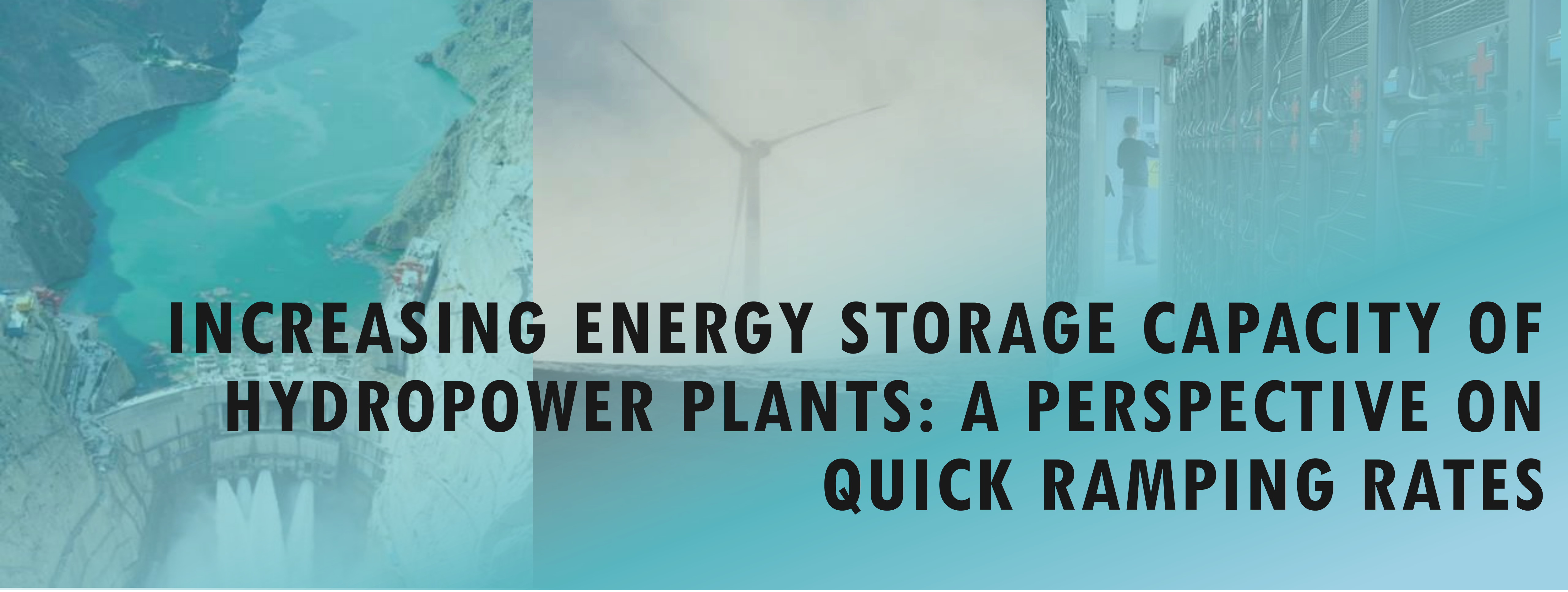

INCREASING ENERGY STORAGE CAPACITY OF HYDROPOWER PLANTS: A PERSPECTIVE ON QUICK RAMPING RATES

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The role of storage capacity
of hydropower plants
WG1 PEN@HYDROPOWER
Webinar
3 July 2024

OUTLINE

- Energy storage and energy storage application
- Hybridization of hydropower with batteries
- Model predictive control for stress-informed control of (high-head) hydropower
- Results and conclusions

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ENERGY STORAGE

Energy storage refers to converting a primary source of energy into a storable form that can be converted to electricity for later use

Grid-to-grid energy storage technologies

- Pumped-storage hydropower
- Batteries
- Flywheels
- Ultracapacitors
- Power-to-x (to-power)

X-to-grid technologies

- Hydropower
- Solar fuels
- Concentrated solar power

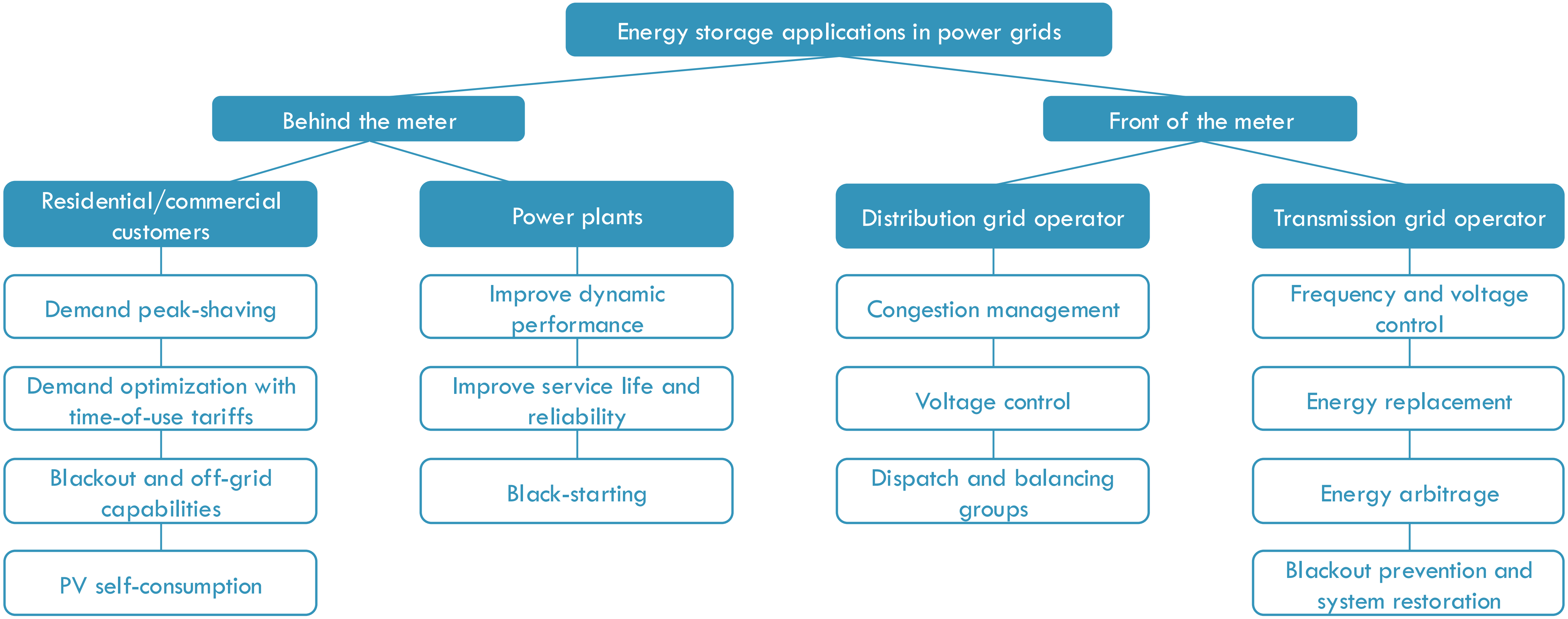
"Virtual" energy storage:

- Flexible demand

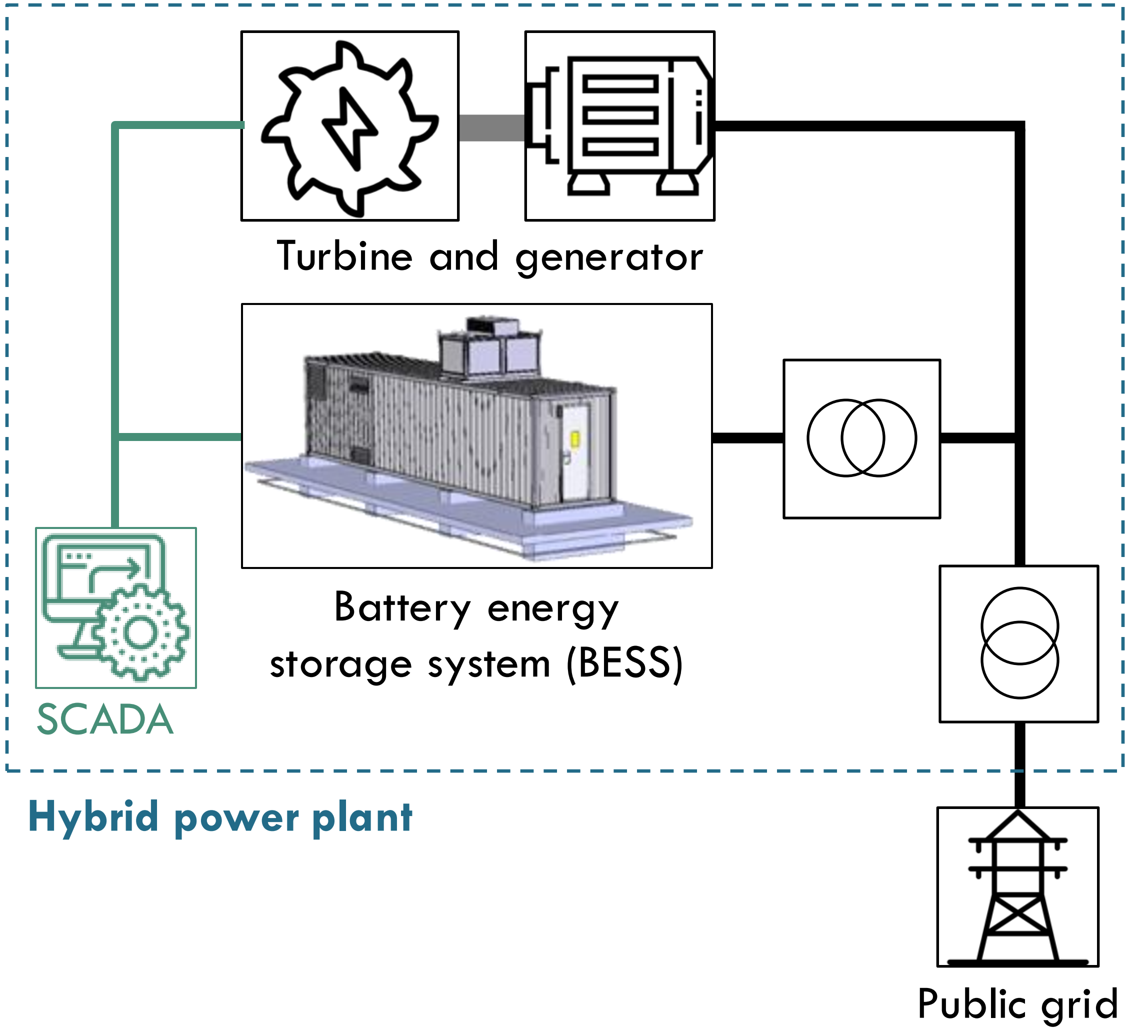
Performance metrics/attributes

- Power and energy density
- Round-trip efficiency
- Response time
- Calendar and cycle ageing
- Scalability

TAXONOMY OF ENERGY STORAGE APPLICATIONS



HYBRID HYDROPOWER PLANTS

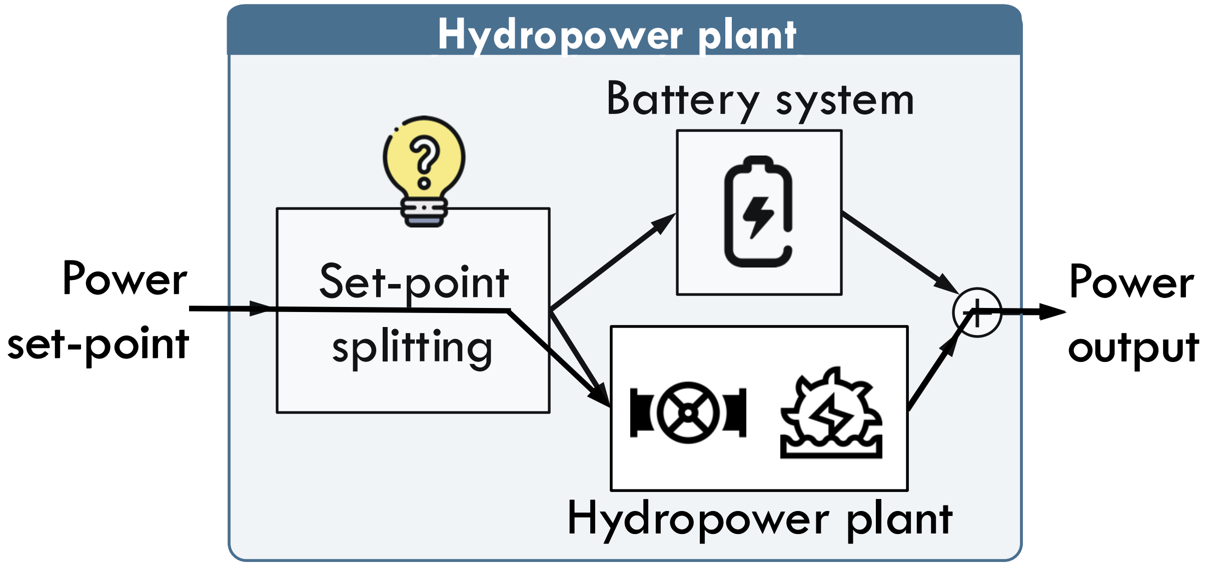


Motivations

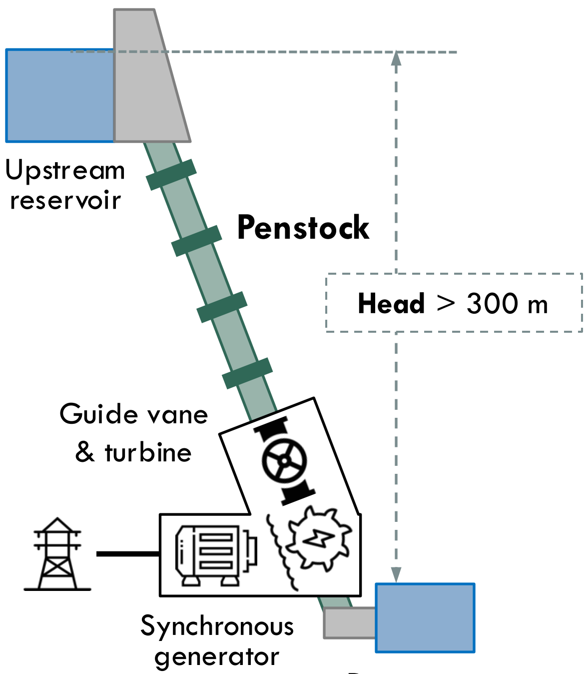
- Increase plant flexibility (hydro ramping rate: ≅ 20% of the nominal capacity per minute, battery 2000% **per second**)
- Reduce wear of mechanical components – important with ageing hydropower infrastructure!

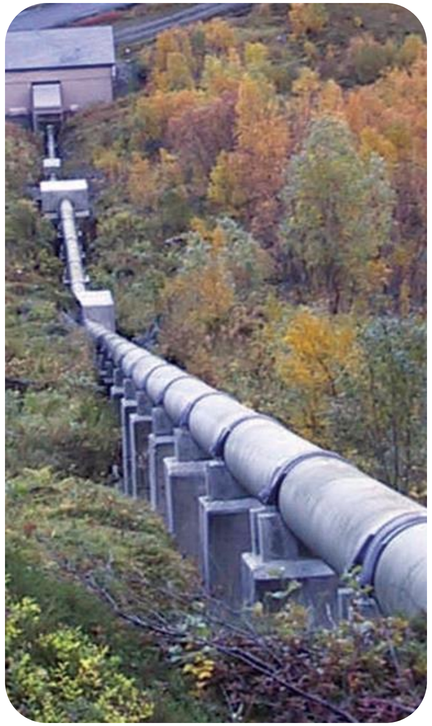
HYBRID HYDROPOWER PLANTS – CONTROL PROBLEM
(CASSANO 2022B)

Control problem



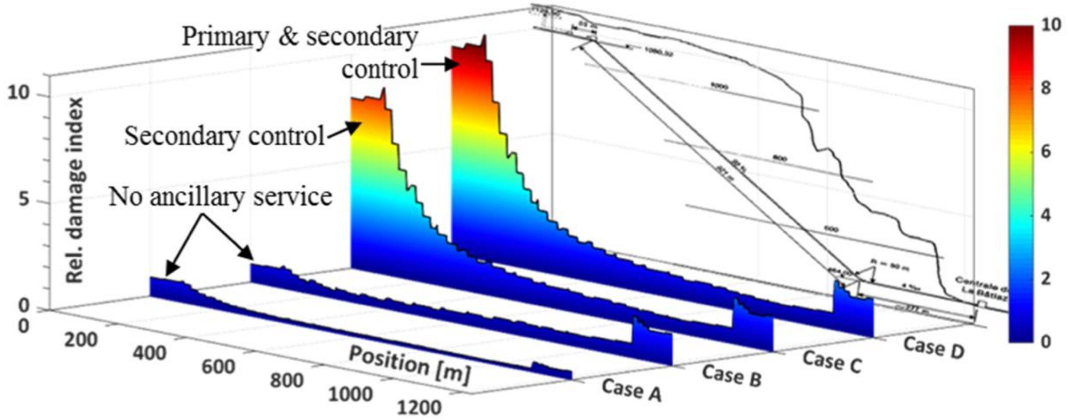
PENSTOCK FATIGUE IN MEDIUM- AND HIGH-HEAD PLANTS





Open-air penstock

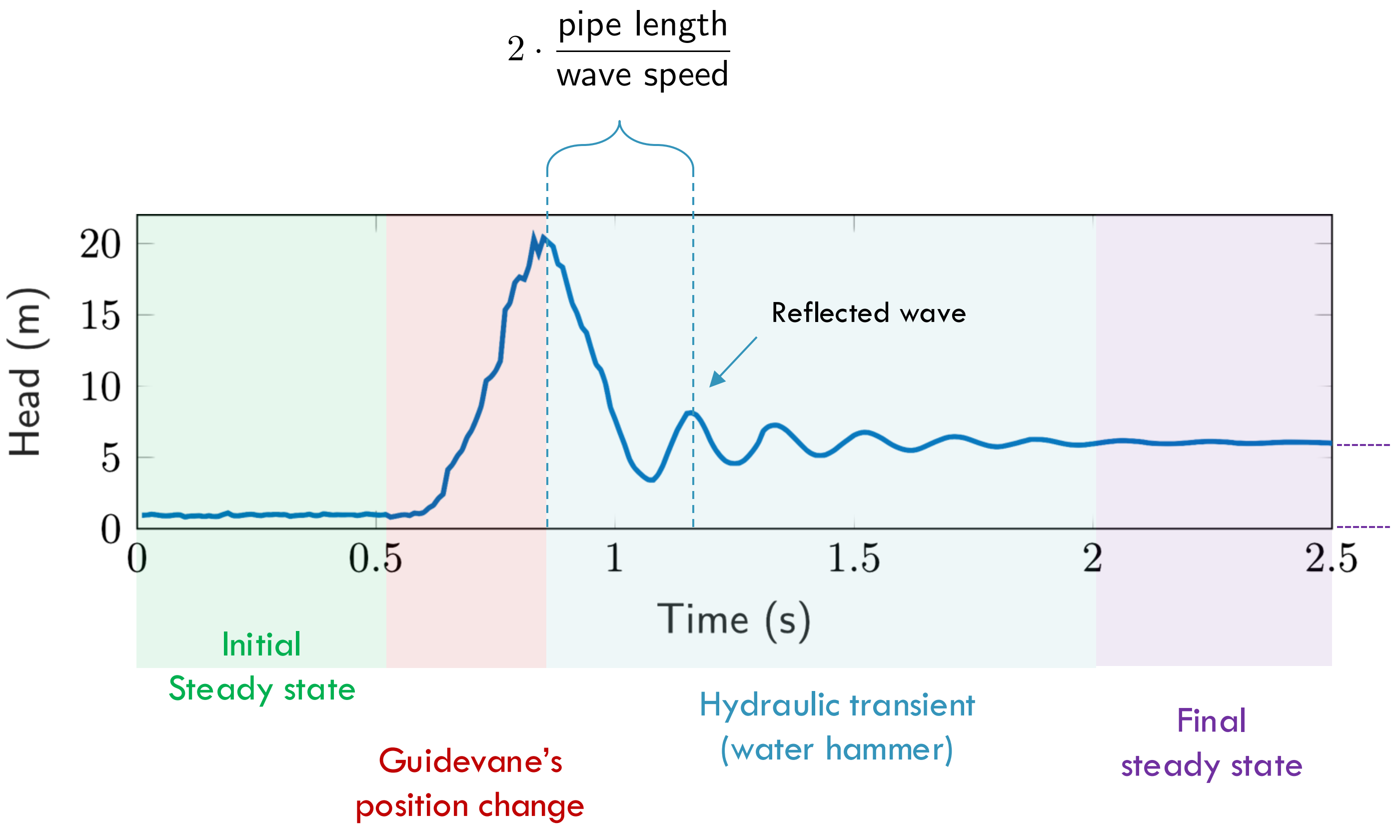
Relative damage index of penstock when plant provides primary and secondary frequency control:

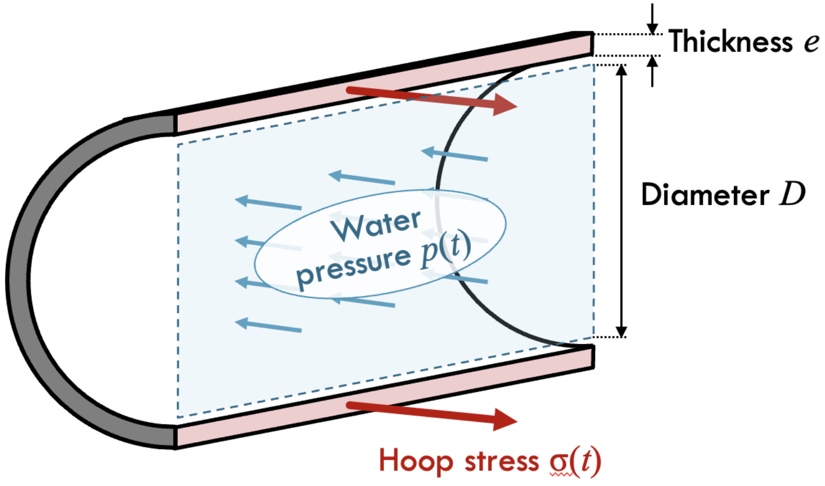


[Dreyer et al. (2019). Digital clone for penstock fatigue monitoring]

How can we modify the set point of the plant to avoid damaging the penstock and use the battery to preserve the original level or power regulation?

WATER HAMMER



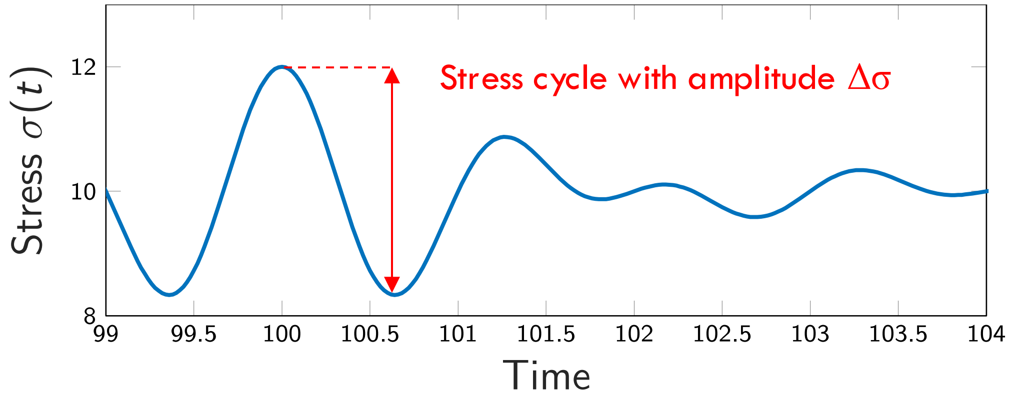


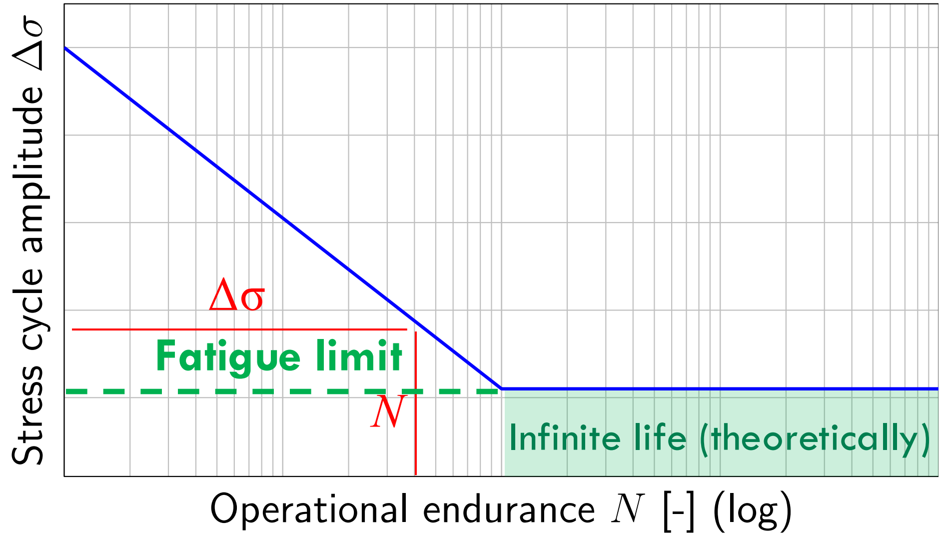
Hoop stress $\sigma(t)$

$$\sigma(t) = [h(t) - z]\,\rho g \frac{D}{2e}$$

Variations of head (dynamic pressure) → Variations of stress → Damages to the pipe

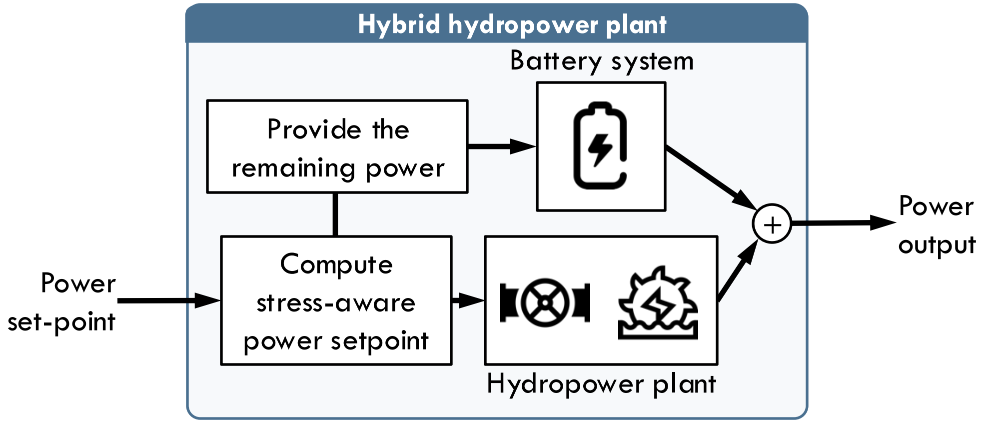
FROM STRESS HISTORY TO SERVICE LIFE





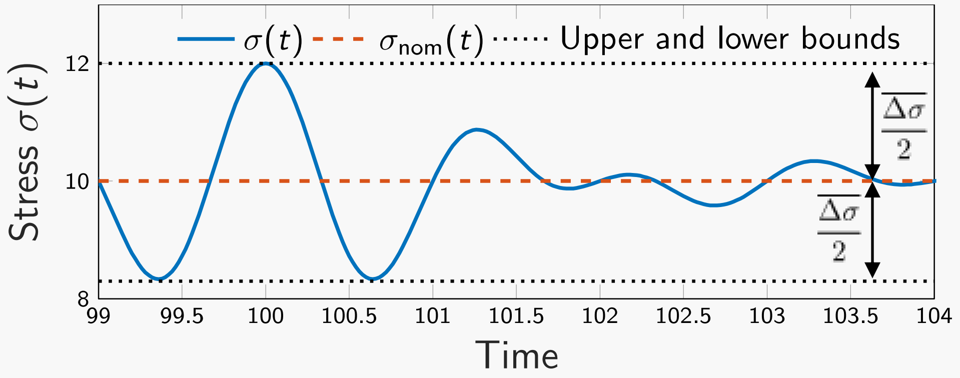
- The SN (or Wöhler's) curve tells the number of cycles N that a component can endure at a given stress cycle $\Delta\sigma$.
- In ferrous materials, stress below the fatigue limit won't virtually impact on residual life.

Can we design a plant controller that ensures penstock stress to stay below the fatigue limit?



STRESS CONSTRAINTS
(CASSANO 2022A)

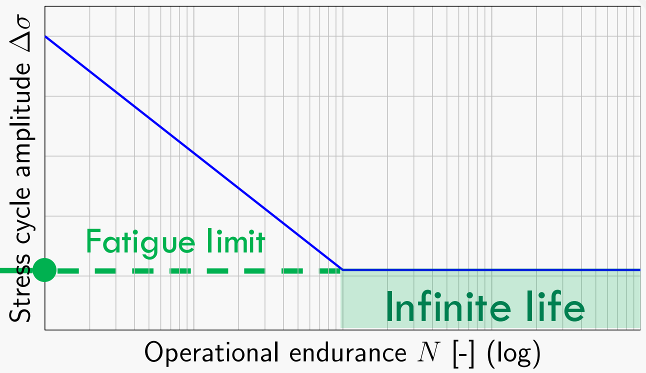
Consider this stress signal over time:



If the bounds hold at all times, i.e.:

$$\sigma_{\text{nom}} - \frac{\overline{\Delta\sigma}}{2} \leq \sigma(t) \leq \sigma_{\text{nom}} + \frac{\overline{\Delta\sigma}}{2} \qquad (1)$$

then the largest possible variation of the stress is $\overline{\Delta\sigma}$.



Using the head-to-hoop stress model from former slide, Eq. (1) can be rewritten as:

$$\underline{h} \leq h(t) \leq \overline{h}$$

where

$$\underline{h} = h_{\text{nom}} - \overline{\Delta\sigma}\frac{1}{\rho g}\frac{e}{D}$$

$$\overline{h} = h_{\text{nom}} + \overline{\Delta\sigma}\frac{1}{\rho g}\frac{e}{D}$$

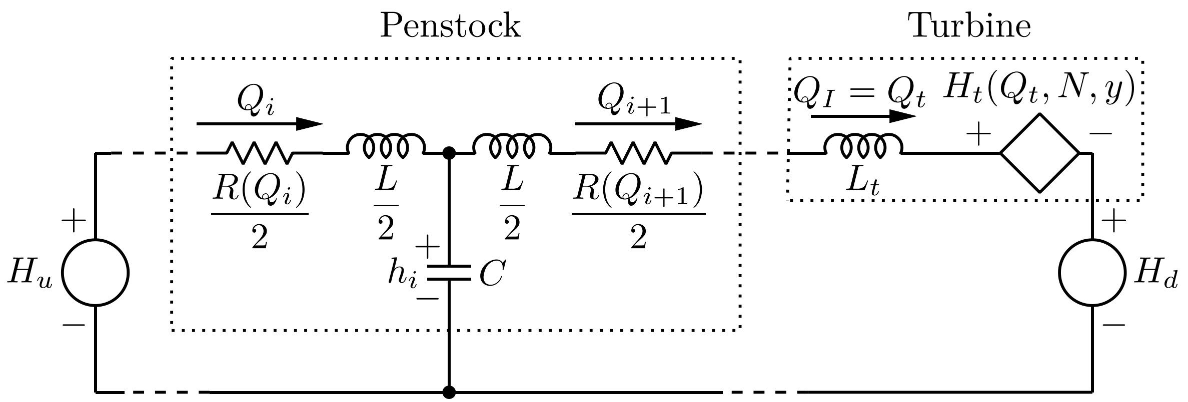
Assuming we can model the head as a function of the controllable valve position, $y(t)$, i.e.:

$$h(t) = f(y(t))$$

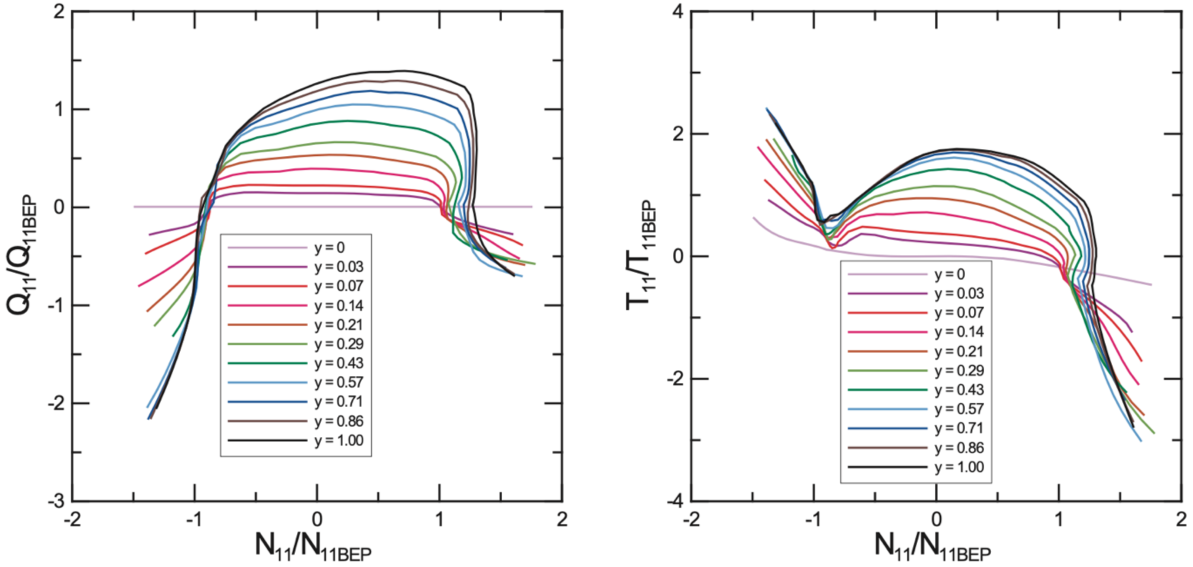
then we can formulate open-loop stress constraints with model predictive control (MPC).

1-D EQUIVALENT CIRCUIT MODEL OF HYDROPOWER PLANTS

The equivalent circuit model of the complete plant is obtained by combining the penstock model, turbine model, and reservoirs



Quasi static model of the hydraulic turbine captures the relation between its state variables (e.g., Francis: specific energy (gH), torque, rotational speed, flow, guide vane opening)



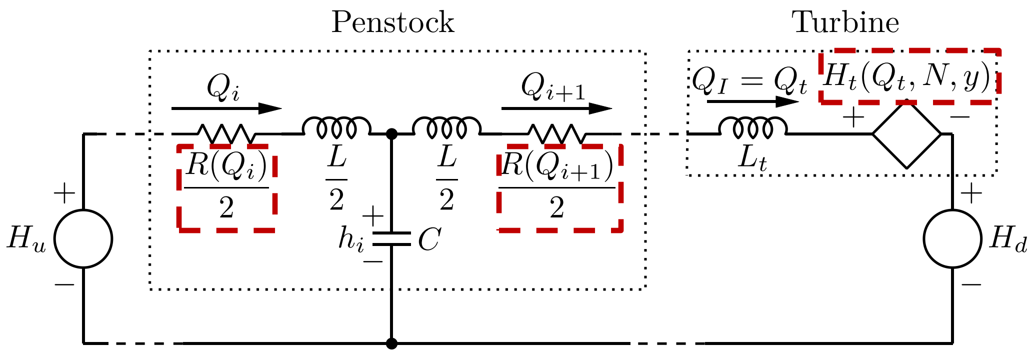
Volumetric flow (left) and torque (curve) characteristics of a Francis turbine

LINEARIZED HYDROPOWER PLANT MODELS
(CASSANO 2021)

Equivalent circuit model nonlinear due to:

- the pipe resistance R depends on the volumetric flow Q_i (bi-linearity)
- characteristic curves of the turbine are nonlinear

Convenient to linearize in a small-signal context



Linearization procedure:

- the pipe resistance is considered constant, assuming small variations of the flow
- first order Taylor approximation for the turbine characteristics (head and torque)

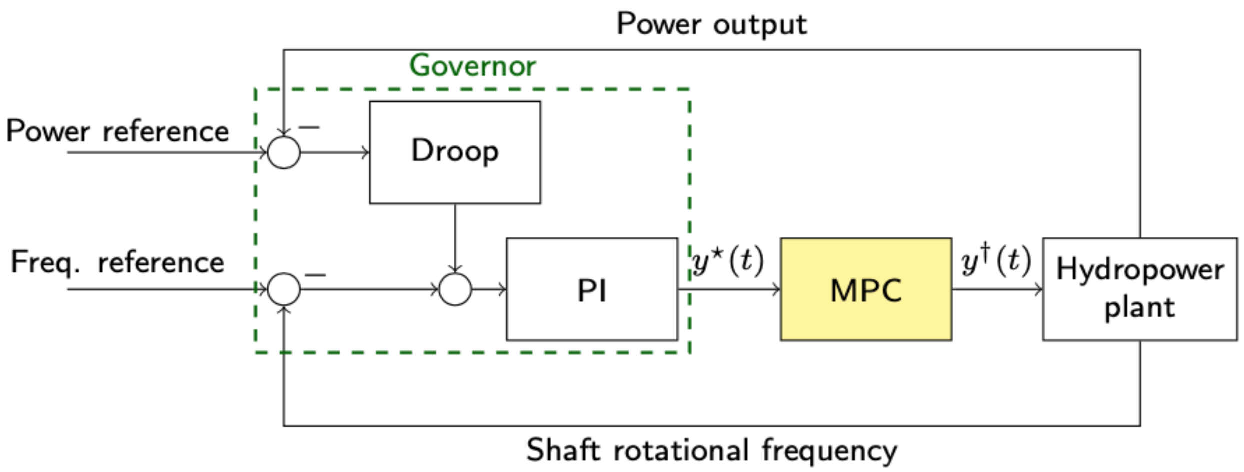
Linear and time-invariant state space model:

State vector $\boldsymbol{x} \triangleq [Q_1, \ldots, Q_I, h_1, \ldots, h_I, Q_t] \in \mathrm{R}^{2I+1}$

$$\dot{\boldsymbol{x}}(t) = A\boldsymbol{x}(t) + B_y y(t) + B_z \begin{bmatrix} H_u(t) \\ \mu - H_d(t) \end{bmatrix}$$

$$y(t) = C\boldsymbol{x}$$

MODEL PREDICTIVE CONTROL (MPC): FORMULATION



MPC problem

Track the original guide vane setpoint $y^\star$ as well as possible

$$\boldsymbol{y}^o = \underset{\boldsymbol{y}^\dagger \in \mathbb{R}^{T+1}}{\arg\min} \left\{ \sum_{\tau=t}^{t+T} \left(y^\dagger(\tau) - y^\star(\tau) \right)^2 \right\}$$

subject to

Head at all penstock elements from linearized equivalent circuit model $\quad h_i(\tau+1) = f(y^\dagger, \boldsymbol{x}(t)), \quad \forall i \wedge \tau$

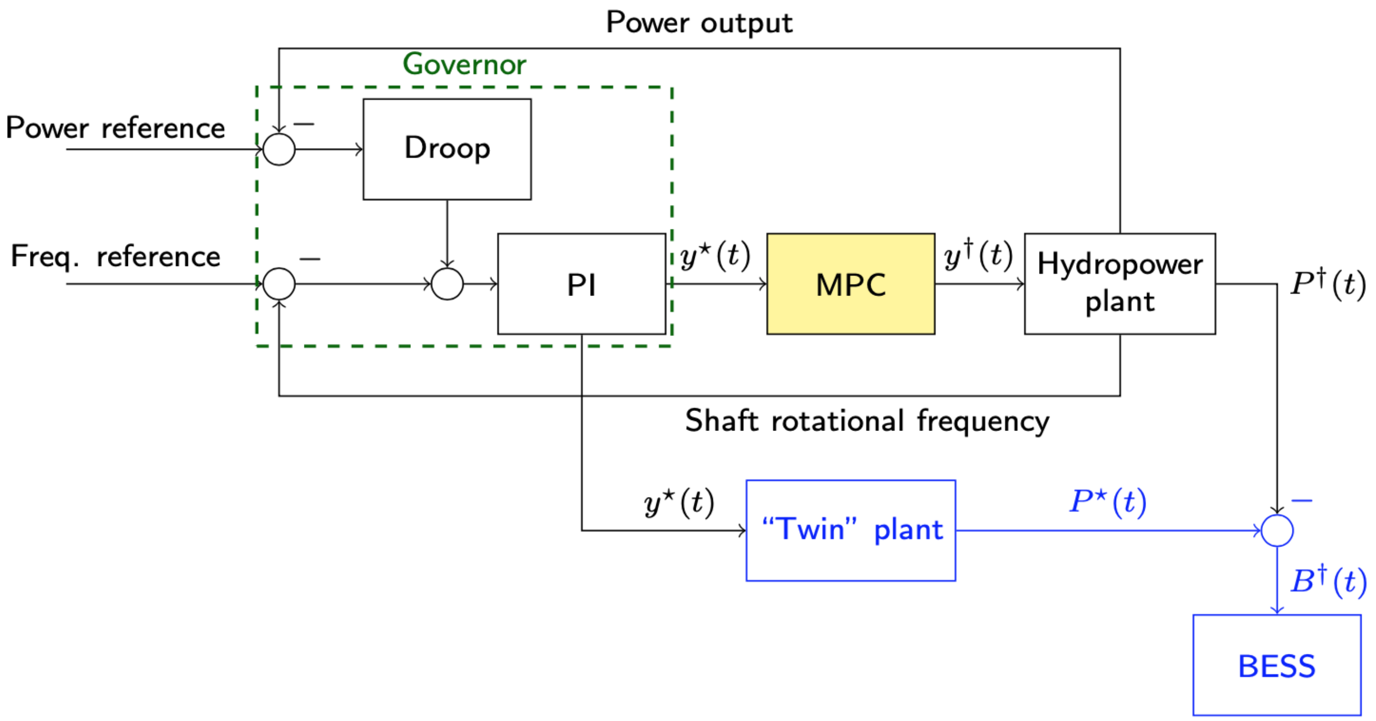
Head (stress) constraints $\quad \underline{h} \leq h_i(\tau+1) \leq \overline{h}, \quad \forall i \wedge \tau$

Guide vane limits $\quad \underline{y} \leq y^\dagger(\tau) \leq \overline{y}, \quad \forall \tau$

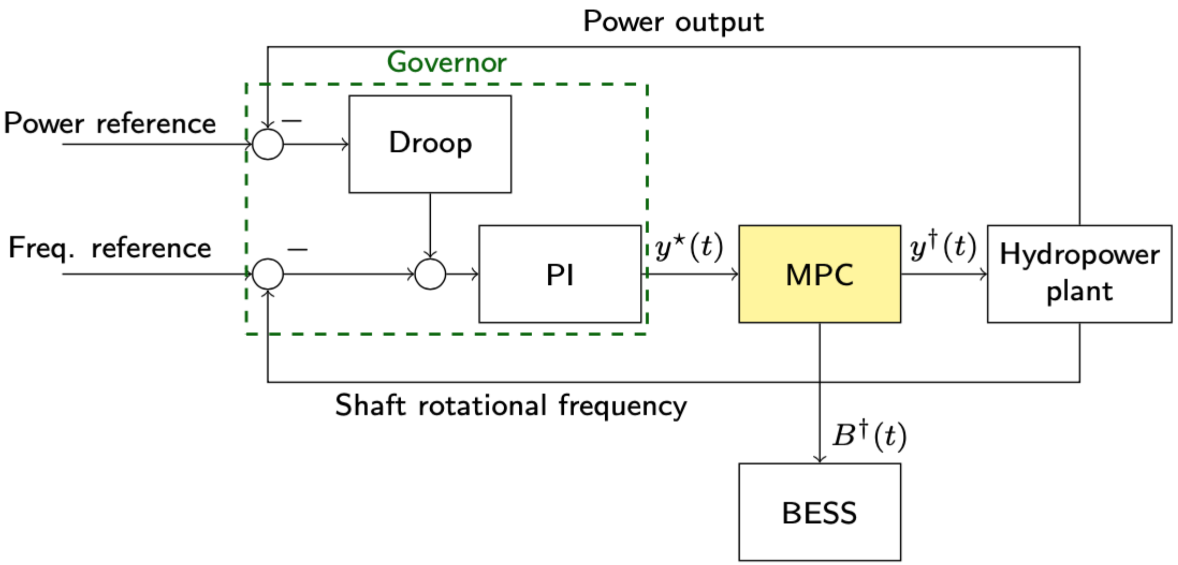
MPC applied in a receding horizon manner at t+1, t+2, … with updated information (and re-linearization).

EXTENSION TO HYBRID PLANT (CASSANO 2022B)

The hybrid plant should mimic the behavior of the hydropower plant with the original setpoint $y^\star$.



EXTENSION TO HYBRID PLANT (CONT'D)



STEP 1. Compute hydropower plant setpoint with MPC:

$$\boldsymbol{y}^o = \underset{\boldsymbol{y}^\dagger \in \mathbb{R}^{T+1}}{\arg\min} \left\{ \sum_{\tau=t}^{t+T} \left(y^\dagger(\tau) - y^\star(\tau)\right)^2 \right\}$$

subject to

$$h_i(\tau+1) = f(y^\dagger, \boldsymbol{x}(t)), \qquad \forall i \wedge \tau$$

$$\underline{h} \leq h_i(\tau+1) \leq \overline{h}, \qquad \forall i \wedge \tau$$

$$\underline{y} \leq y^\dagger(\tau) \leq \overline{y}, \qquad \forall \tau$$

STEP 2. Calculate battery power output as the difference between the (estimated) twin plant and real plant

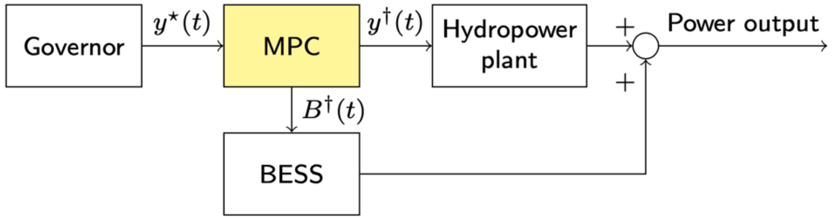
$$y^\dagger(t) = y^o(0)$$

$$B^\dagger(t) = P^\star(t) - P^\dagger(t)$$

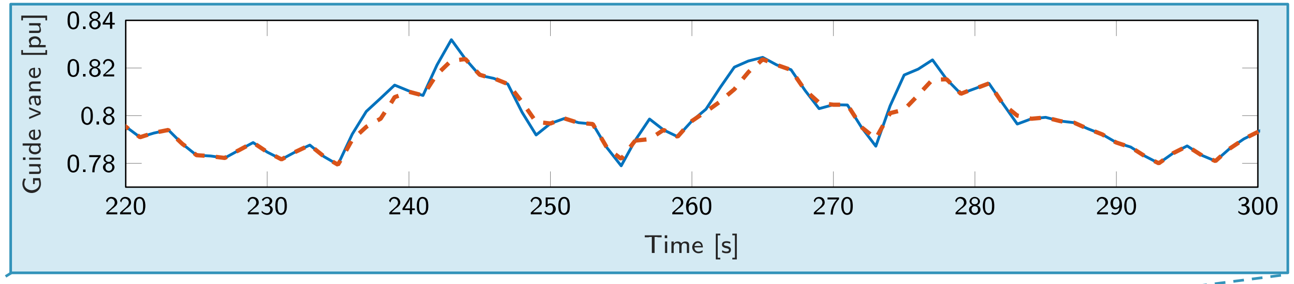
Converter and battery power limits $B^\dagger(t) = \text{saturator}\left(B^\dagger(t), \overline{B}, \underline{B}\right)$

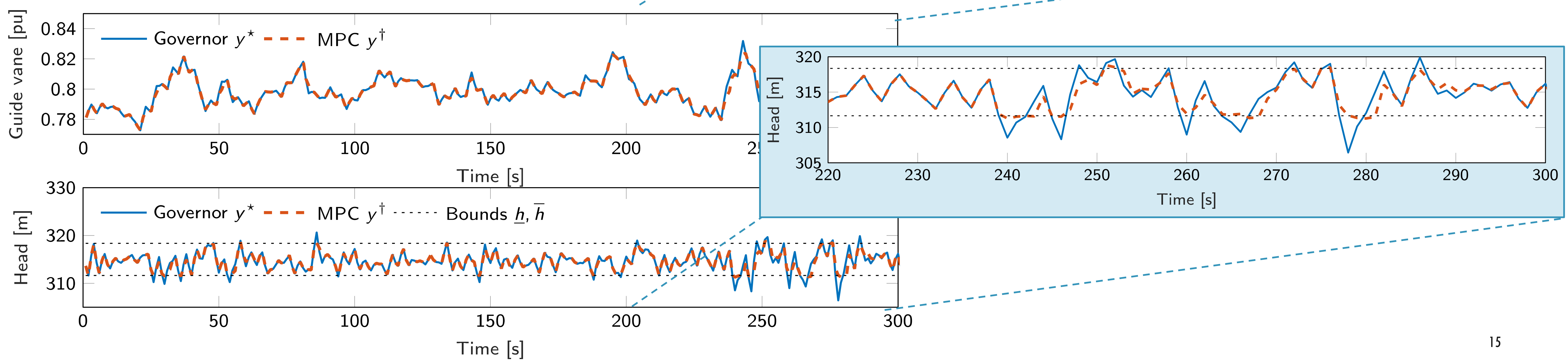
A scheduler at a slower time pace ensures correct battery charge levels (not covered here)

RESULTS: PENSTOCK'S STRESS CONSTRAINTS ACTIVATION

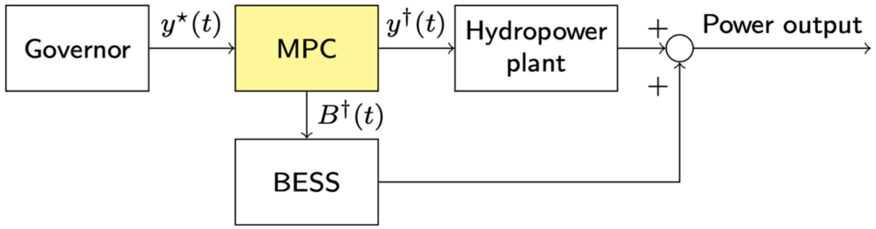


Simulation settings: primary frequency control, droop 2%, plant modeled with nonlinear equivalent circuit model, generator with swing equation and steady-state power-angle model.

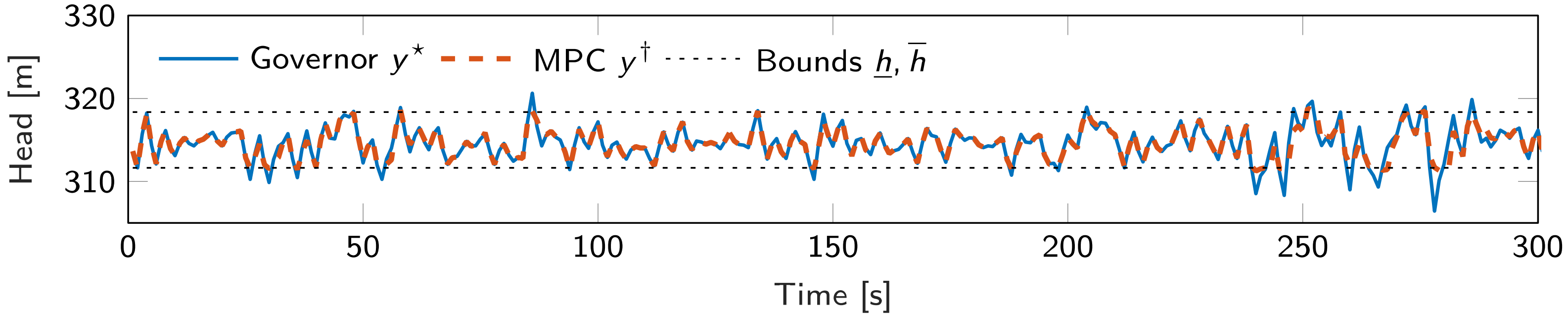




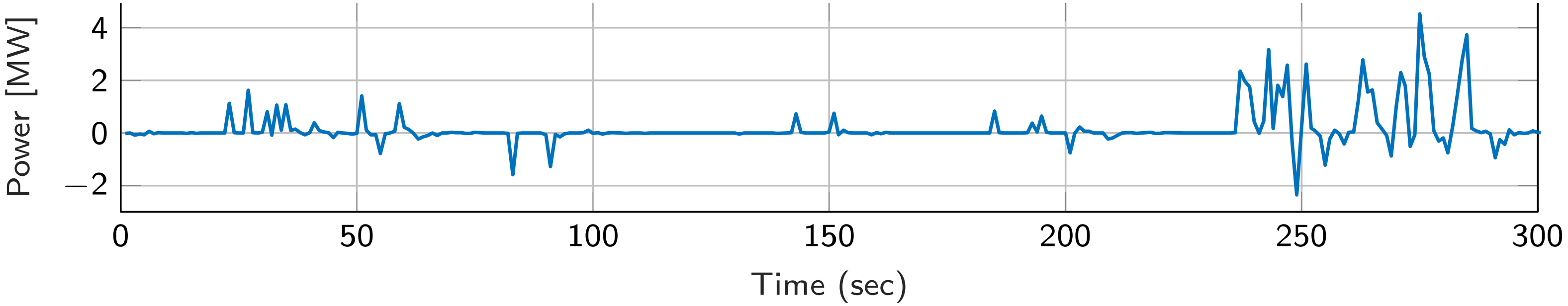
RESULTS: HYBRID OPERATIONS



Head and stress constraints

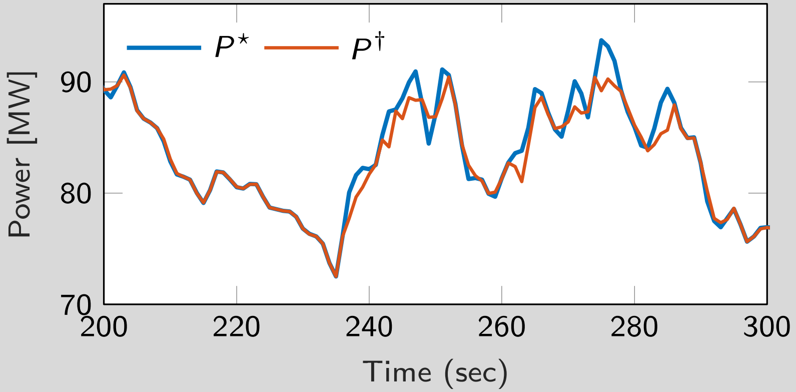


Battery contribution

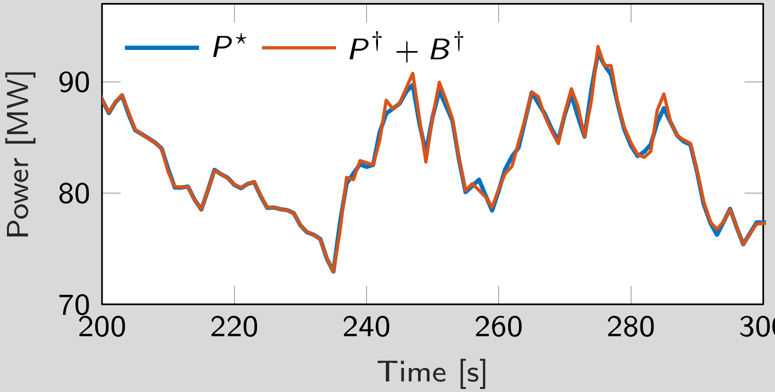


Tracking performance compared to the plant with the original setpoint:

No battery:



With battery:



PENSTOCK DAMAGE

Methodology to assess fatigue: for each penstock element i:

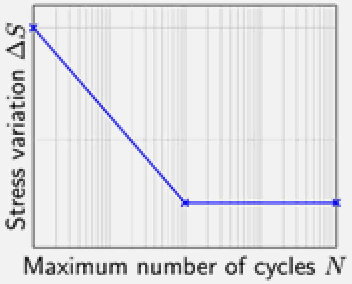
Convert head time series $h_i(t)$ to stress $\sigma_i(t)$

↓

Apply rain-flow counting to $\sigma_i(t)$ to identify stress variations $\Delta\sigma_{ij}$ and their number n_{ij}

↓

Select a SN curve, e.g.:



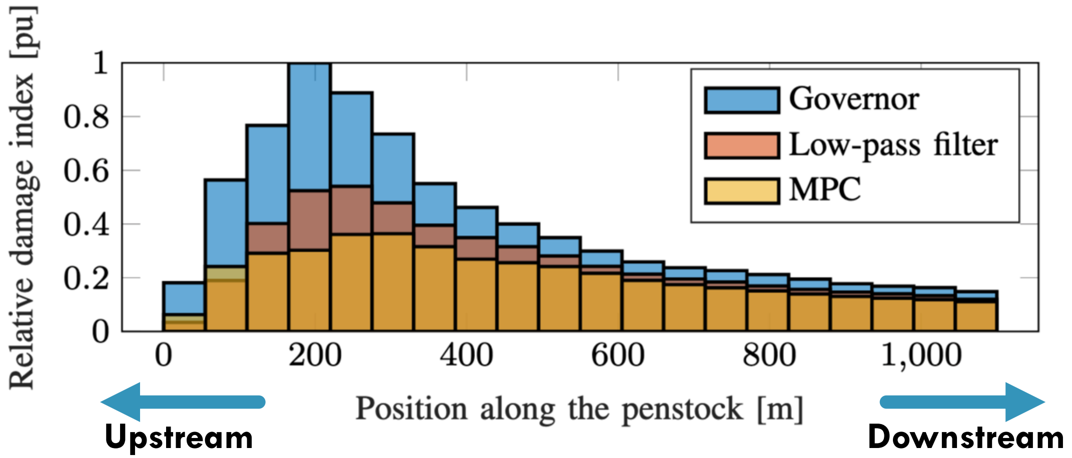
Damage index (Miner's rule):

$$D_i = \sum_{j=1}^{J} \frac{n_{ij}}{N(\Delta S_{ij})}$$

(**near 0**: no damage; **near 1 or larger**: critically damaged - possibly)

Benchmark controller: 1st order low-pass filter (LPF)

Cut-off frequency set to achieve the same power regulation as the MPC (measured as correlation coefficient between the grid frequency signal and the power output)



Relative damage index: damage index divided the largest damage index over all components and methods

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