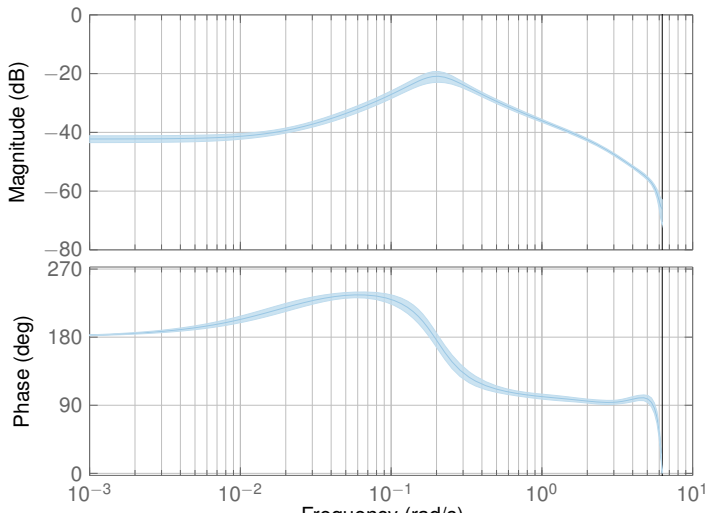
# Results

## Results from the power system



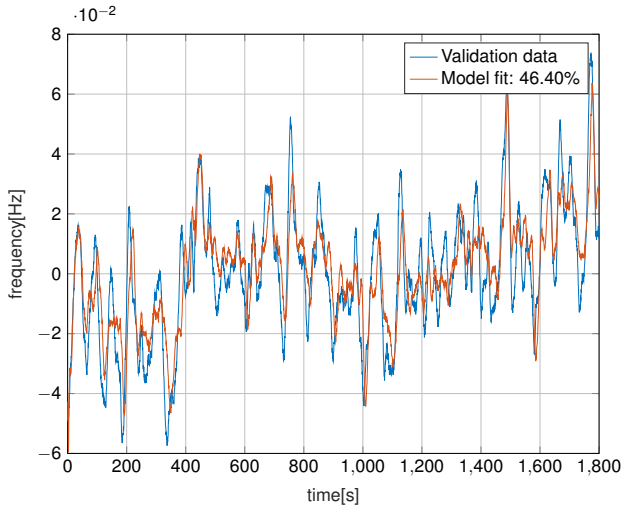
### Bode Diagram

From: u1 To: y1



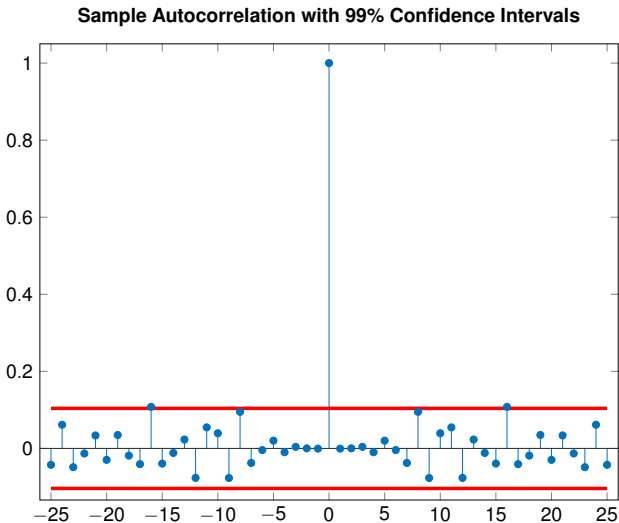
# Results

## Results from the power system



# Results

## Results from the power system



## Conclusions and further work



- It is indeed possible to identify the turbine dynamics(closed loop with electromechanical dynamics) using PMU measurements.
- Look into the assumptions