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AEOLUS: Wind farm control concepts

Hierarchical wind farm control for power/load optimization

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SEVENTH FRAMEWORK PROGRAMME

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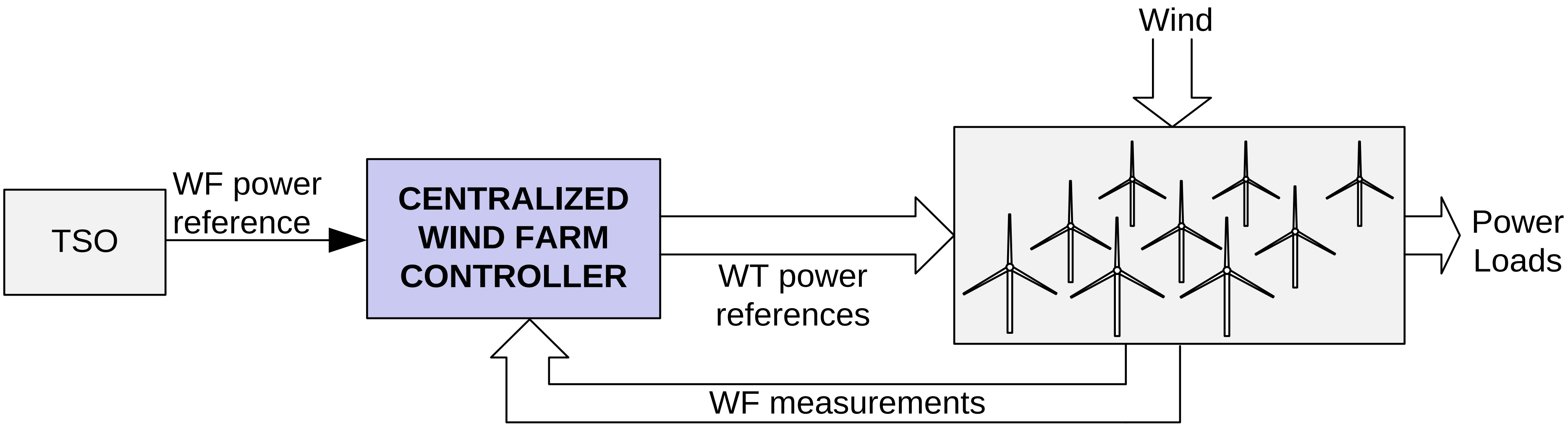
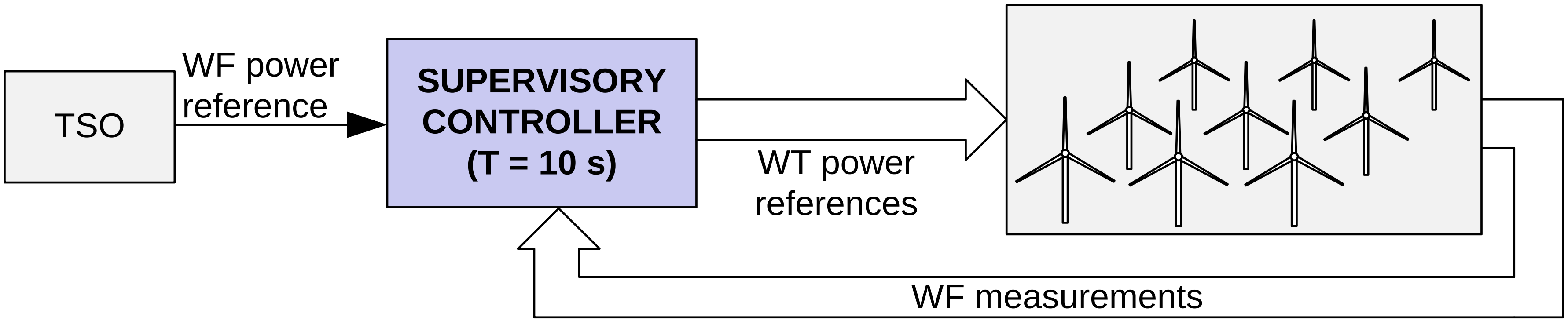
Outline

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

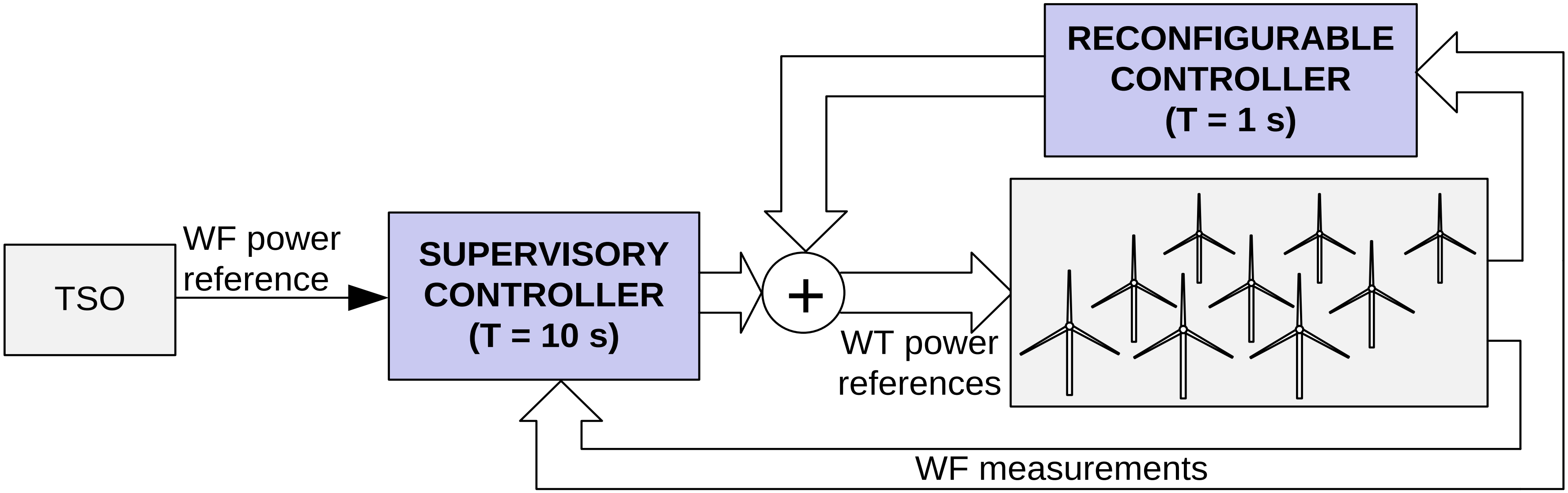
Centralized wind farm controller



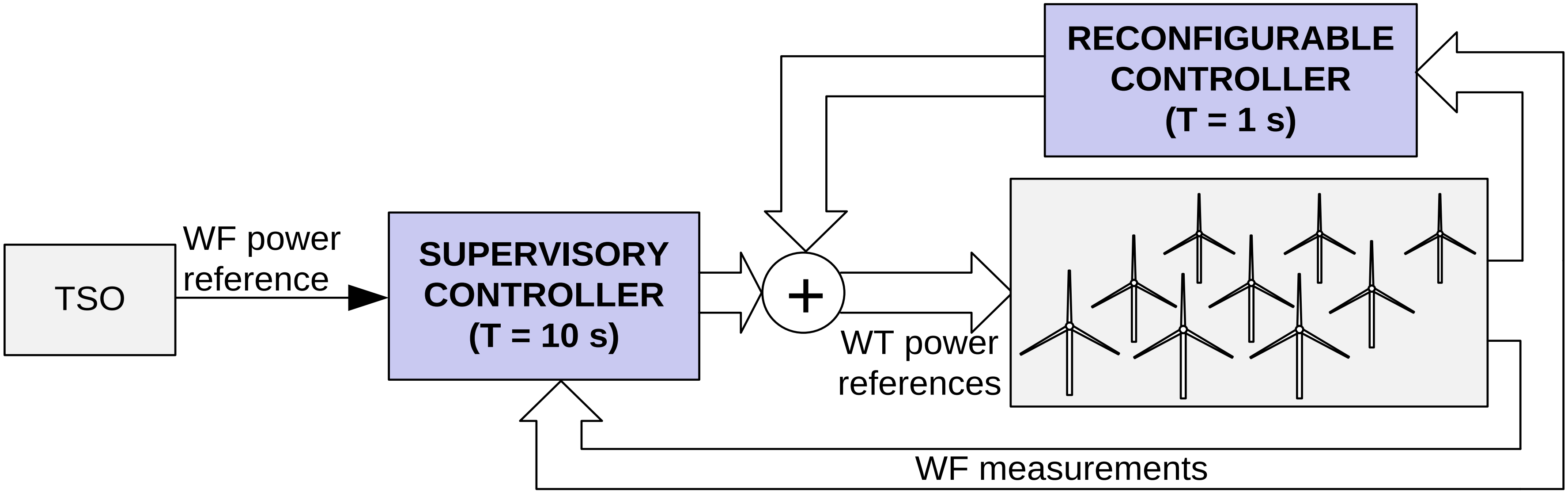
Supervisory controller



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

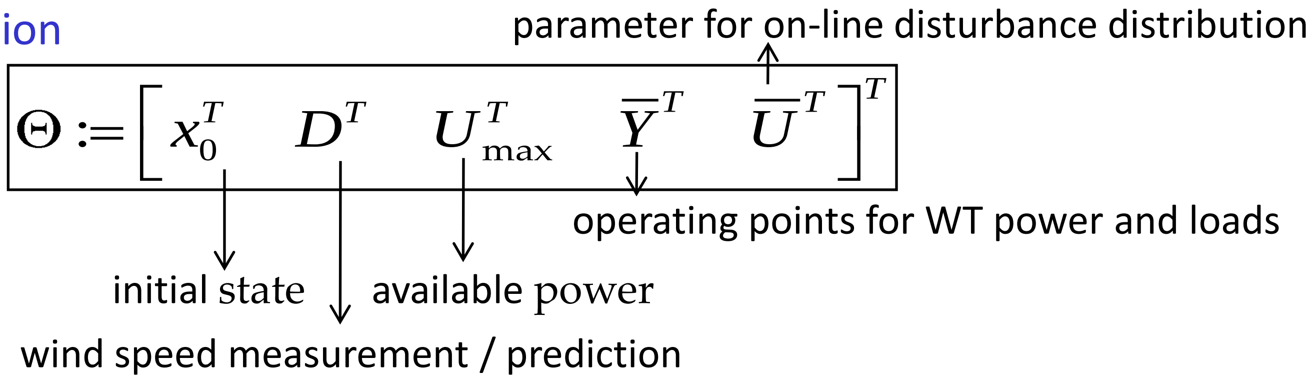
  Parameters: wind turbine state estimates, wind speed estimates, optimal operating points
- **On-line**:
  - fix the measured/estimated/obtained parameters to obtain a sensitivity function that describes how much a wind turbine benefits/suffers by changing its power reference
  - superpose the wind turbine 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

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

Parametrization



parameter for on-line disturbance distribution

$$\Theta := \begin{bmatrix} x_0^T & D^T & U_{\max}^T & \overline{Y}^T & \overline{U}^T \end{bmatrix}^T$$

operating points for WT power and loads

initial state

available power

wind speed measurement / prediction

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)

$$V^j(\overline{U}^j) := J^{*j}(\underbrace{x_0^j(t), D^j(t), U_{\max}^j(t)}_{\text{measured/estimated}}, \underset{\substack{\downarrow \\ \text{from nominal controller}}}{\overline{Y}^j(t)}, \overline{U}^j)$$

2. Compute the optimal disturbance compensation

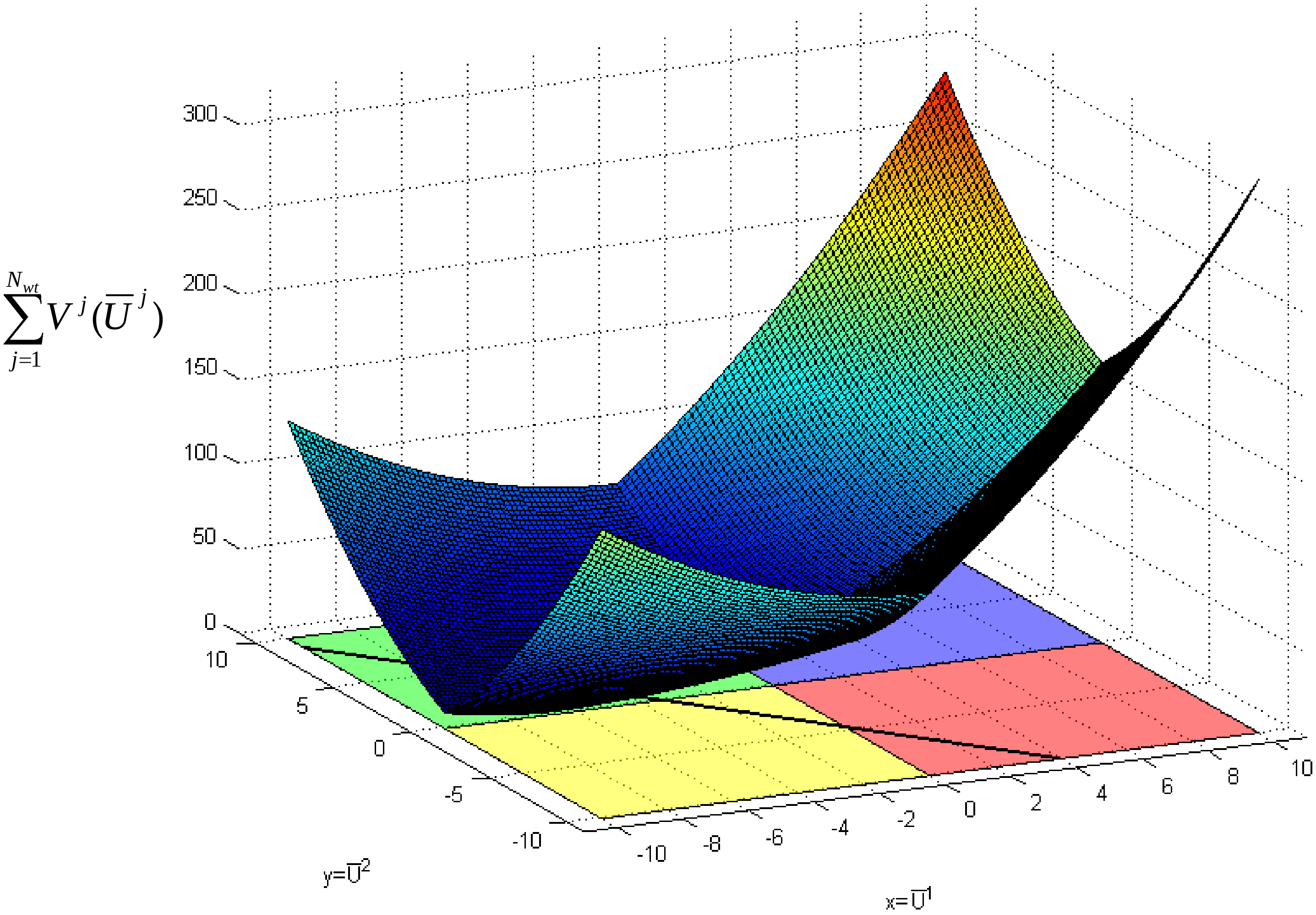
$$\overline{U}^* = \underset{\overline{U}^1,\ldots,\overline{U}^{N_{\mathrm{wt}}}}{\arg\min} \sum_{j=1}^{N_{wt}} V^j(\overline{U}^j)$$

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

3. Compute control inputs

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

Optimal disturbance compensation in 2D



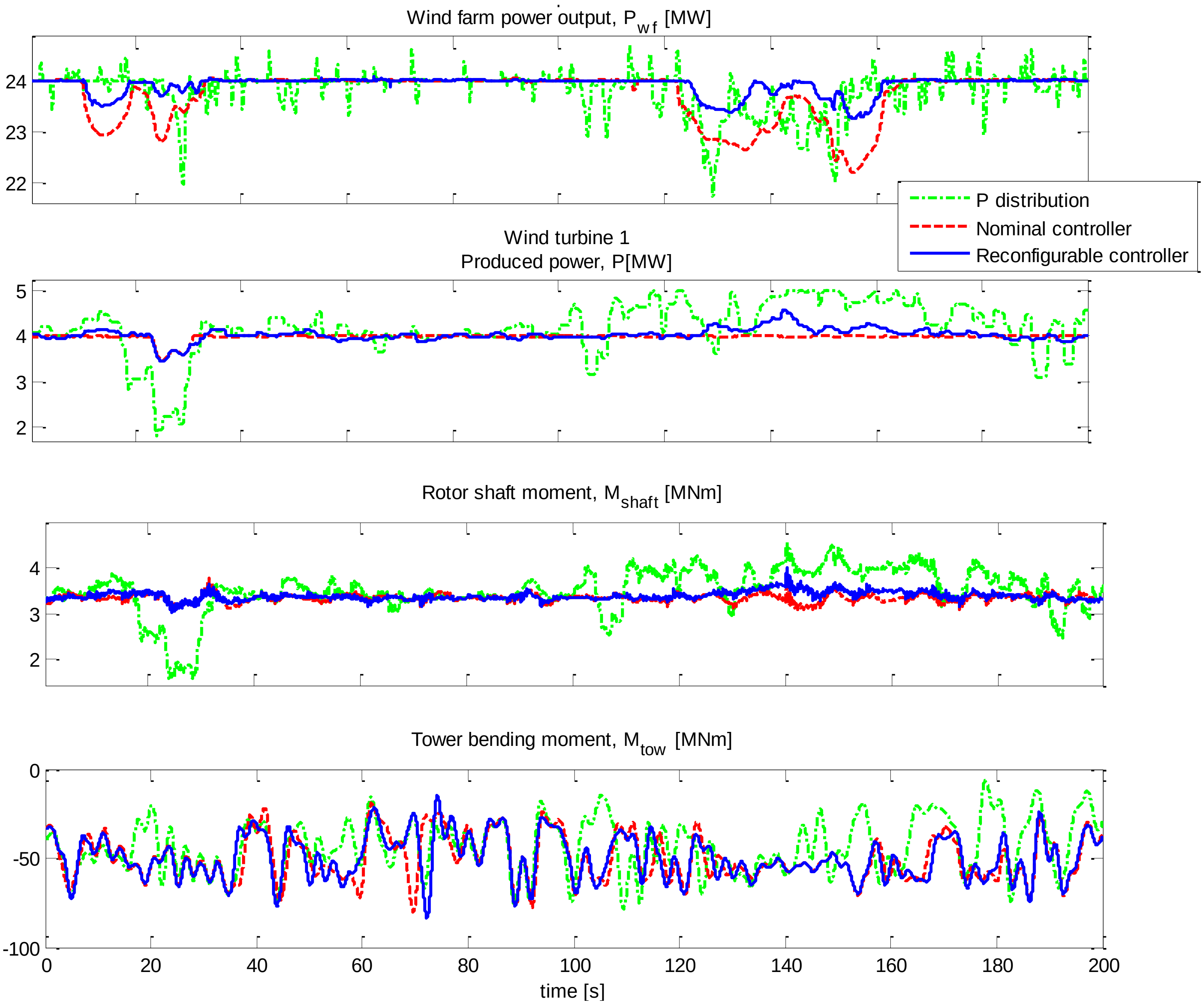
Simulation experiments

- 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

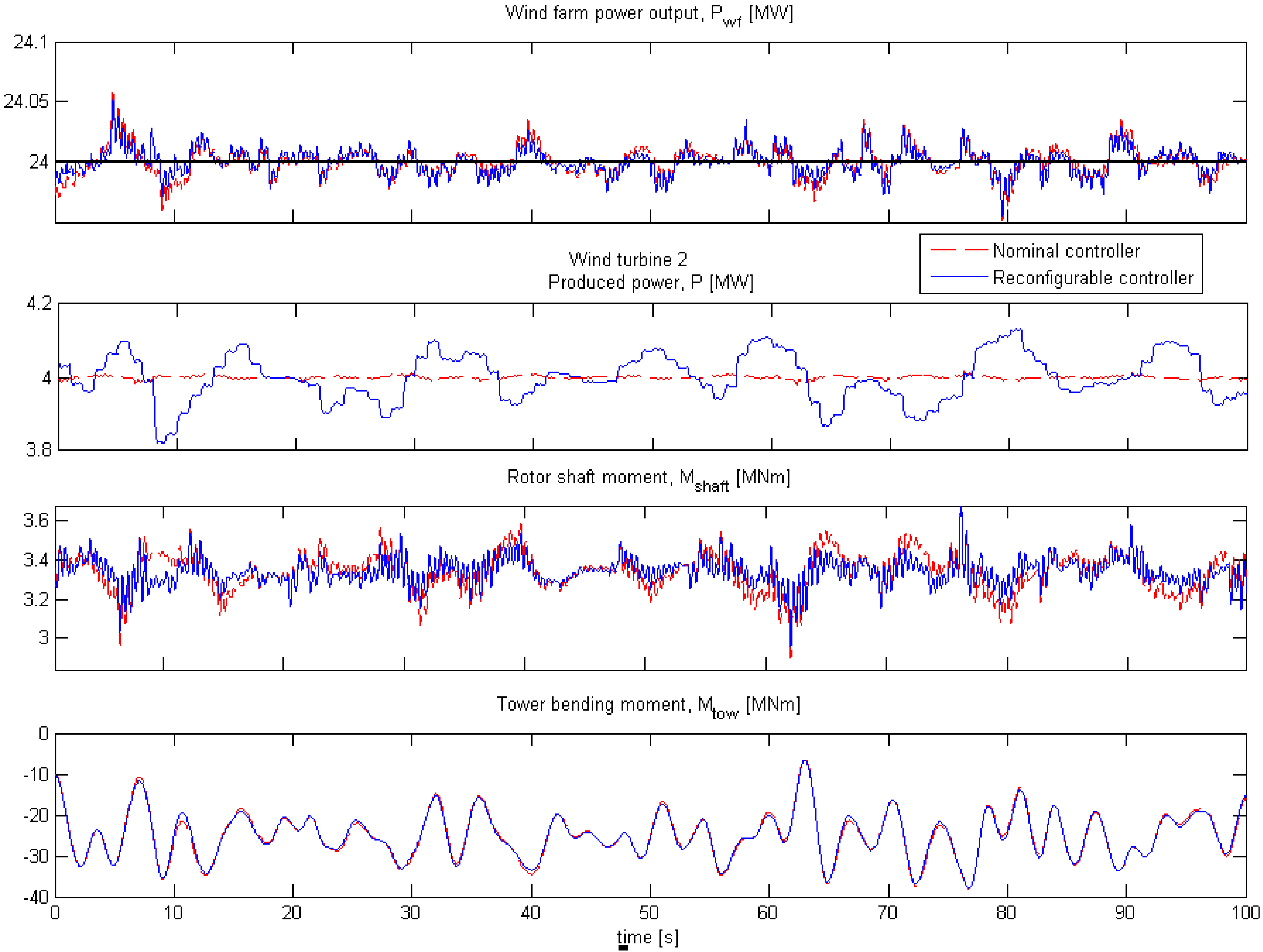


Experiment 1: Power recovery

	Wind farm power STD [kW]		Average WT shaft DEL [kNm]		AverageWT 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]	AverageWT 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 redestribution of power references
  - When operating close to production limit controller succesfully restores power while maintaing 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!