Optimization of Joint Operation of Fast and Slow Storage

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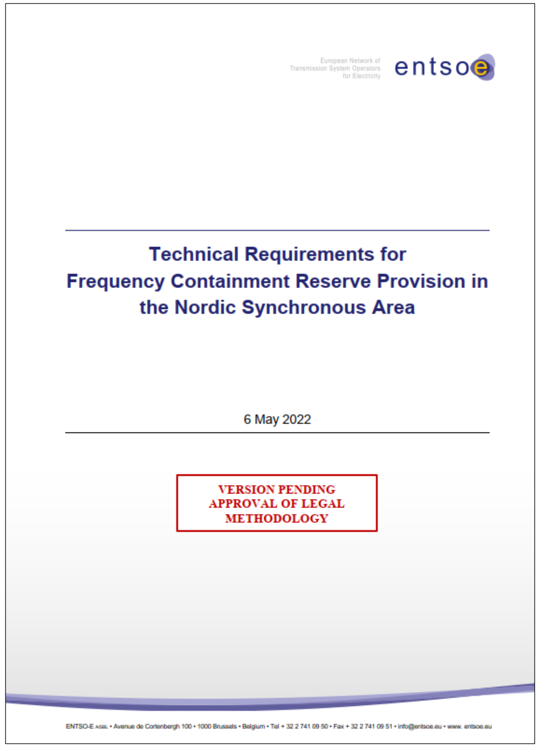
Frequency Reserves in the Nordics

- Continuous oscillations and declining frequency quality observed in the grid
- New proposed criteria for delivery of FCR-N and FCR-D in the entire Nordic Power System, currently under legal review
- From September 14th 2023* all FCR-providing units will be tested with step/ramp and sine sweep tests, having to demonstrate
  - stability in power system terms and
  - a faster FCR response.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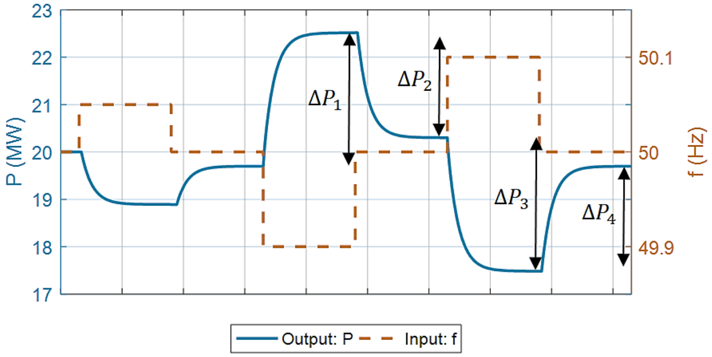
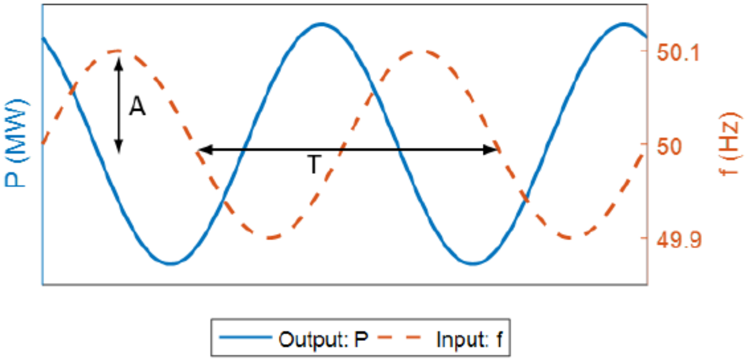
Technical Requirements for
Frequency Containment Reserve Provision in
the Nordic Synchronous Area

6 May 2022

VERSION PENDING
APPROVAL OF LEGAL
METHODOLOGY





*preliminary date

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Frequency Reserves in the Nordics

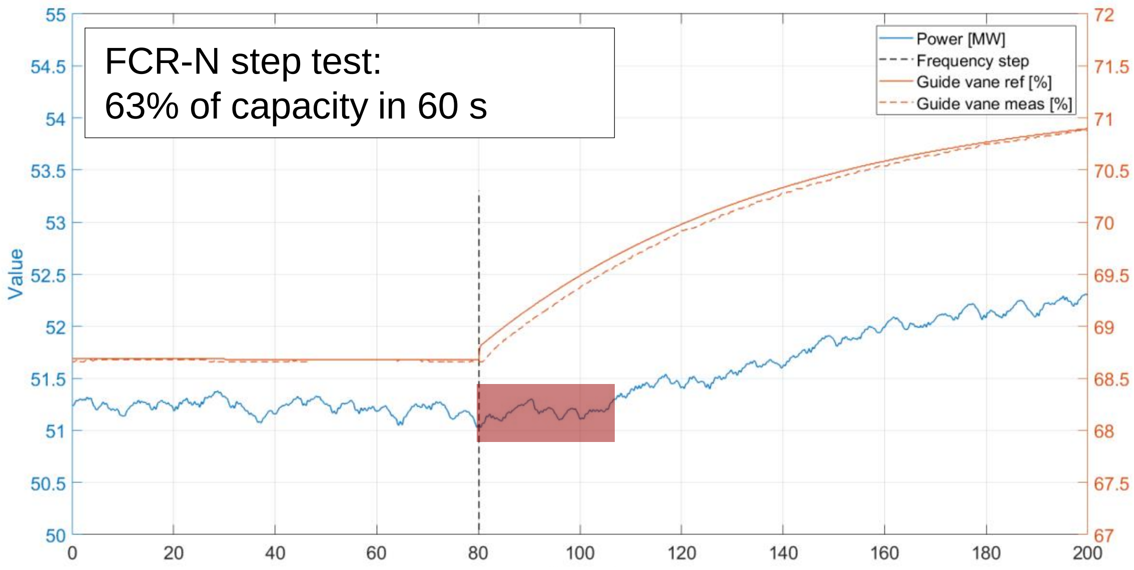
- Hydropower provides around 90% of the FCR capacity today[1]
- Installed capacity is Sweden:
  ~50% Francis turbines
  ~50% Kaplan and Bulb turbines

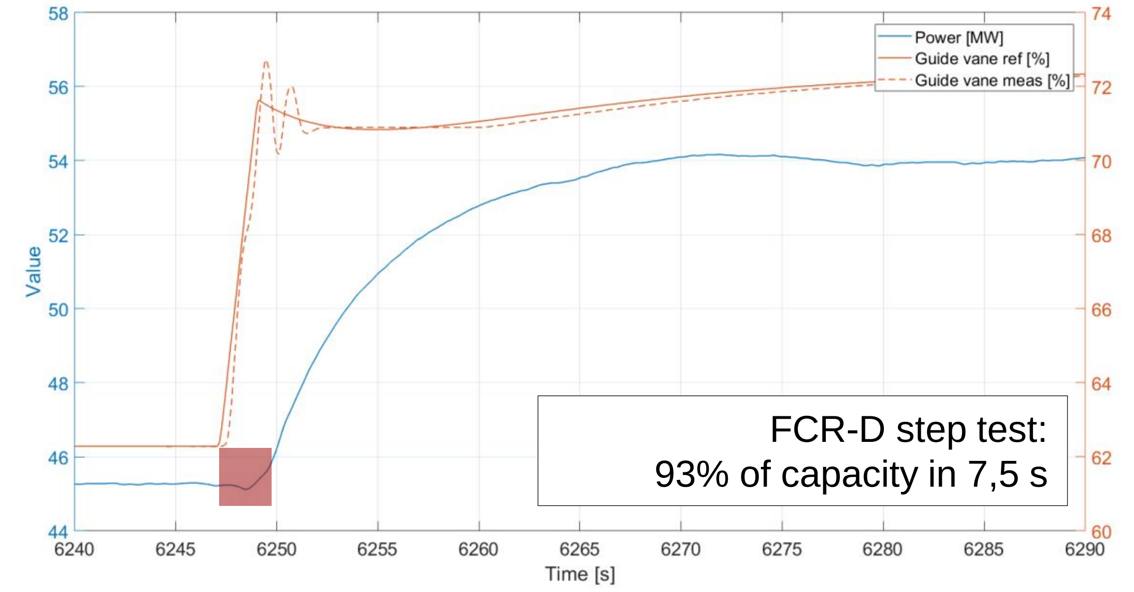
- FCR performance influenced by multiple physical factors:
  - Turbine type
  - Unit head
  - Length and geometry of waterways
  - Servo system type

[1]: ENTSO-E – FCP Project Summary

Frequency Reserves in the Nordics

- Faster changes of power = quicker servo movements and quicker water speed transients
- Reaching the physical performance limits of some units
- Hydropower units are facing challenges to deliver FCR in the future
- Expected to result in higher mechanical wear and tear of the unit





Joint Operation of Hydropower and Storage

- Installing a storage system (e.g. batteries, supercaps) and operating it together with the hydropower unit
- Foreseen benefits of joint operation:
  - Faster and stable combined FCR response
  - Decreased wear-and-tear on hydropower unit compared to stand-alone operation
  - Decreased size of storage and cycling unit compared to stand-alone operation
- Industrial PhD project goals:
  - Suggest joint regulation strategies depending on the objective
  - Develop a guideline for dimensioning the energy storage
  - Implement the hybrid system in lab-scale experiments

Joint Operation of Hydropower and Storage

The optimization problem

FCR criteria

- Can be achieved in different ways
- Clear minimum requirements
- Optimization of joint performance

Hydropower unit

- Performance controlled by turbine governor
- Can be changed, physical limitations
- Optimization of wear and tear

Storage system

- Performance controlled by electronics
- Can be designed
- Optimization of power and/or energy ratings (cost)

Joint Operation of Hydropower and Storage

The optimization problem

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Minimum FCR requirements used as a design parameter

Hydropower unit

- Performance controlled by turbine governor
- Can be changed, physical limitations
- Optimization of wear and tear

Performance not changed, used as design input

Storage system

- Performance controlled by electronics
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- Optimization of power and/or energy ratings (cost)

Performance designed, optimized for power and energy ratings

SVC Svenskt Vattenkraftcentrum

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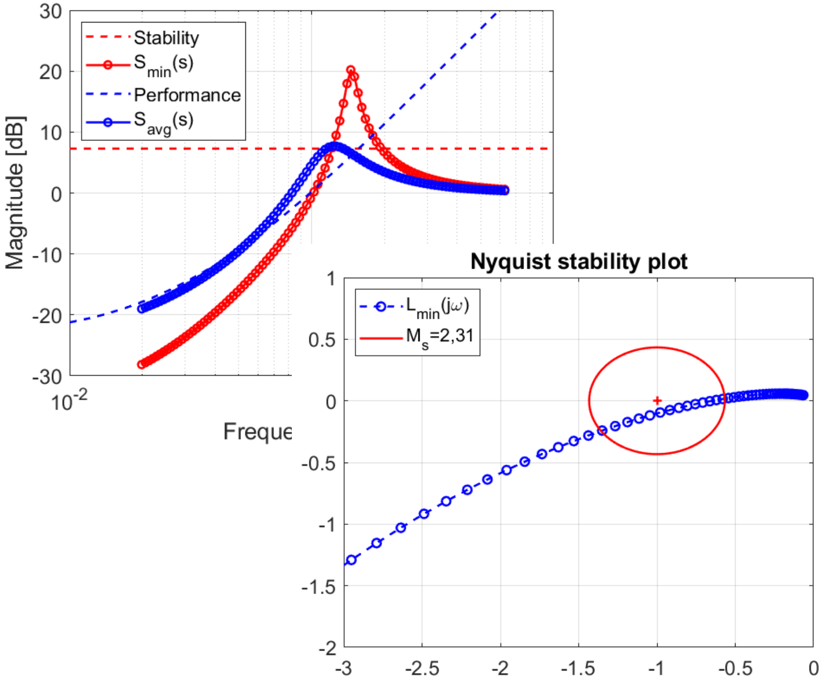
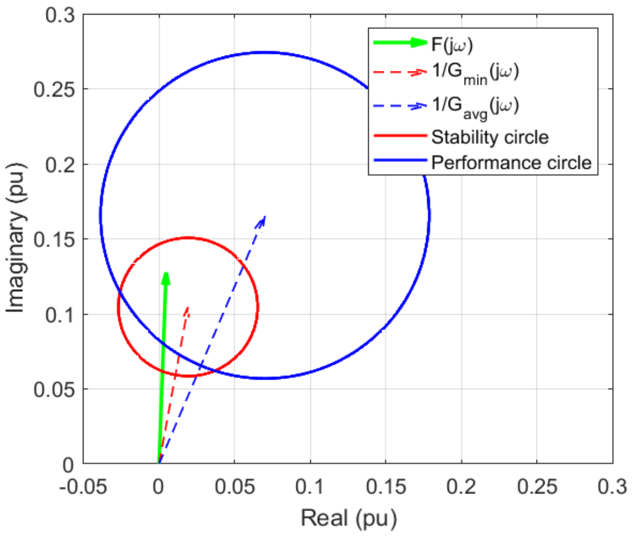
Storage System Design for Improved FCR

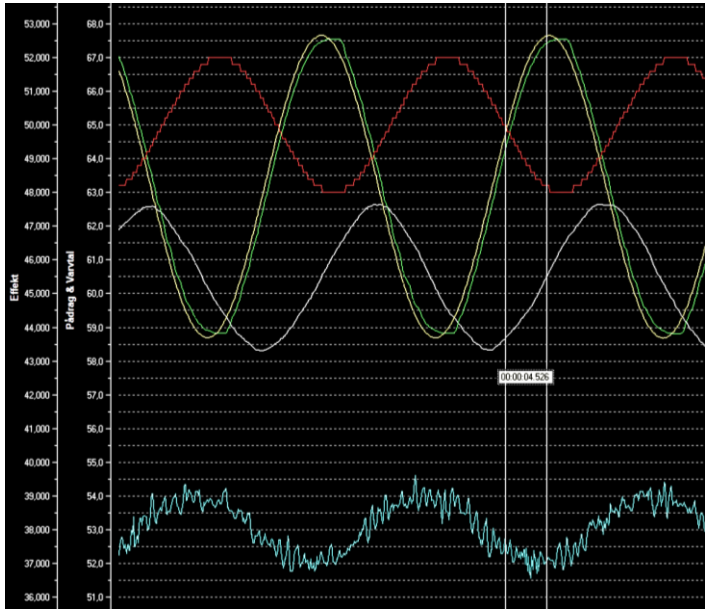
- Using FCR criteria as a design parameter requires a useful formulation of the requirements



power system formulation



useful formulation for the unit



unit test results

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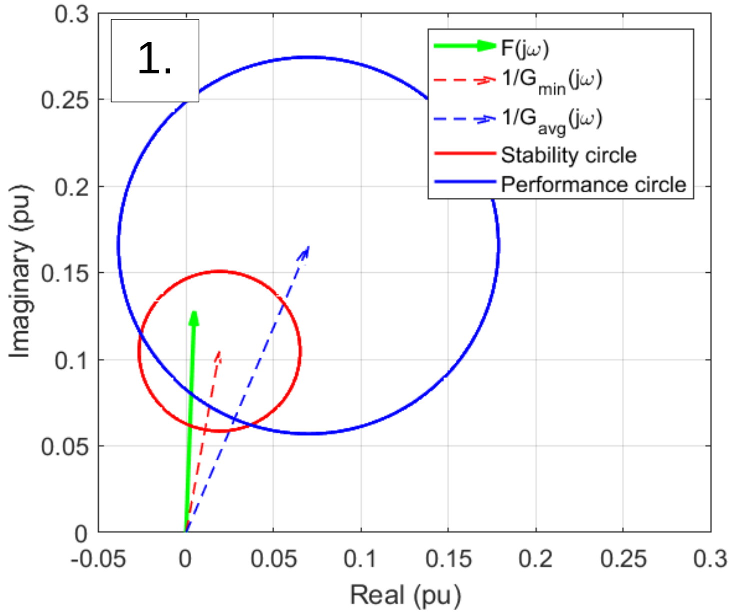
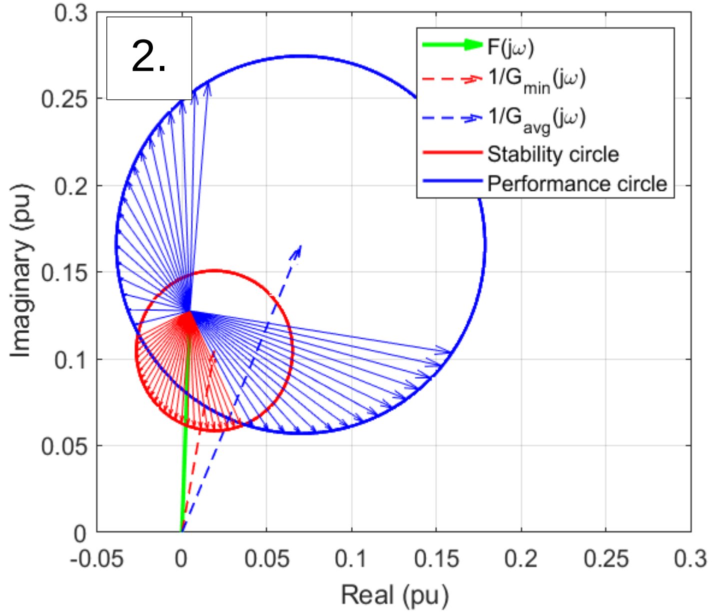
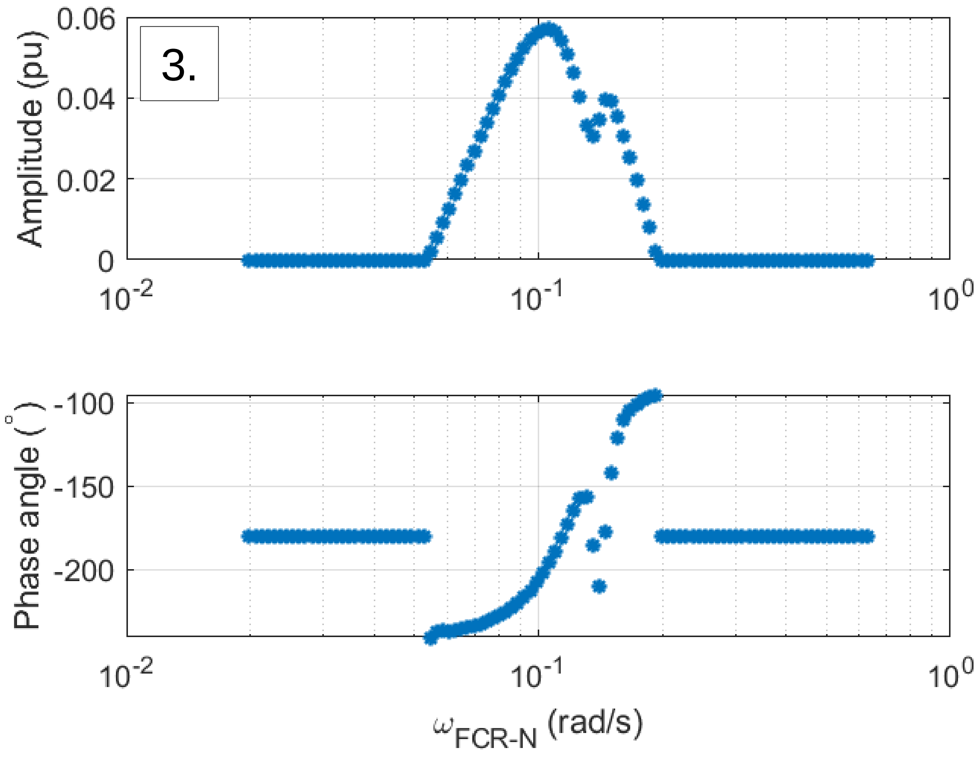
Storage System Design for Improved FCR

1. Record the performance of an existing hydropower unit in the FCR plane plots
2. Specify the additional power response vectors needed to satisfy FCR criteria
3. Repeat this for all tested frequency sinusoids and create a modified Bode plot with the minimum necessary contribution



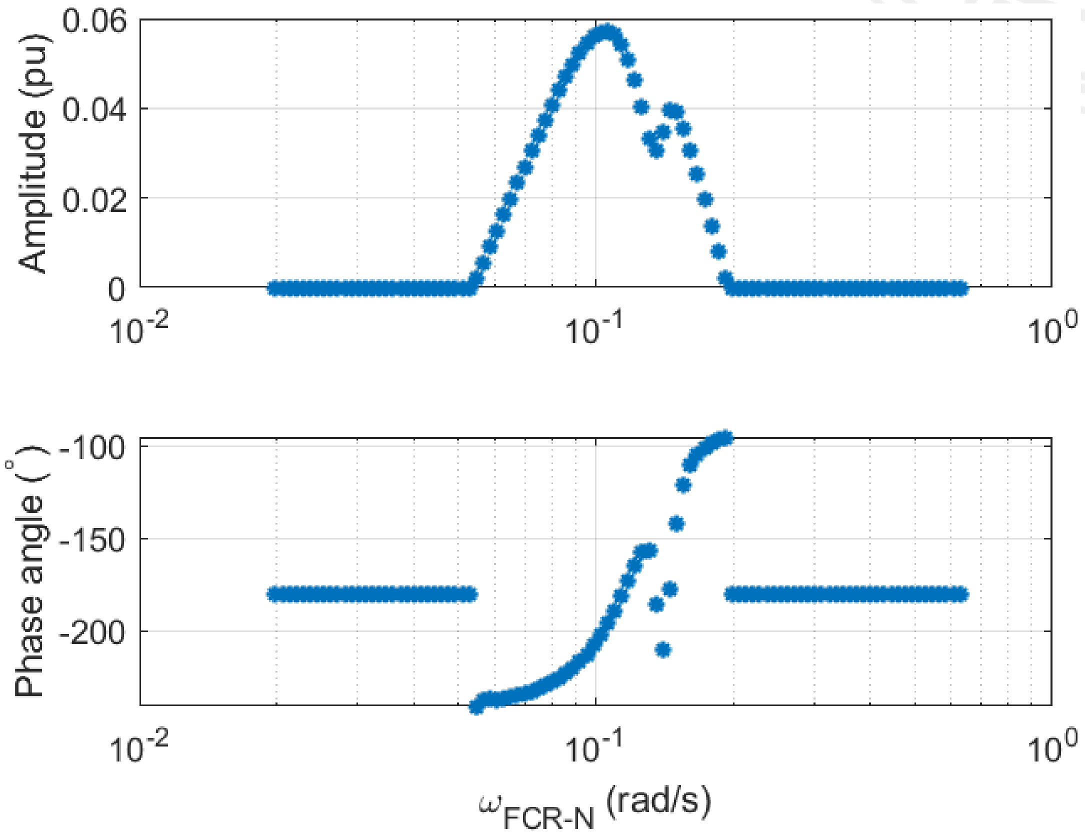




Storage System Design for Improved FCR

- No contribution is needed at higher and lower frequencies
- A stable, non-oscillatory response is best
- A simple and practical implementation which fits these observations is a bandpass filter

$$F_s(s) = \frac{K\omega_l s}{(s+\omega_h)(s+\omega_l)}$$



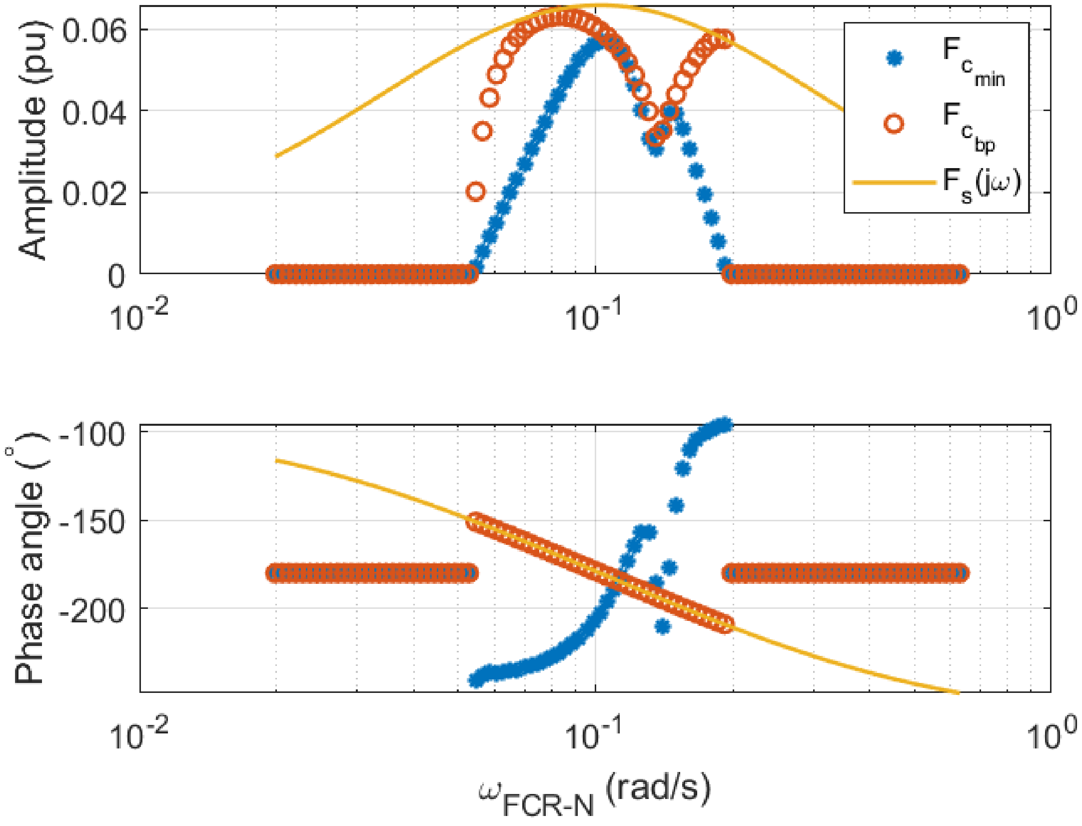
Storage System Design for Improved FCR

minimum contribution
bandpass contribution
storage response

- No contribution is needed at higher and lower frequencies
- A stable, non-oscillatory response is best
- A simple and practical implementation which fits these observations is a bandpass filter

$$F_s(s) = \frac{K\omega_l s}{(s+\omega_h)(s+\omega_l)}$$

- Contribution from bandpass filter is specified by matching the phase angle
- Storage response is designed by exceeding the amplitude
- Both power and energy ratings of the storage system can be calculated from the filter response



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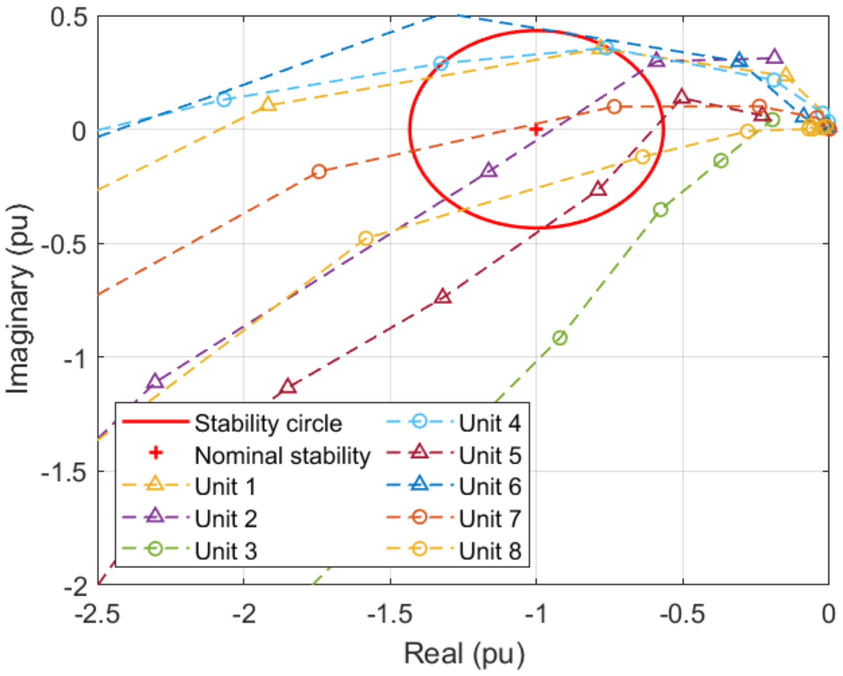
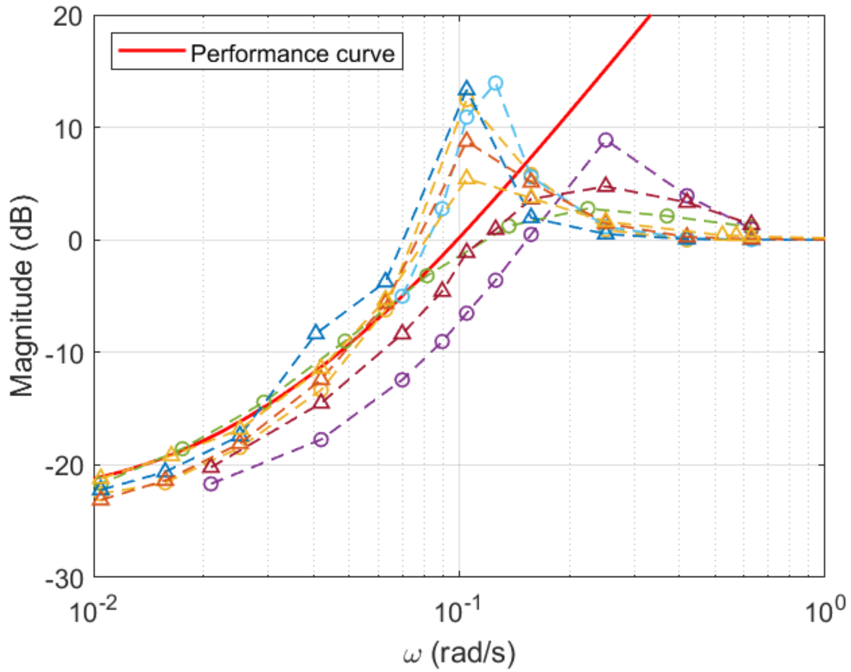
Storage System Design Results

- FCR criteria tests from 8 Swedish hydropower units
- All units fail the FCR criteria to various degrees
- Stability evaluated with Nyquist curve and performance with the sensitivity function plot

TABLE II
OVERVIEW OF FIELD-TESTED SWEDISH HYDROPOWER UNITS.

Unit	Turbine type	Power rating	FCR gain	Head
1	Kaplan	24 MW	10 %	23 m
2	Kaplan	24 MW	5 %	23 m
3	Francis	46 MW	20 %	60 m
4	Francis	93 MW	10 %	216 m
5	Kaplan	52 MW	10 %	30 m
6	Kaplan	71 MW	11 %	52 m
7	Francis	156 MW	9 %	86 m
8	Francis	170 MW	14 %	135 m





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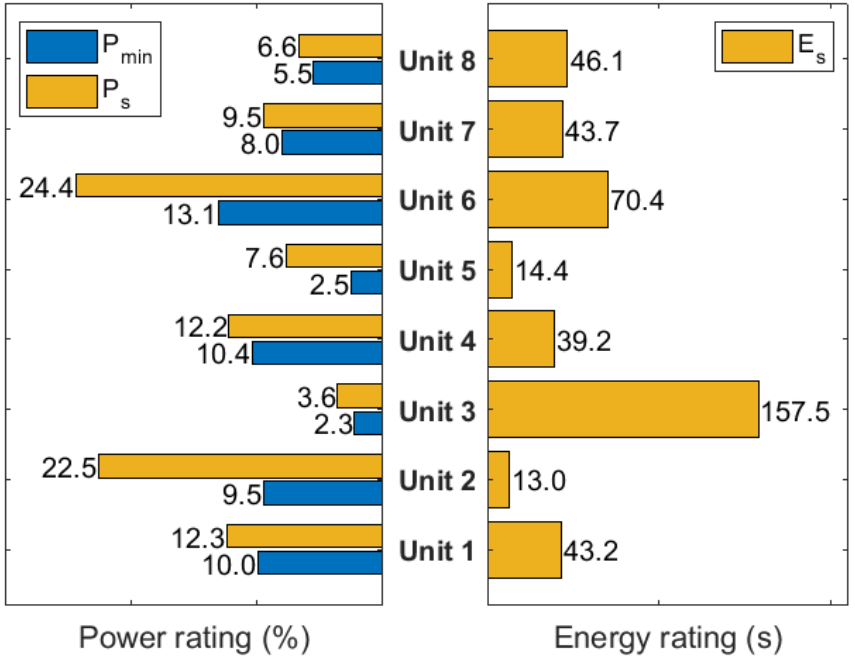
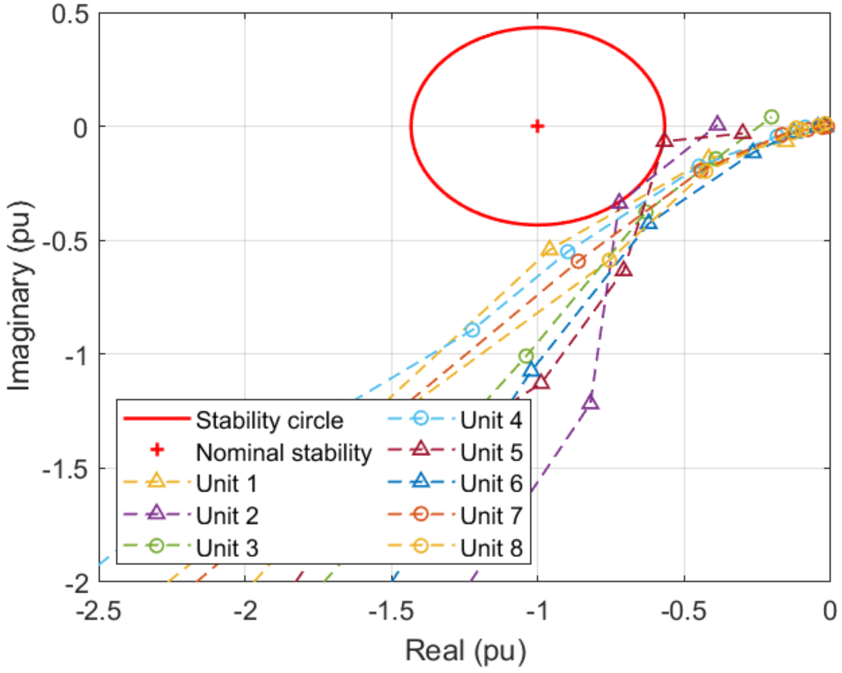
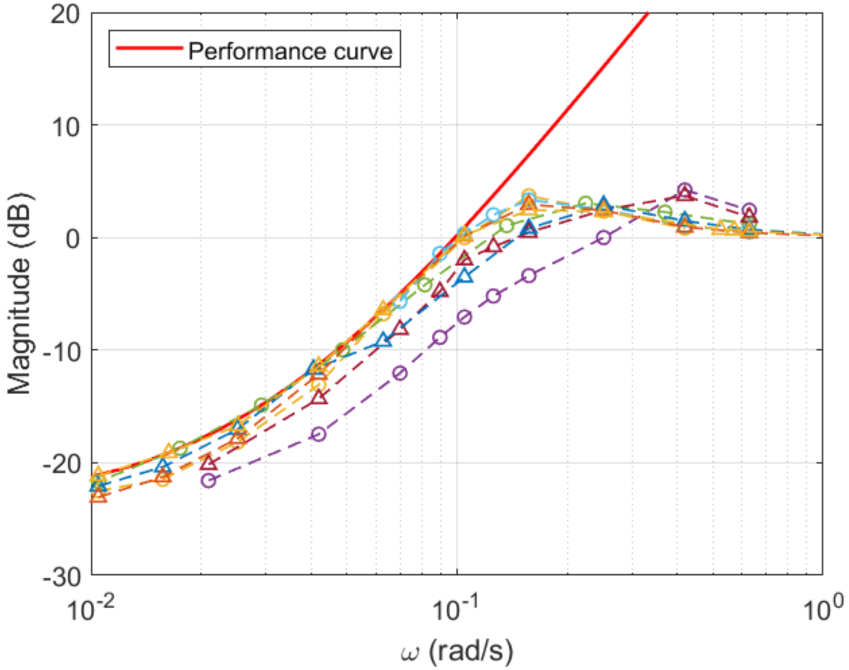
Storage System Design Results

- Storage system designed individually for each unit
- All 8 units satisfy the FRC criteria with the added storage
- Power ratings of storage system are close to the minimum, with very low energy ratings







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Joint Operation of Hydropower and Storage

The optimization problem

FCR criteria	Hydropower unit	Storage system
• Can be achieved in different ways • Clear minimum requirements • Optimization of joint performance	• Performance controlled by turbine governor • Can be changed, physical limitations • Optimization of wear and tear	• Performance controlled by electronics • Can be designed • Optimization of power and/or energy ratings (cost)
SVC (Svenskt Vattenkraftcentrum): Minimum FCR requirements used as a design parameter	Performance not changed, used as design input	Performance designed, optimized for power and energy ratings
fortum: Minimum FCR requirements used as a design parameter	Performance changed, optimized for wear and tear and flow oscillations	Performance designed to satisfy FCR criteria

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Fortum Pilot in Forshuvudforsen

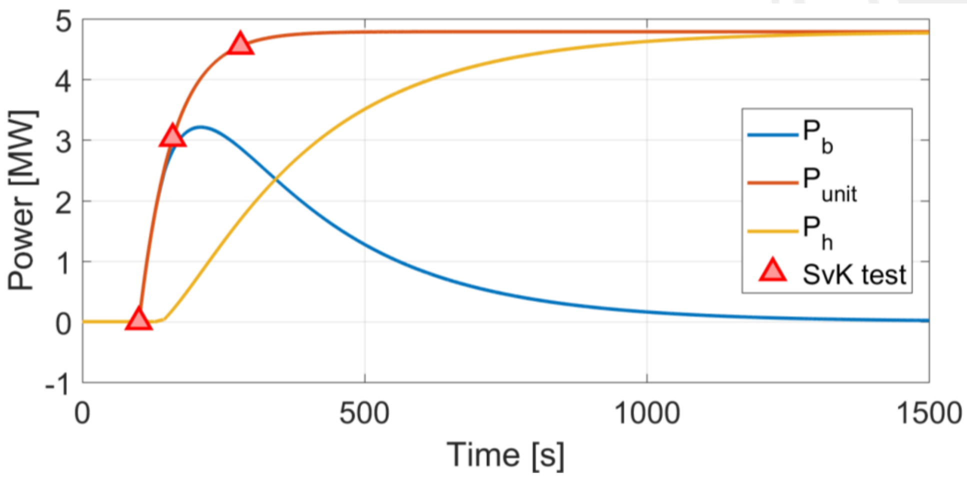
Run-of-river HPP with two 25 MW Kaplan units and high running hours

Unit 2 equipped with a 5 MW / 6 MWh Tesla BESS in 2019

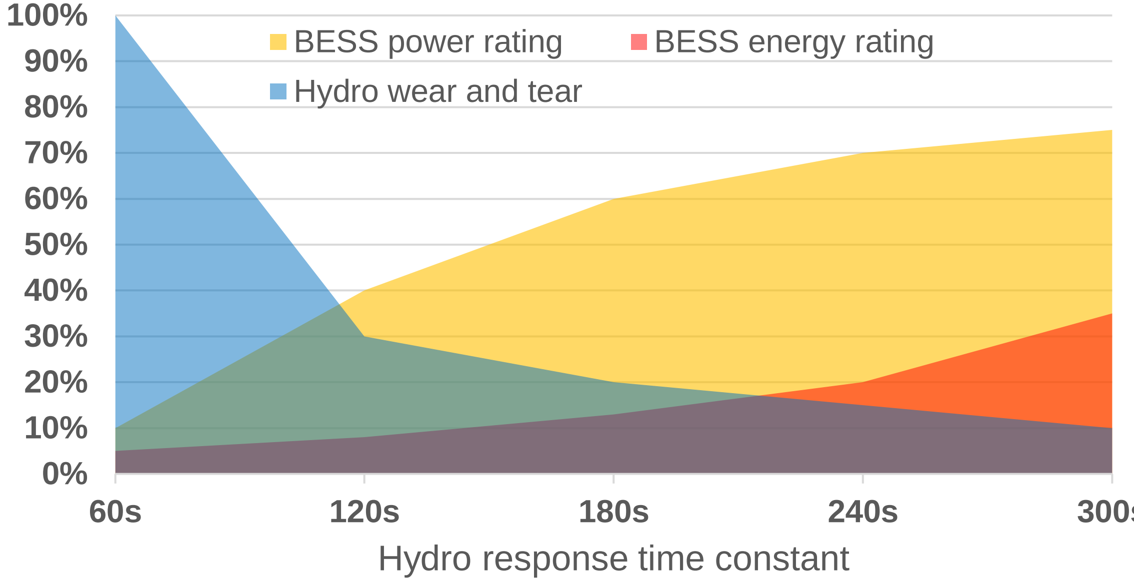
Hybrid unit successfully providing FCR-N and FFR since commissioning

Fortum Pilot in Forshuvudforsen

- Joint operation following the FCR criteria and highly adaptable
- Contribution from hydropower unit optimized through the response time constant
- The BESS provides the necessary difference
- The trade-off: reduce mechanical wear and tear and water flow oscillations while preserving battery lifetime



Effects of changing the hydro unit contribution [2]



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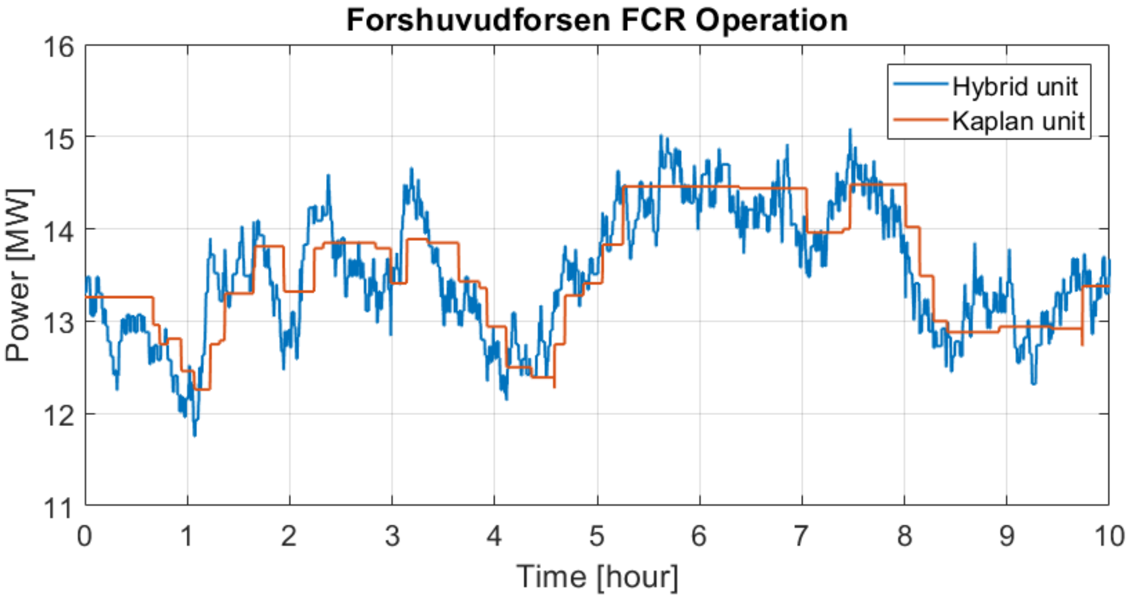
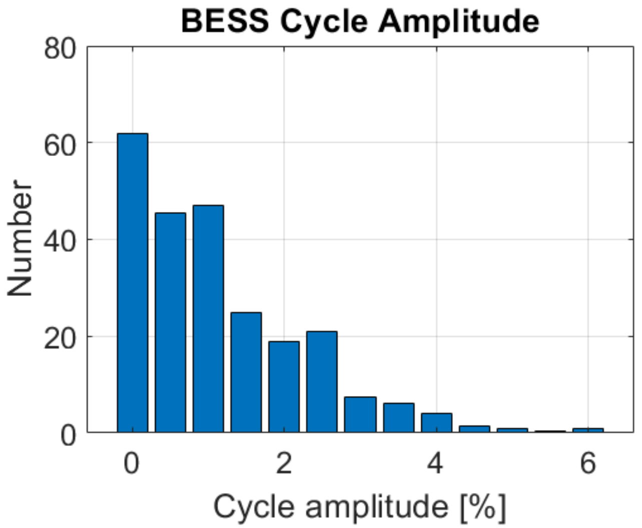
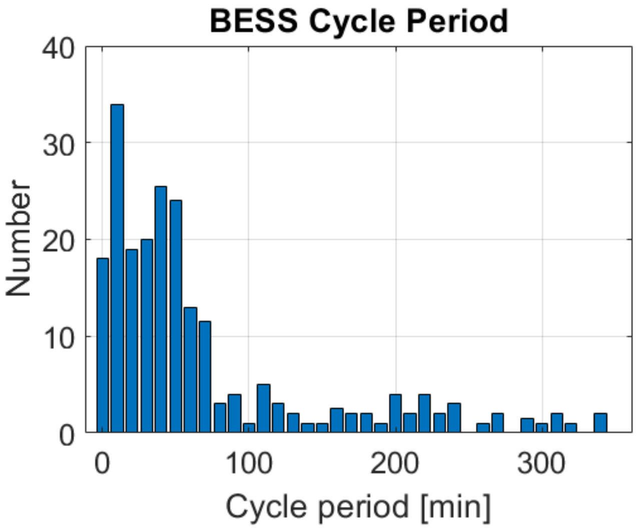
[2]: Danilo Laban – "Hydro Battery Hybrid Systems for Frequency Regulation", MSc Thesis

Fortum Pilot in Forshuvudforsen

- Joint operation successfully tested according to FCR criteria
- The distance of guide vane movements during FCR reduced by ~90% compared to stand-alone operation
- Continuous operation with a small SOC deviation
- BESS lifetime prolonged by reducing cycle amplitude and period







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Conclusions

- FCR requirements are challenging the physical performance limits of some units
- Joint operation with storage systems is an efficient and resilient way of improving FCR services and possibly stacking other services
- Benefits from the hydropower perspective include reduced mechanical wear and tear and a reduced impact of FCR on waterways
- Multiple optimization possibilities exists for the joint operation
- We are in need of guidelines how to build up these systems when it comes to control schemes and storage system sizing