Distributed feedforward control of wind farms: prospects and open problems

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The main idea

Load reduction in turbines located in farm

- Nowadays each turbine controlled separately
- Accounting for the whole farm might be beneficial
  - sharing wind speed measurements with neighbors
  - cooperation in terms of power production

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Distributed feedforward control

- assess potential of this scheme
- outline open theoretical problems

Outline

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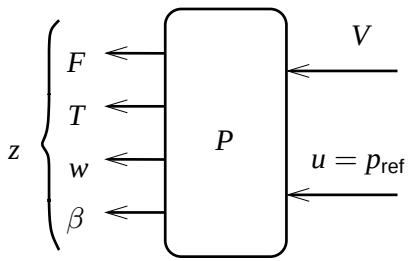
Individual turbine model

NREL 5 MW turbine with standard internal controller (IV'th operating region)



Inputs:

V - wind speed; p_{ref} - power reference;

Outputs:

F - thrust force; T - shaft torque

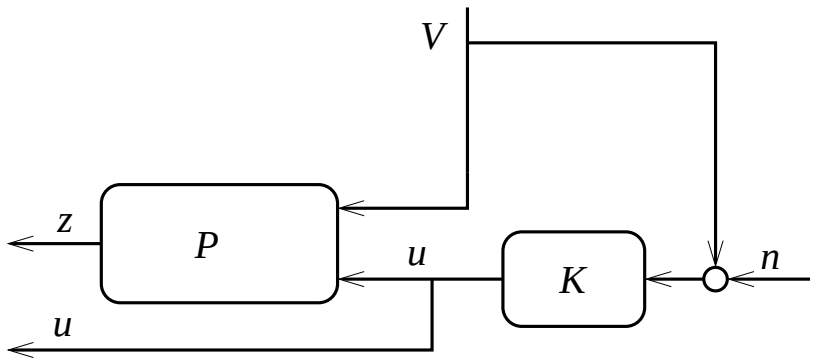
w - rotor speed; β - pitch angle;

Neglecting electrical circuit dynamics (power production = power reference)

Linearized around operating point (all signals represent deviaitons)

Problem formulation

Measured disturbance attenuation

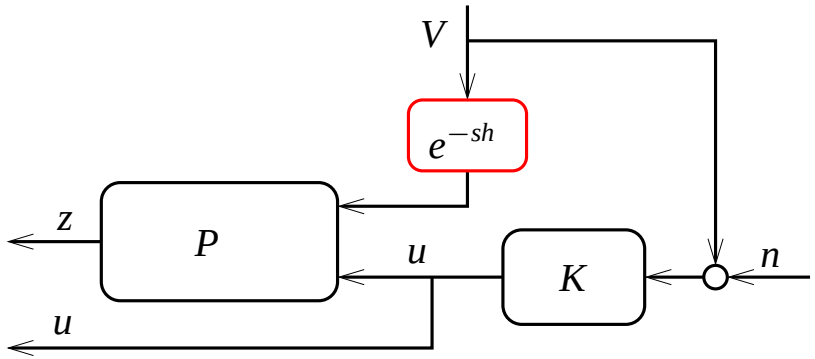


Deviations of wind speed V are disturbances measured with noise n

The aim is to keep deviations of turbine outputs small

Problem formulation

Measured disturbance attenuation



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Availability of preview is captured by delay operator e^{-sh}

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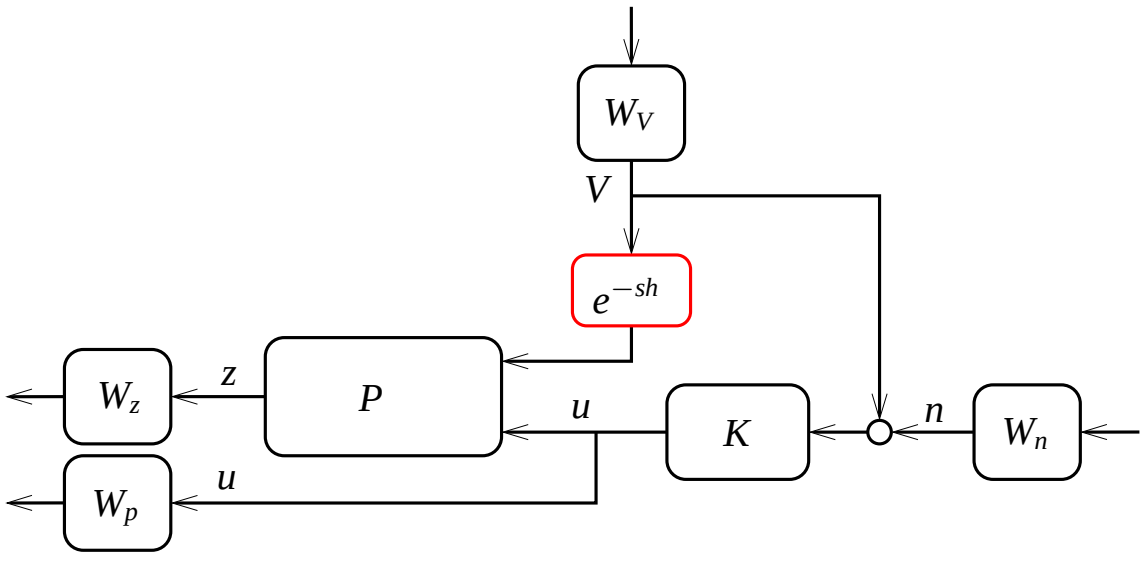

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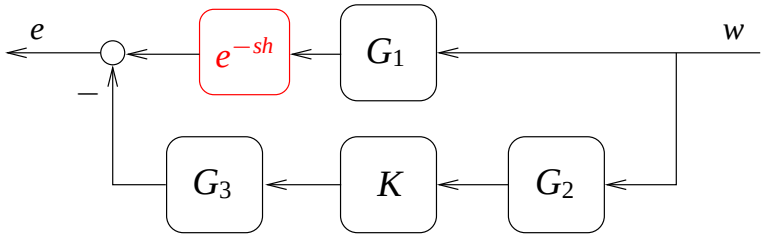
Model matching

Problem can be cast as model matching optimization



$$\min_{K \in H^\infty} ||e^{-sh} G_1 - G_3 K G_2||_2$$

- Unified setting for estimation and feedforward control
- Preview is captured by delay operator e^{-sh}
  - may improve performance ☺
  - renders problem infinite dimensional ☹

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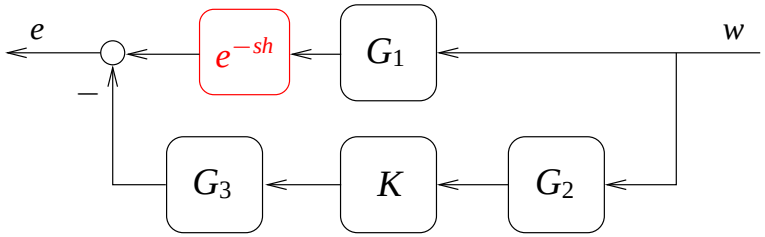

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Is there convenient numerically feasible solution

- one-side problem is well studied (without measurement noise)
- recently solution was extended to two-side problem

(Kristalny & Mirkin, MTNS 2010)

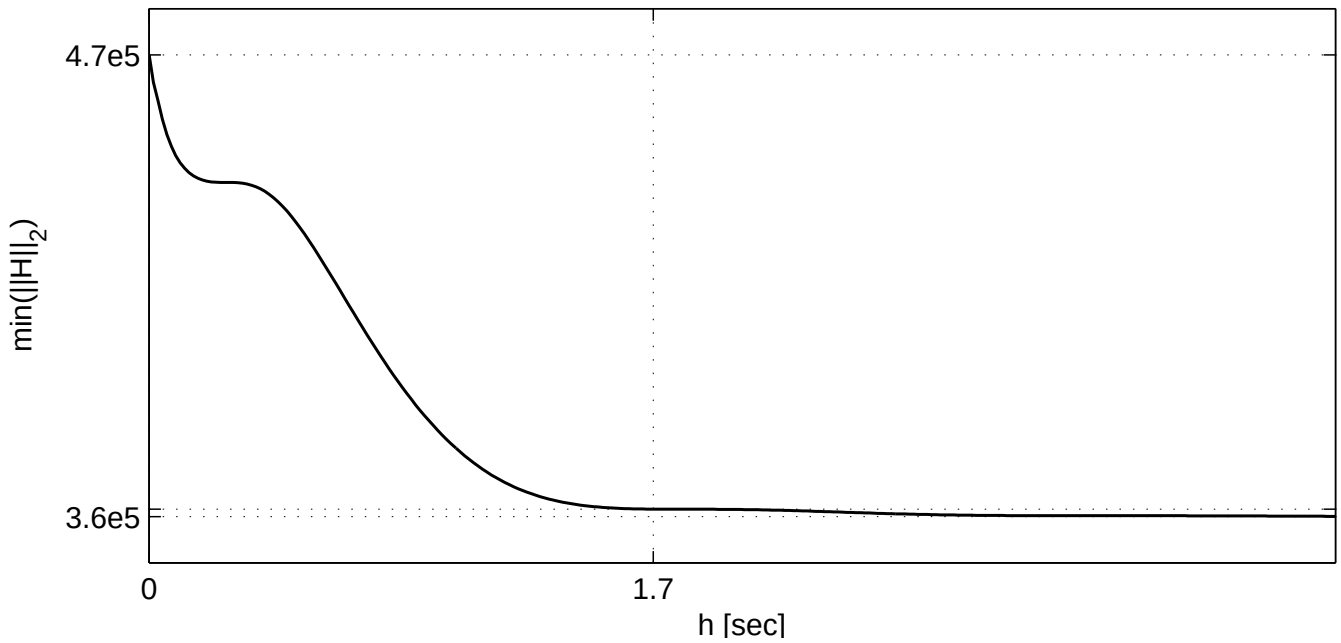
Solution properties

- explicit state-space formulae are available
- based on:
  - two Sylvester equations (asymptotic performance)
  - two Riccati equations (transient performance)

  of the same dimension as in preview-free case
- solution structure is convenient for implementation

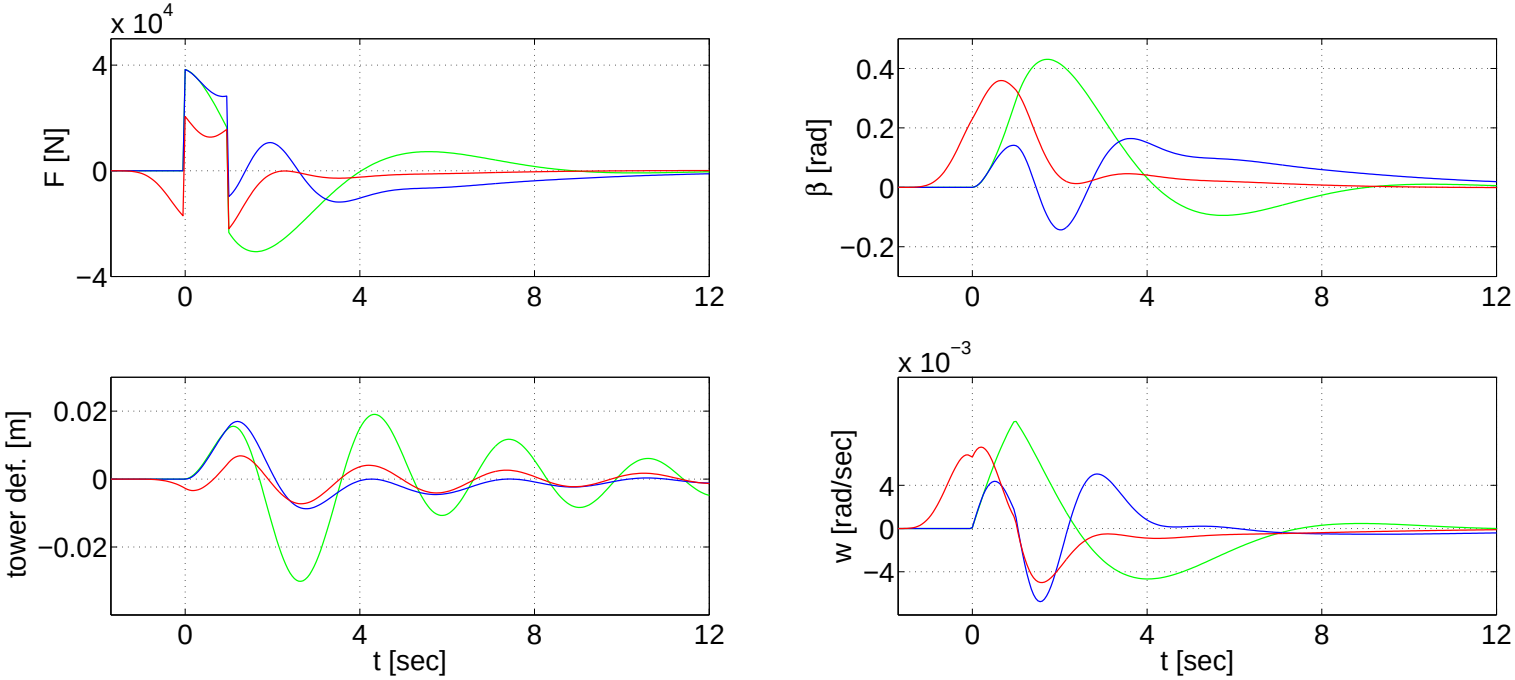
  (Contains finite dimensional blocks and FIR)
- influence of preview length on performance can be analyzed

Performance vs. preview length



- The relevant scale of preview is a number of seconds
- 98 % of improvement achieved with 1.7 sec preview

Simulation results



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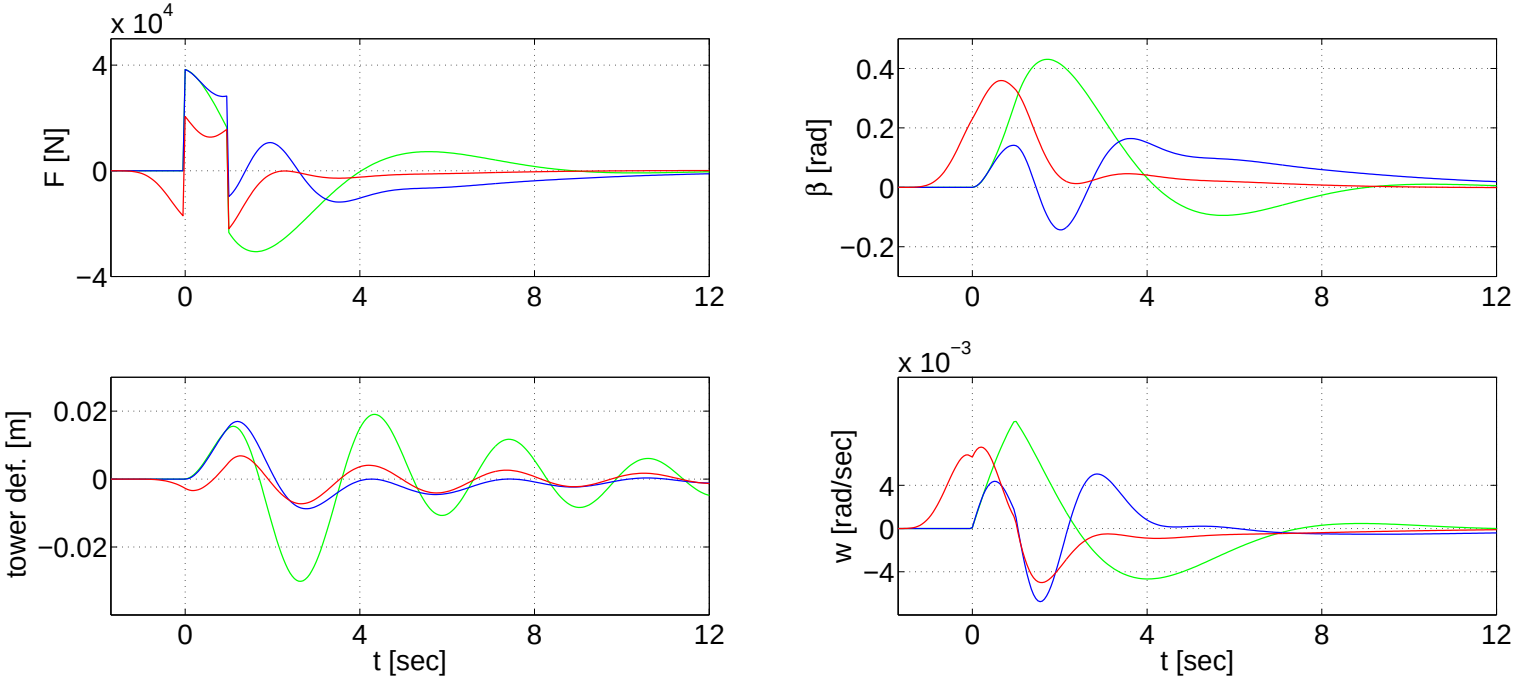
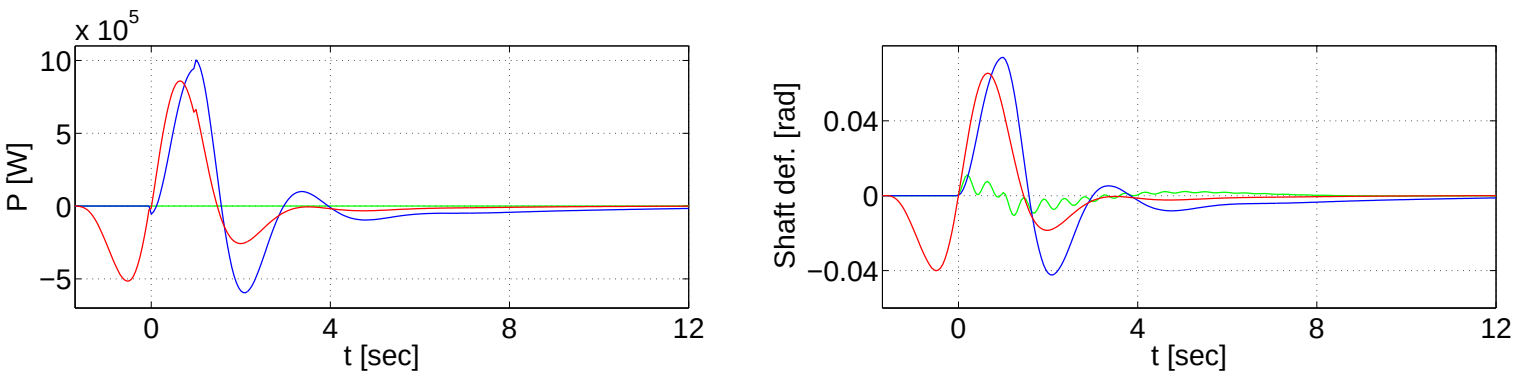




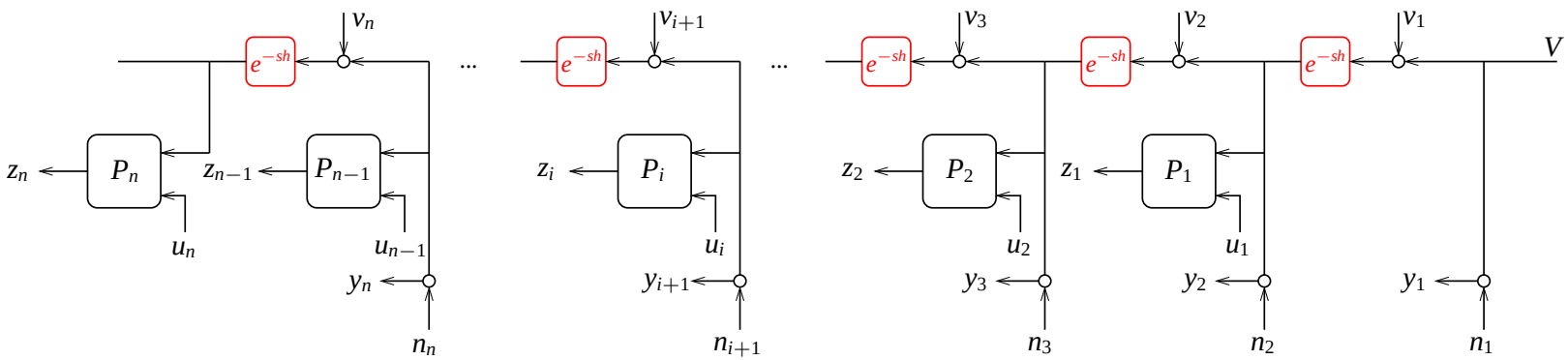
Outline

Wind farm model

Wake effects: mean speed deficit, increase of turbulence

- important in quasi-static analysis of farm
  (distribution of nominal powers among turbines in farm)
- less important for dynamics around specified operating point

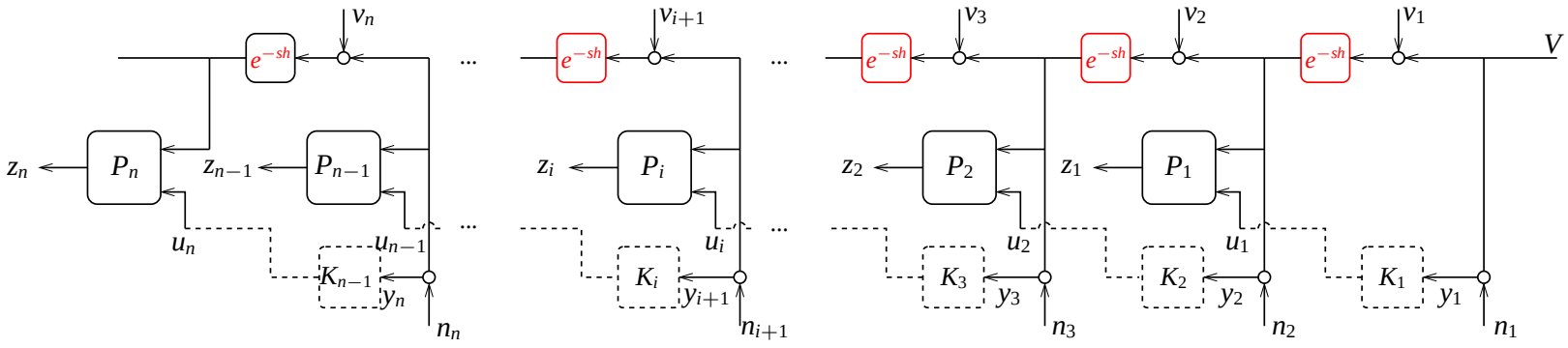
Neglect influence of pitch on wind flow



Wind propagation modeled as delay and additive noise

Distributed feedforward control

Preview control from previous part can be applied to each turbine in farm



Drawback:

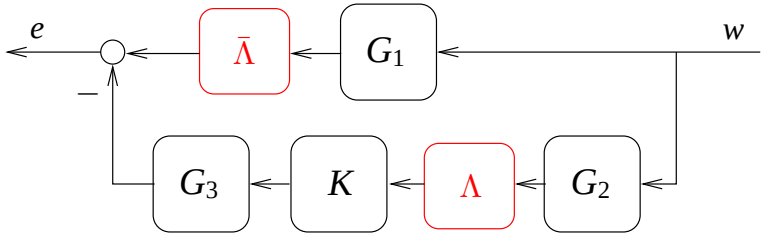
adjustment of turbines power $\Rightarrow$ fluctuations in overall power production

Cooperation between turbines can be beneficial

- requires formulation that takes the entire farm into account

Decentralized model matching

Problem can be cast as decentralized model matching optimization



$$\min ||e^{-sh} G_1 - G_3 K G_2||_2$$

for $K = \text{diag}\{K_1 \dots K_N\} \in H^\infty$

Diagonal constraint on parameter K

- relevant in various distributed control problems (quadratic invariance)

Complicated structure of delays $(\Lambda, \bar{\Lambda})$

- discretization leads to numerical difficulties

These problems are open!

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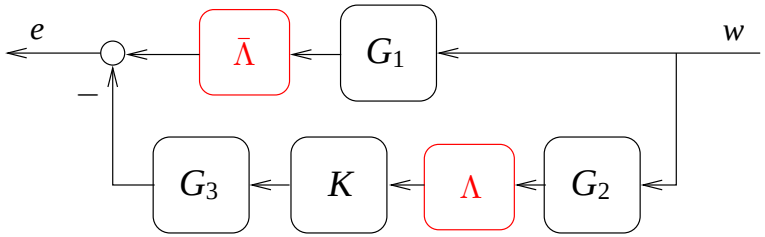

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Diagonal constraint on parameter K

- relevant in various distributed control problems (quadratic invariance)
- preliminary frequency domain solution (in terms of Hadamard product)

Complicated structure of delays $(\Lambda, \bar{\Lambda})$

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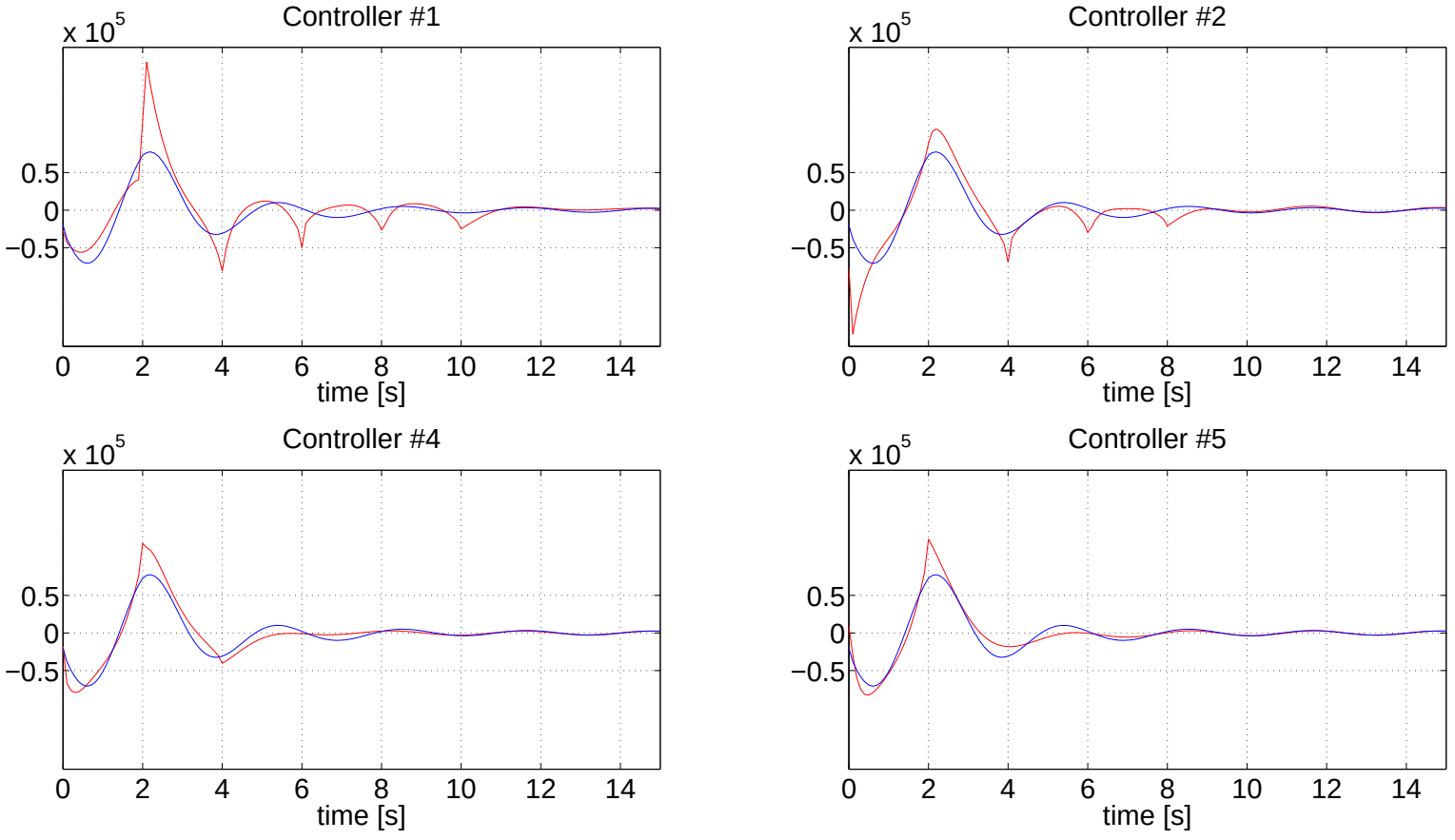
Approximate solution available.

Optimal controllers

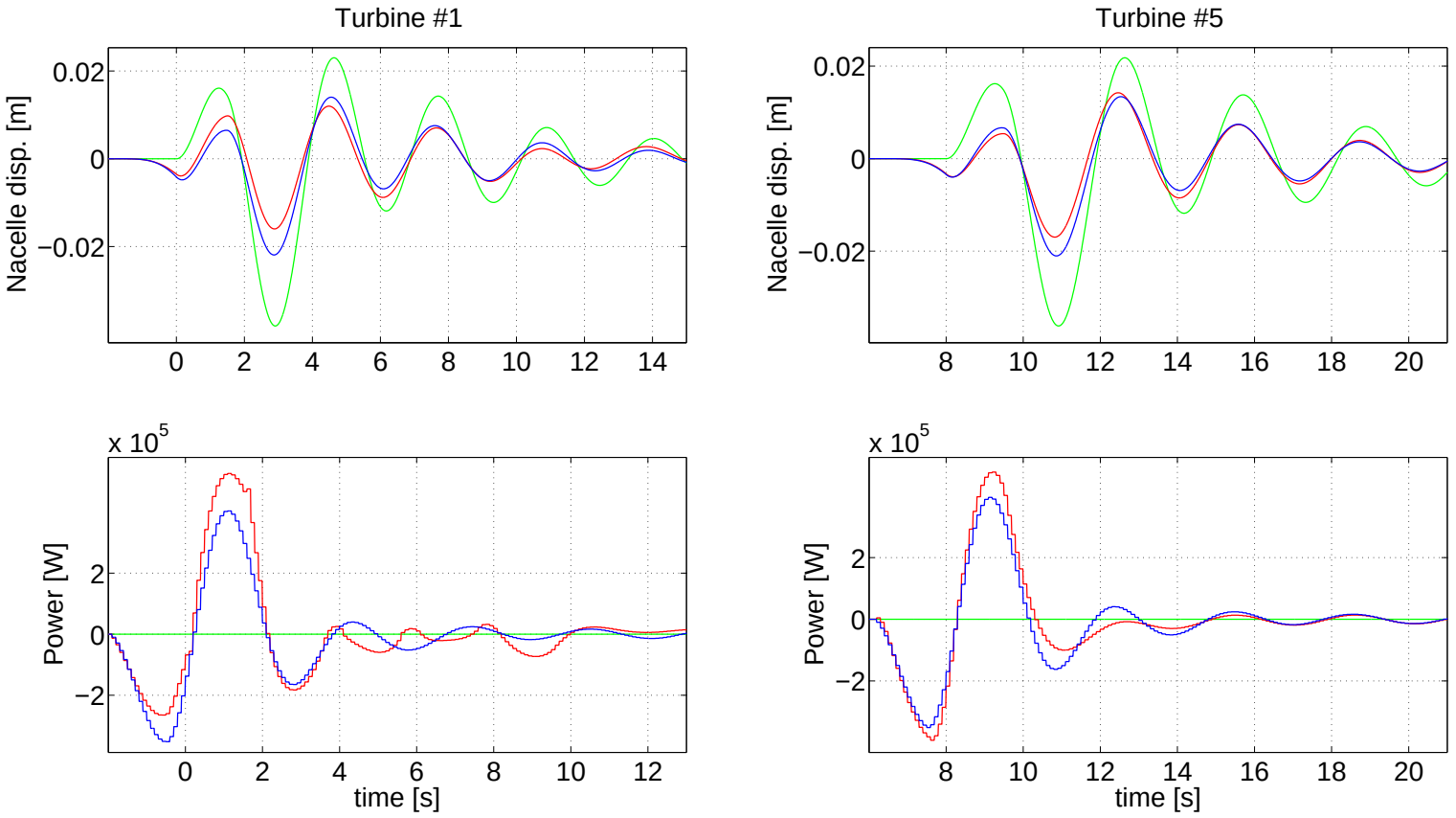
Impulse responses of optimal controllers



Each controller takes care of downwind turbines

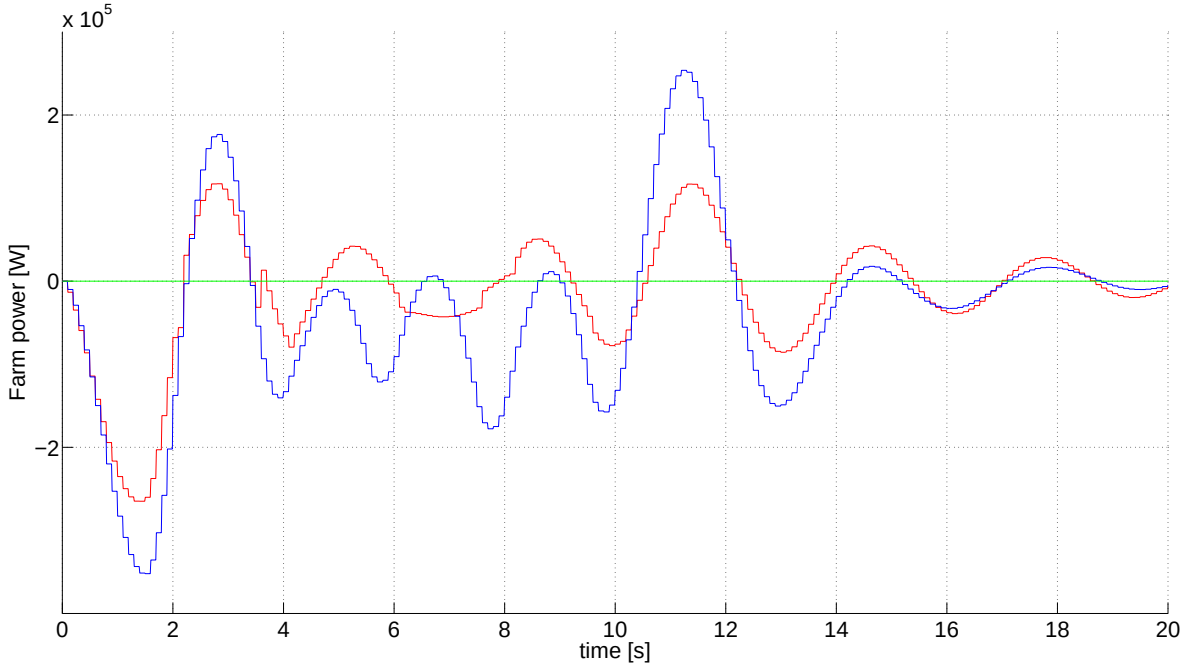
(peaks in time multiples of h)

Simulation results



- Slight decrease in tower oscillations
- Demands more deviations in individual turbine powers

Simulation results - improvement in overall power production



- decrease in deviations of overall farm power production
- without deterioration in terms of load reduction

Summary

- Preview advantageous for load reduction
- Convenient methods for controller synthesis exist
- Next: considering turbine without internal controller

- Cooperation between turbines might be advantageous
- Distributed feedforward control scheme
  - open theoretical problems
  - requires reliable model of wind propogation

Thank you for attention!