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AEOLUS: Wind farm control concepts

Hierarchical wind farm control for power/load optimization

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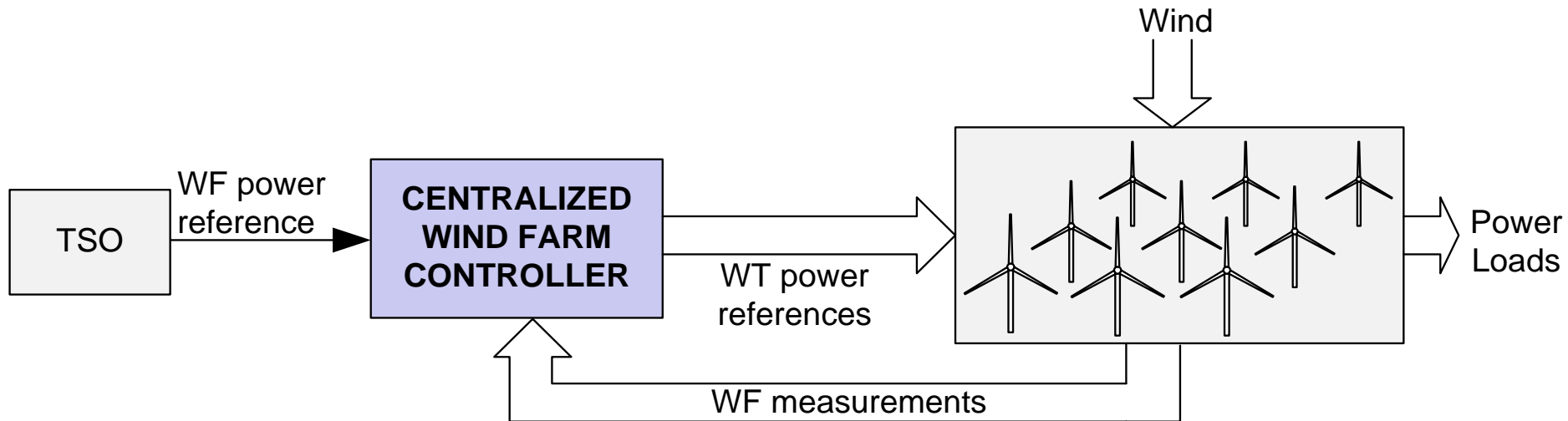


Outline

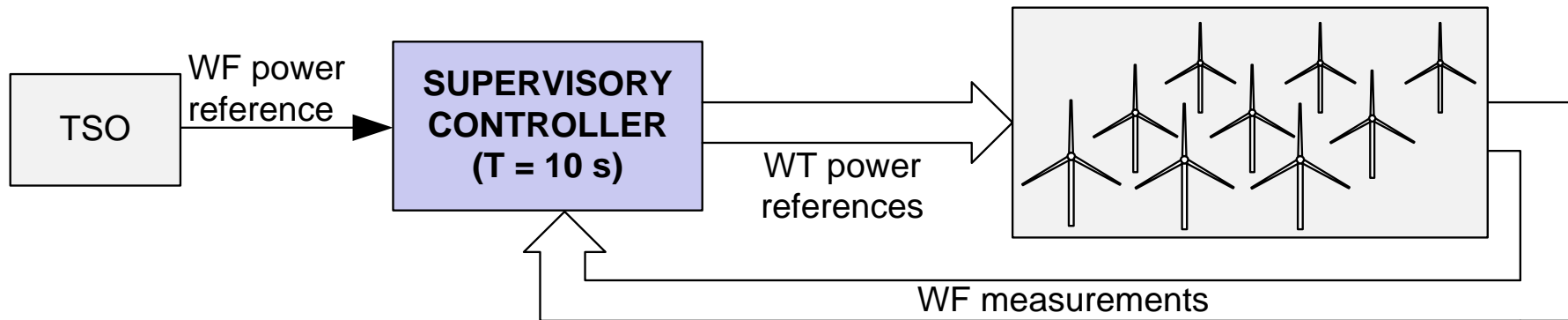
- Hierarchical wind farm controller for power/load optimization
 - definition and motivation
- Reconfigurable controller design
- Case studies
- Conclusion



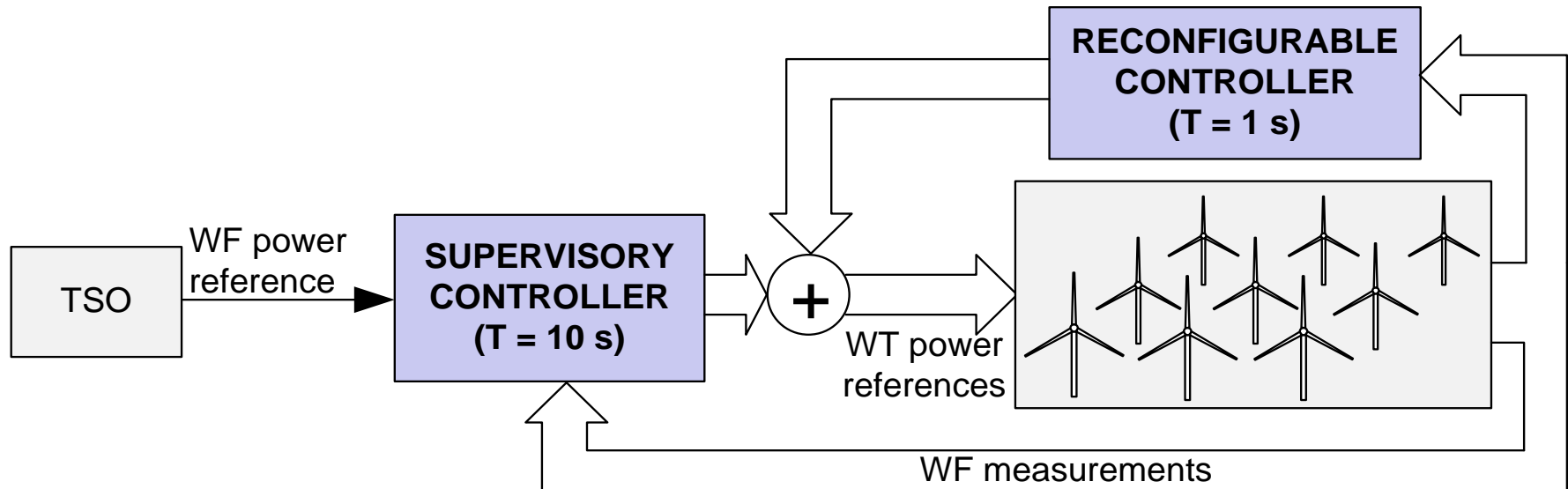
Centralized wind farm controller



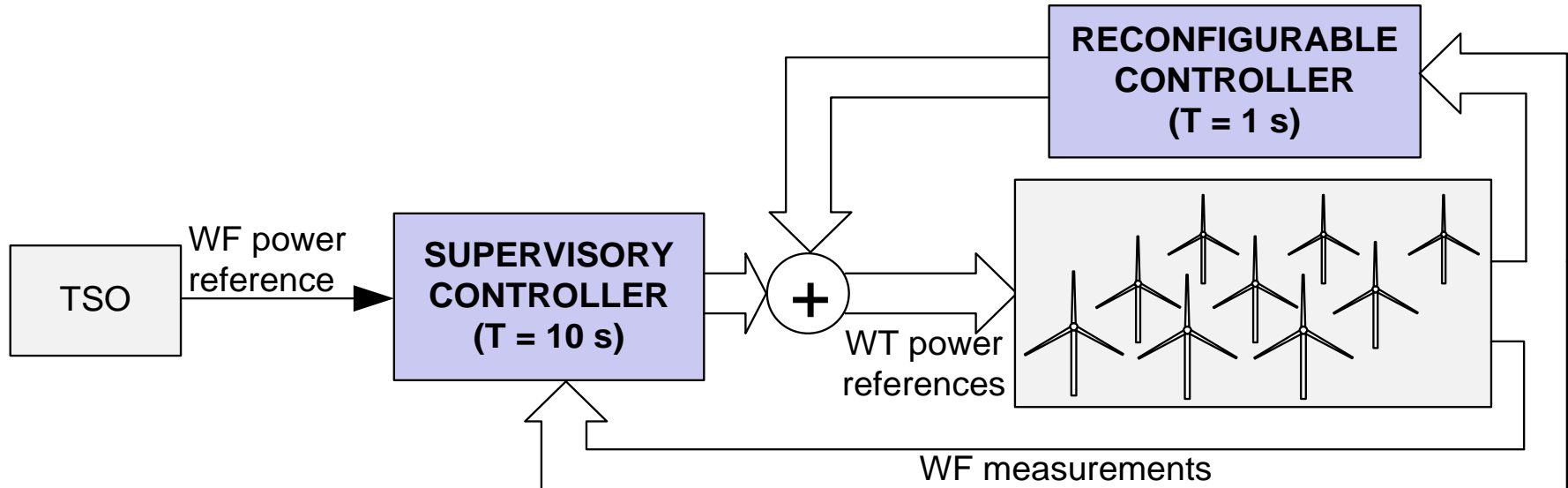
Supervisory controller



Hierarchical wind farm controller



Hierarchical wind farm controller



Supervisory controller

- uses the wind field model
- determines optimal wind farm operating points

Reconfigurable controller

- uses the wind turbine model
- determines optimal short term deviations from the operating points

Common objective

improvement of power tracking and minimization of loads

Reconfigurable controller

Control problem features

- MIMO optimal control problem with constraints, large number of system states and control variables
- Real-time implementation requirement - computation time less than one second \Rightarrow on-line Model Predictive Control approach inadequate

Outline of the proposed solution

- Approach: **“Divide and conquer.”**
- Define an optimal control problem for a single wind turbine

Wind turbines decoupled \Rightarrow wind farm optimal control problem is a (constrained) superposition of wind turbine control problems
- **Off-line:** generate a parametrical solution to the WT control problem

Parameters: wind turbine state estimates, wind speed estimates, optimal operating points
- **On-line:**
 - fix the measured/estimated/obtained parameters to obtain a sensitivity function that describes how much a wind turbine benefits/suffers by changing its power reference
 - superpose the wind turbine control problems
 - introduce coupling - the wind farm power reference add-up to the required wind farm power
 - find the optimal deviations to operating points by solving the constrained optimization problem



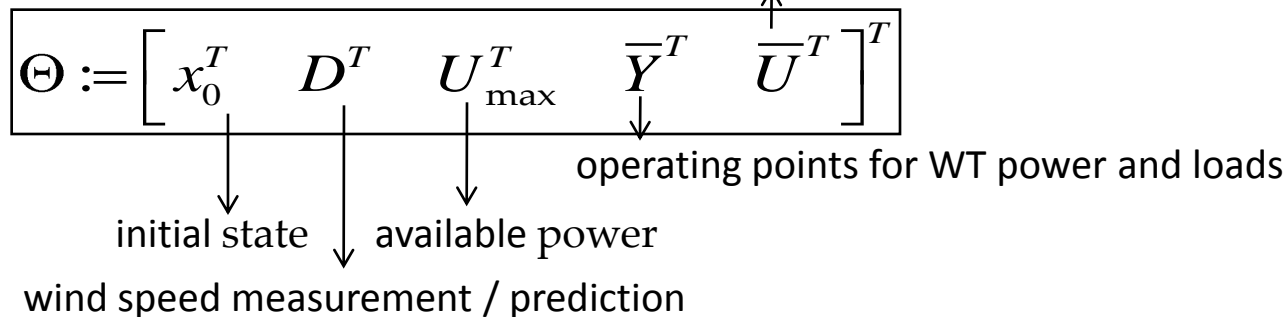
Reconfigurable controller design – OFF-LINE

Constrained finite-time optimal control problem for a single wind turbine

$$\begin{array}{ll} \min_U & J(x_0, D, U_{\max}, \bar{Y}, \bar{U}, U) = (Y - \bar{Y})^T Q_y (Y - \bar{Y}) + (U - \bar{U})^T R (U - \bar{U}) \\ \text{subject to} & \begin{cases} Y = Ax_0 + BU + B_d D + F \\ E_U U + E_x x_0 \leq E(U_{\max}) \end{cases} \end{array}$$

Parametrization

parameter for on-line disturbance distribution



Off-line parametric solution

Optimizer:

$U^*(\Theta)$ continuous PieceWise Affine function over polyhedra

Value (sensitivity) function:

$J^*(\Theta)$ continuous convex PieceWise Quadratic function over polyhedra

Reconfigurable controller design – ON-LINE

1. Take measurements and data from nominal controller and insert into parameter Θ to extract the value function (j is the index of an individual wind turbine)

$$V^j(\bar{U}^j) := J^{*j}(\underbrace{x_0^j(t), D^j(t), U_{\max}^j(t)}_{\text{measured/estimated}}, \bar{Y}^j(t), \bar{U}^j)$$

↓
from nominal controller

2. Compute the optimal disturbance compensation

$$\bar{U}^* = \arg \min_{\bar{U}^1, \dots, \bar{U}^{N_{wt}}} \sum_{j=1}^{N_{wt}} V^j(\bar{U}^j)$$

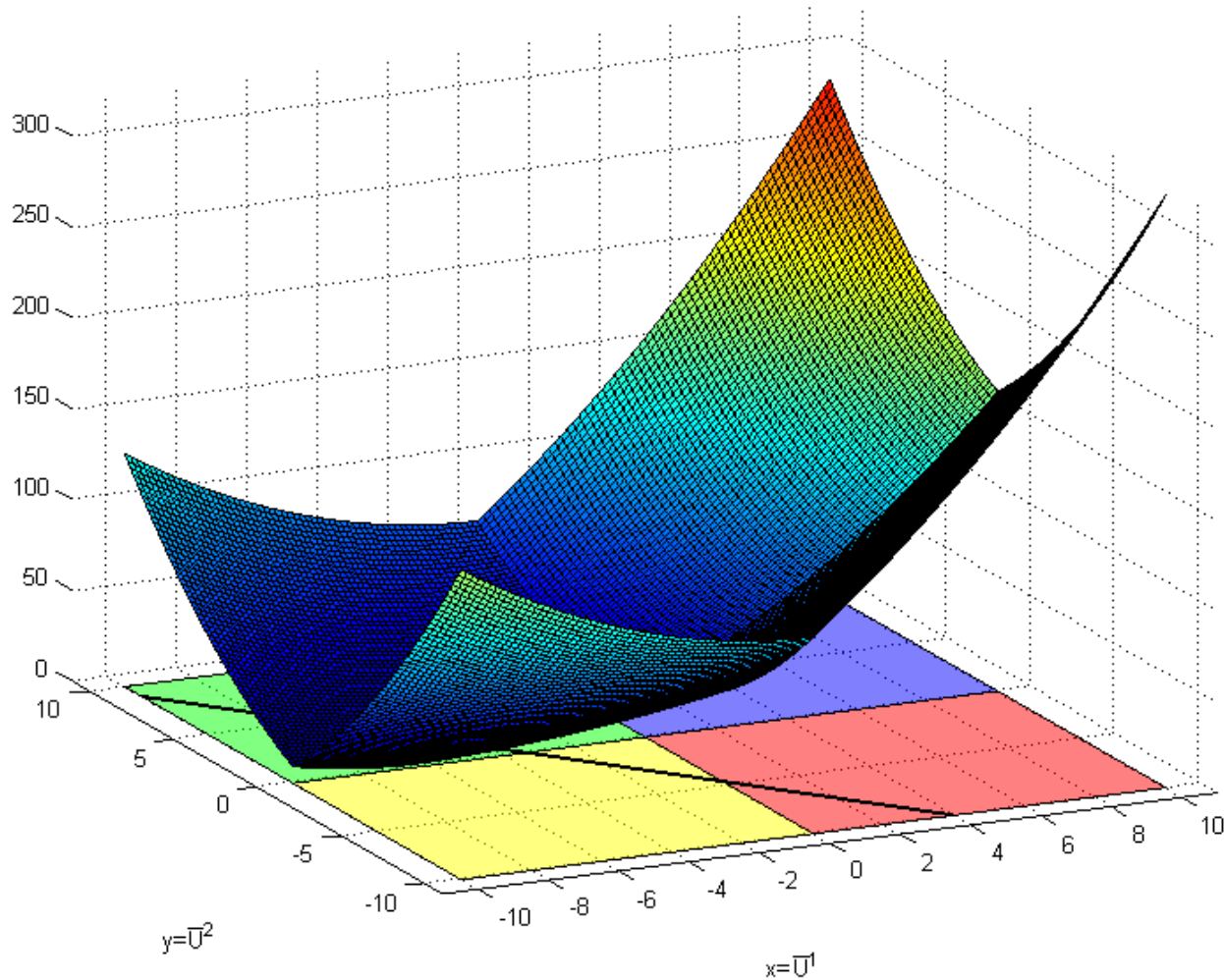
subject to $\sum_{j=1}^{N_{wt}} \bar{U}^j = P_{WF}^{ref}$

3. Compute control inputs

$$P_{ref}^j = U^{j*}(x_0^j(t), D^j(t), U_{\max}^j(t), \bar{Y}^j(t), \bar{U}^{j*})$$

Optimal disturbance compensation in 2D

$$\sum_{j=1}^{N_{wt}} V^j(\bar{U}^j)$$

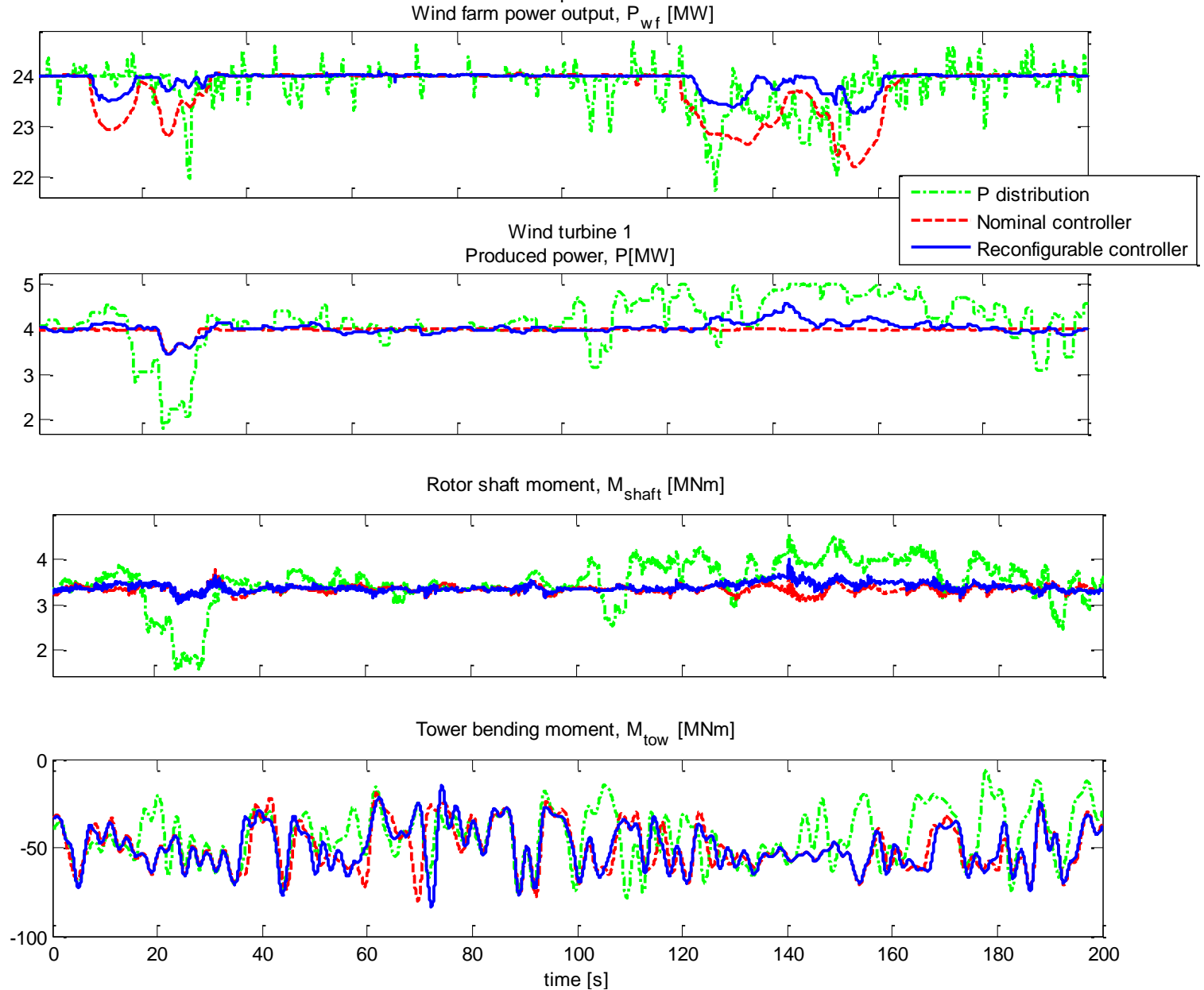


Simulation experiments

- 6 NREL wind turbines
- Optimal distribution from nominal controller considered given and constant during simulation time
- Performance of three controllers is compared:
 - **Constant references** - power demands are held constant during simulation
 - **P distribution** - power demands oscillate proportionally to the available power
 - **Reconfigurable controller** - prediction horizon 4 seconds, 3th order WT model
- Two simulation scenarios presented:
 - **Power recovery**
 - mean wind speed 12 m/s, available power drops below nominal, reconfigurable controller primarily recovers the wind farm power output
 - **Power curtailment**
 - mean wind speed 18 m/s, reconfigurable controller redistributes the power demand to achieve reduction in loads



Experiment 1: Power recovery



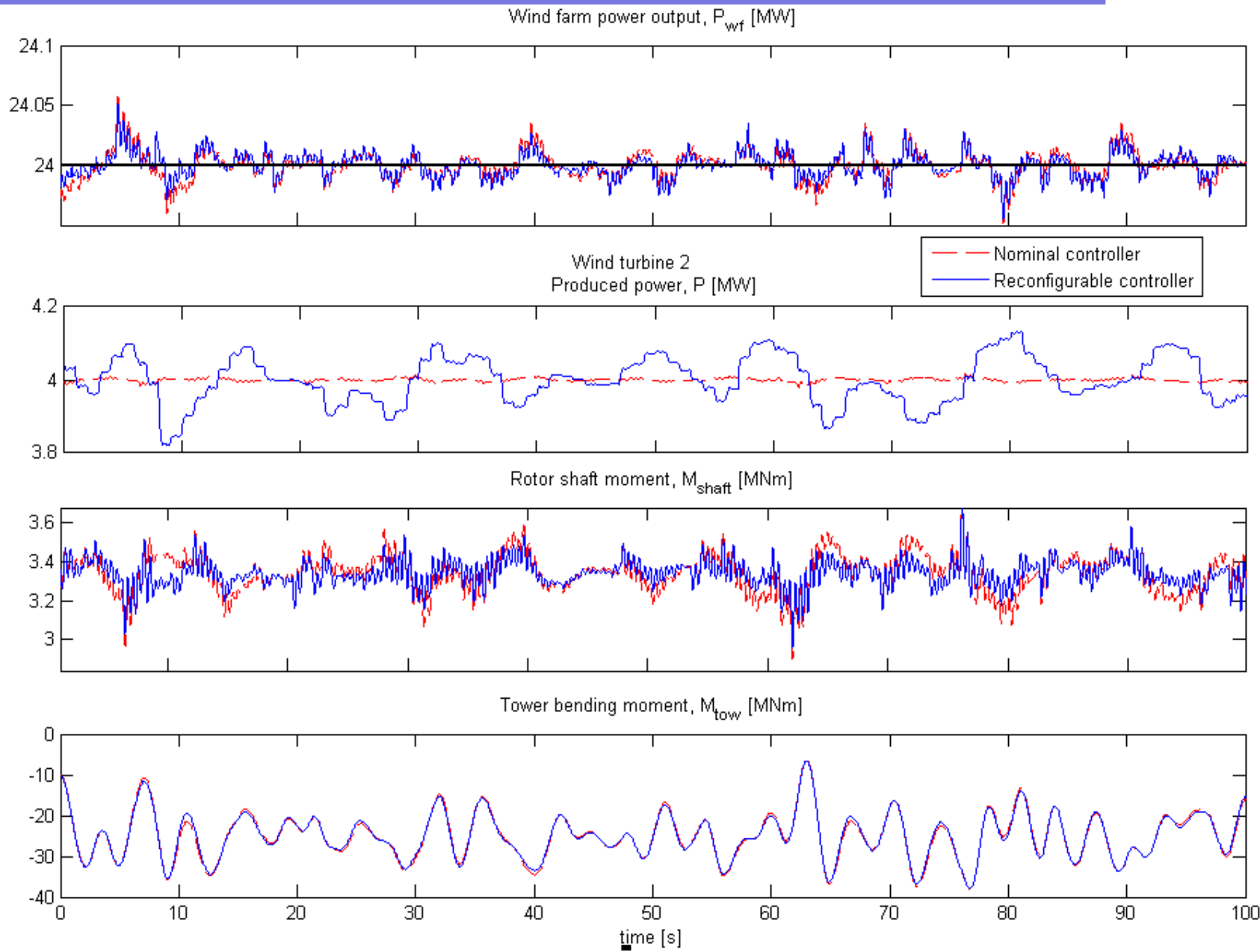
Experiment 1: Power recovery

	Wind farm power STD [kW]	Average WT shaft DEL [kNm]	Average WT tower DEL [MNm]
Constant references	550	1080	134
P distribution	560 +2%	3115 +188%	150 +12%
Reconfigurable controller	400 -27%	1153 +7%	130 -3%

- improved tracking of the wind farm power reference
- power compensation is paid by increases in shaft loads
- tower loads decreased



Experiment 2: Power curtailment



Experiment 2: Power curtailment

	Wind farm power STD [kW]	Average WT shaft DEL [kNm]	Average WT tower DEL [MNm]
Constant references	0	955	71
Reconfigurable controller	0	793 -17%	69 -3%

- the quality of wind farm power tracking is not deteriorated
- shaft loads decreased significantly
- tower loads decreased



Conclusion

- Case studies demonstrate that there is a potential for improvement of wind farm operation by fast redistribution of power references
 - When operating close to production limit controller successfully restores power while maintaining the loads low
 - With enough wind on disposal the reduction of loads is significant

- The proposed control design provides maximal flexibility

Thank you for your attention!

