Wind farm control

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Wind farm control

- Substation controls – electrical: reactive power / voltage etc.
- Active power control: fast frequency response, curtailment, ramp & delta control
- Controlling wake interactions: active power, turbine fatigue loads
  - Traditional sector management: e.g. turning off the most wake-affected turbines
  - **Advanced sector management (quasi-static open-loop control):** turbine set-point manipulation, based on wind conditions such as might be measured, for example, at a nearby met mast, or inferred from SCADA data.
  - …
  - Dynamic feedback control: using multiple measurements across the wind farm, e.g. at the turbines, to understand the current state and optimise the response at each moment (e.g. using state estimation, model predictive control, etc.)
  - …
  - Machine learning approaches

Controlling wind farm wake interactions

- Reduced power!
- increased loading!

Switch this turbine off?

Or reduce the power set-point of this one?

Or maybe yaw the turbine slightly to steer its wake away from the next turbine?

1. What is the optimum* distribution of power and yaw set-points for all the turbines, in this wind condition?
2. How can we maintain optimum* performance in dynamically changing circumstances?

* Optimum has to be defined – depends on energy and loading

Potential benefits

- Increased energy capture in some wind speeds (increased revenue)
- Reduced fatigue loads
  - Reduced O&M cost
  - Increased life of turbines and wind farm
  - Design stage: potentially use cheaper turbines / support structures (designed for lower loads)
  - Design stage: possibility of closer turbine spacing
- Help with grid compliance / provision of ancillary services (active power control)

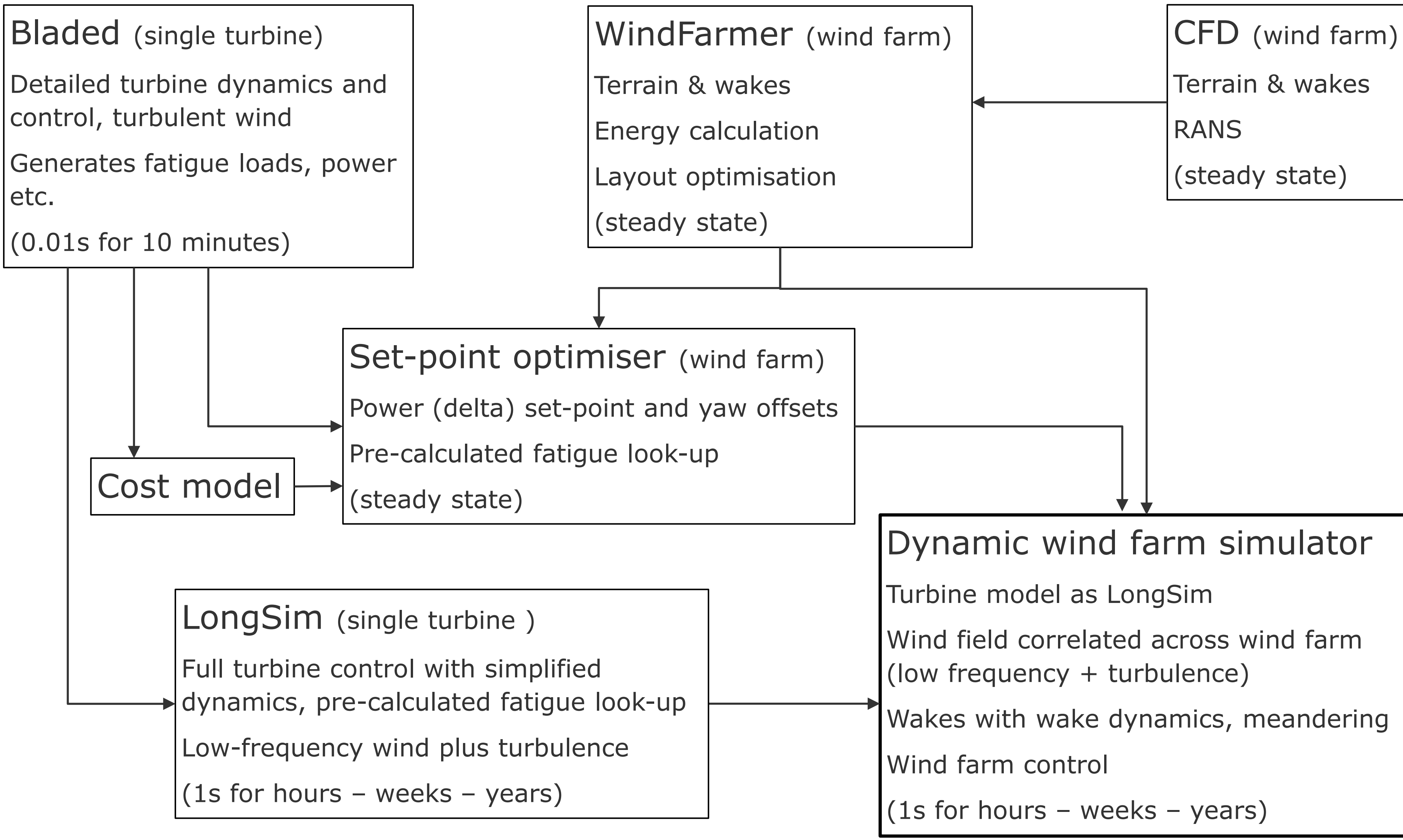
Problems

- Wind farm is a highly complex physical system (atmospheric flow, wakes, turbulence, turbine structural dynamics & control, electrical system)
- CFD modelling of flow is expensive! Need simple (semi-empirical) engineering models
- Cost function to optimise against (not smooth, difficult to formulate, and depends on unknown future conditions, esp. economic)
- High-dimensional optimisation
- Validation is very difficult
  - of models
  - of successful achievement of control objectives

Range of approaches to wind farm control

- Start-stop control
  - Sub-optimal; Limited potential for optimisation
- Quasi-static open-loop control, or "**Advanced Sector Management**"
  - Wind condition defined e.g. by met mast or SCADA data (heavily filtered $\Rightarrow$ slow response)
  - Optimised set-points pre-calculated for each wind condition
  - OK as long as wind conditions are slowly-varying
  - Re-optimise when something changes (e.g. energy price, turbine maintenance, etc., etc.)
- Dynamic closed-loop control (much more advanced)
  - E.g. MPC, with continuous feedback from measurements all over the wind farm
  - Potentially rapid response
  - In principle, should be capable of better performance … … … but is it practical?
- Machine learning approaches
  - Using domain knowledge (not just 'black box')

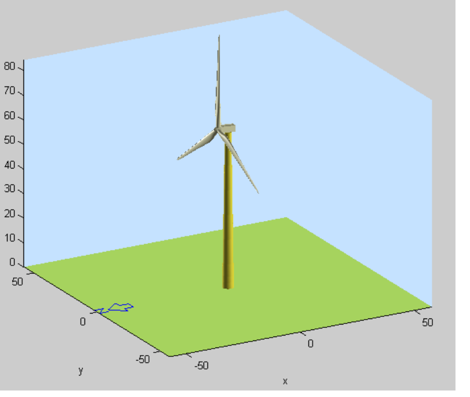
Advanced sector management: Tools for the job



Advanced sector management: example

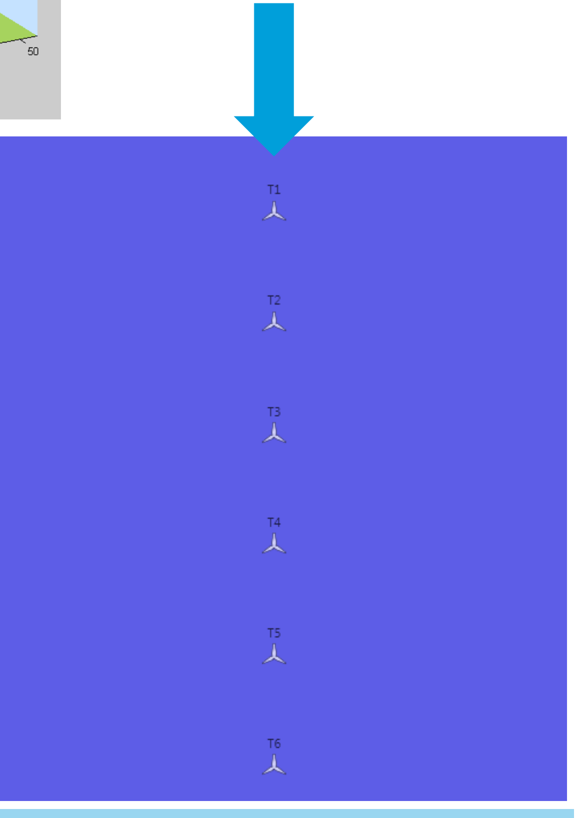
Turbine model

- Rated power 2MW
- Diameter 75m
- Hub height 65m
- Rotor speed Variable, 17.8rpm at rated
- Control Full-span pitch, 3 blades



Wind farm layout

- Straight row of six 2MW turbines
- Regular spacing (different spacings investigated)
- Flat terrain (e.g. offshore)



Test cases

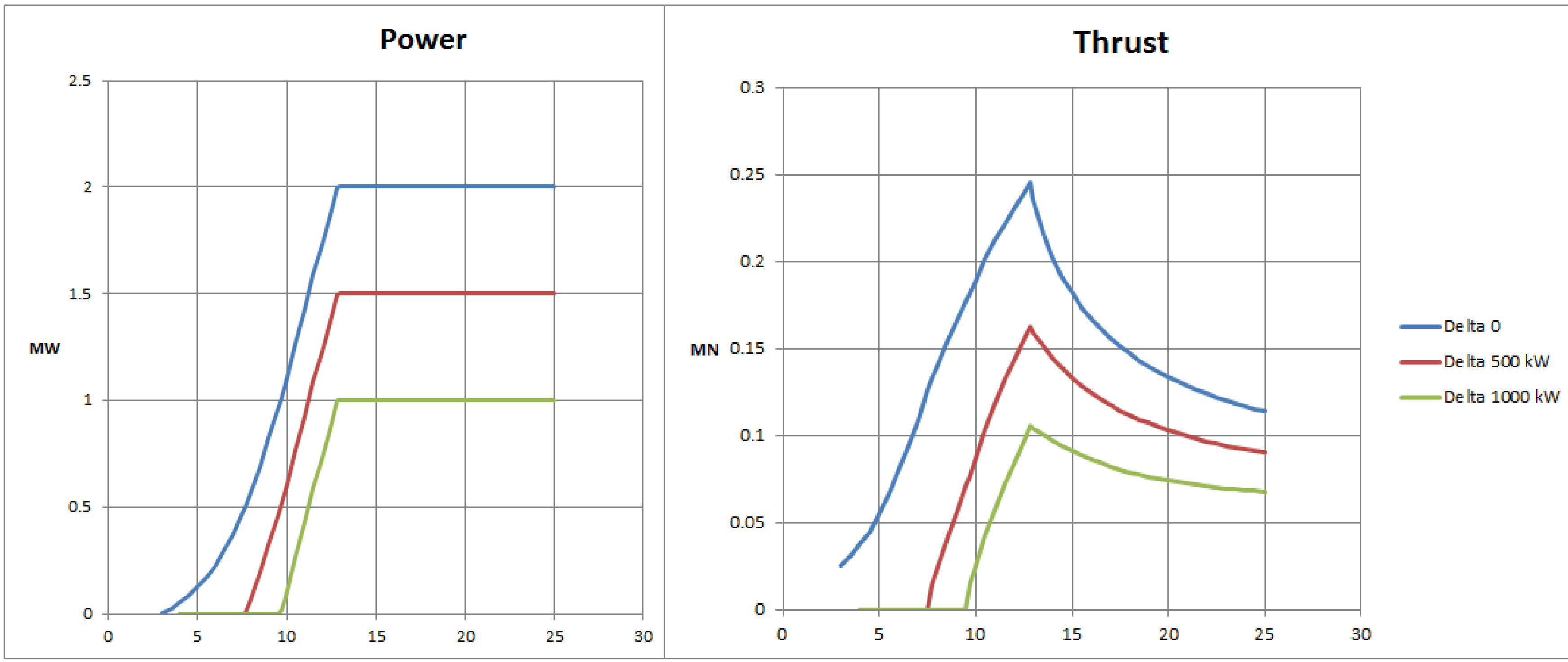
- Ideal (no wakes)
- Base case (no set-point control)
- Optimal case (set-point control)

Benefit function: 2 cases

- Energy only
- Energy & tower base overturning moment (10% change in lifetime DEL equivalent to 1% change in energy)

Delta control settings (as for "spinning reserve")

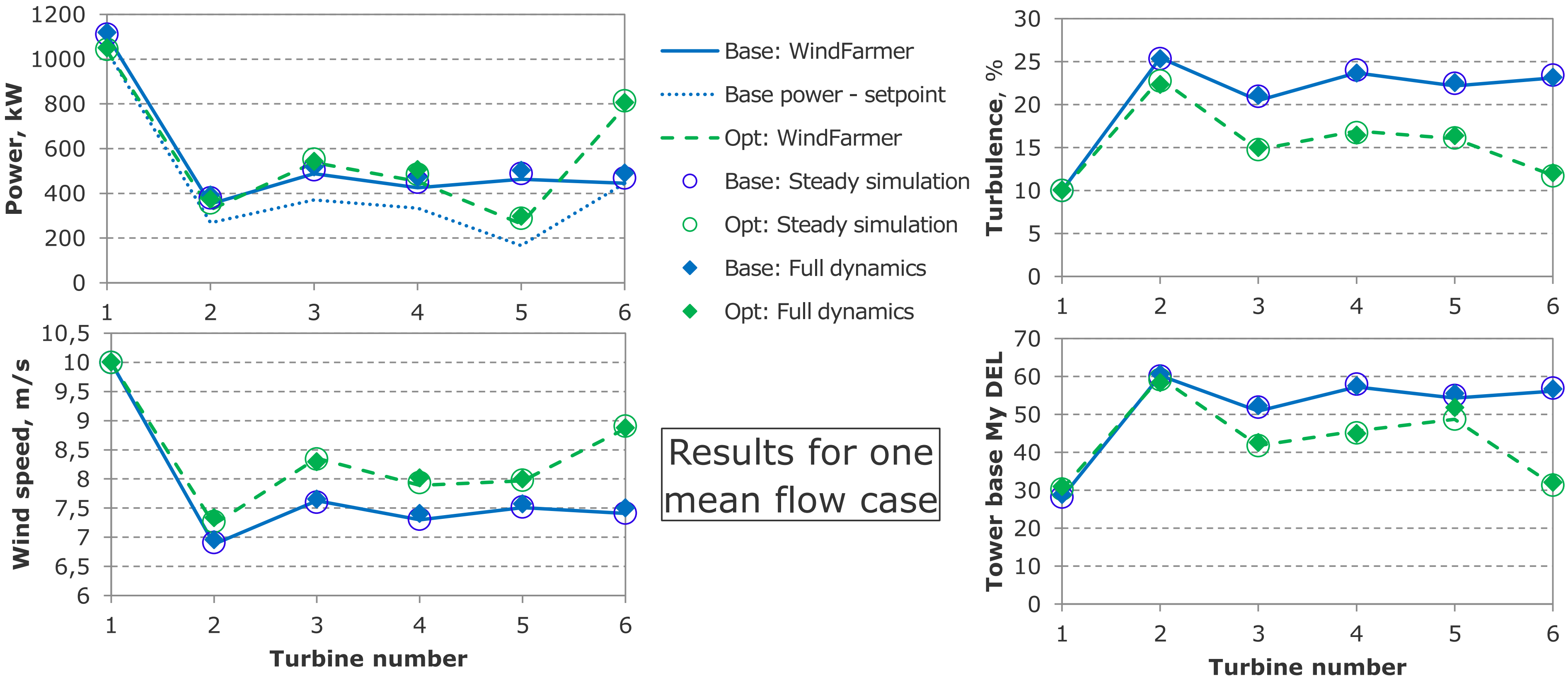
- Power reduced at all wind speeds (increased pitch angle, rotor speed unchanged*)
- This reduces the thrust coefficient, weakening the wake to give higher wind speed and lower turbulence at downstream turbines



* Other power reduction strategies are possible (may change how thrust is affected)

6 turbines, 3D spacing, optimised for power and loads

- Advanced Sector Management: Quasi-static control scheme with set-points from steady-state optimisation code (WindFarmer-based) for each flow case
- Tested in a dynamic time-domain simulation with wake meandering and all the other dynamic effects – does it still work?



Results for 10 m/s, 10% turbulence intensity

- WindFarmer, Steady simulation and Dynamic simulation all give similar results
- Changes in power are very sensitive to small differences
- Changes in loads are more consistent

Mean power:	Base case, kW	Optimal case, kW	Increase, %
WindFarmer	3280.8	3407.9	3.87%
Steady simulation	3401.1	3540.5	4.10%
Dynamic simulation	3496.0	3579.8	2.40%

Total summed over all turbines

Tower base DEL, SN4:	Base case, kNm	Optimal case, kNm	Increase, %	Benefit*
WindFarmer	307.1	257.7	-16.1%	**5.48%**
Steady simulation	310.1	256.5	-17.3%	**5.83%**
Dynamic simulation	311.7	261.0	-16.3%	**4.02%**

*Benefit based on specified cost function: $\Delta B = \Delta P - 0.1 * \Delta L$

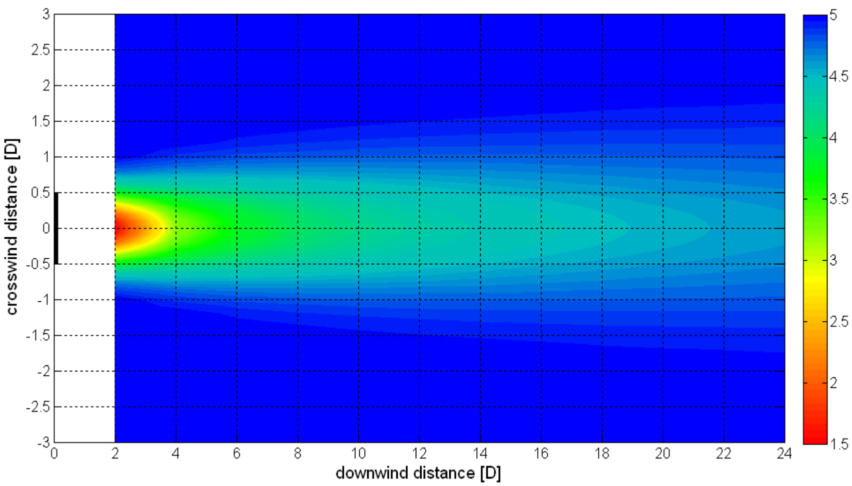
But will this work in realistic dynamic situation?

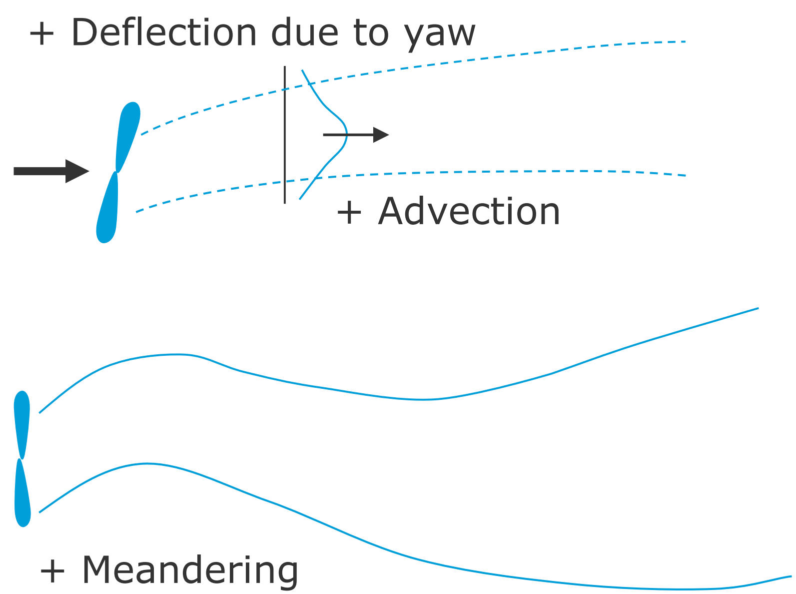
Dynamic wind farm simulator – principles

- Need to capture principal effects dynamically: turbulent atmospheric flow, turbine wakes, turbine control
- Need to run fast: CFD (LES) is too expensive and slow. We want to run repeat simulations of a complete wind farm for hours, days or longer, with timestep ~1s, and mean wind conditions changing over time.

Dynamic wind farm simulator – wake model

WindFarmer's eddy-viscosity
wake model (static)



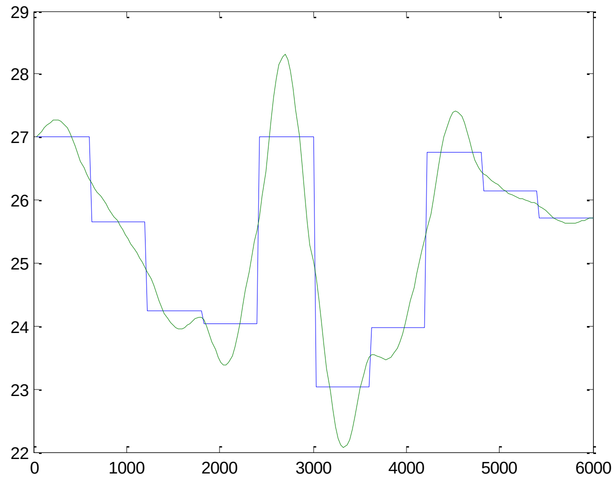


- Wake dynamics (advection & meandering) are driven by low-frequency turbulence

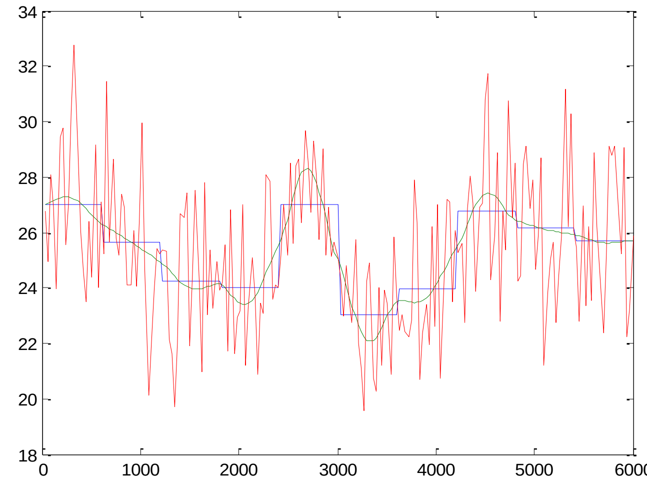
Dynamic wind farm simulator – wind field (distributed across the wind farm)

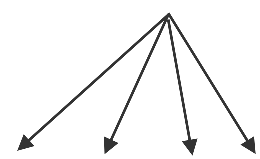
10-minute site data

Fit smooth time history



Add synthetic turbulence





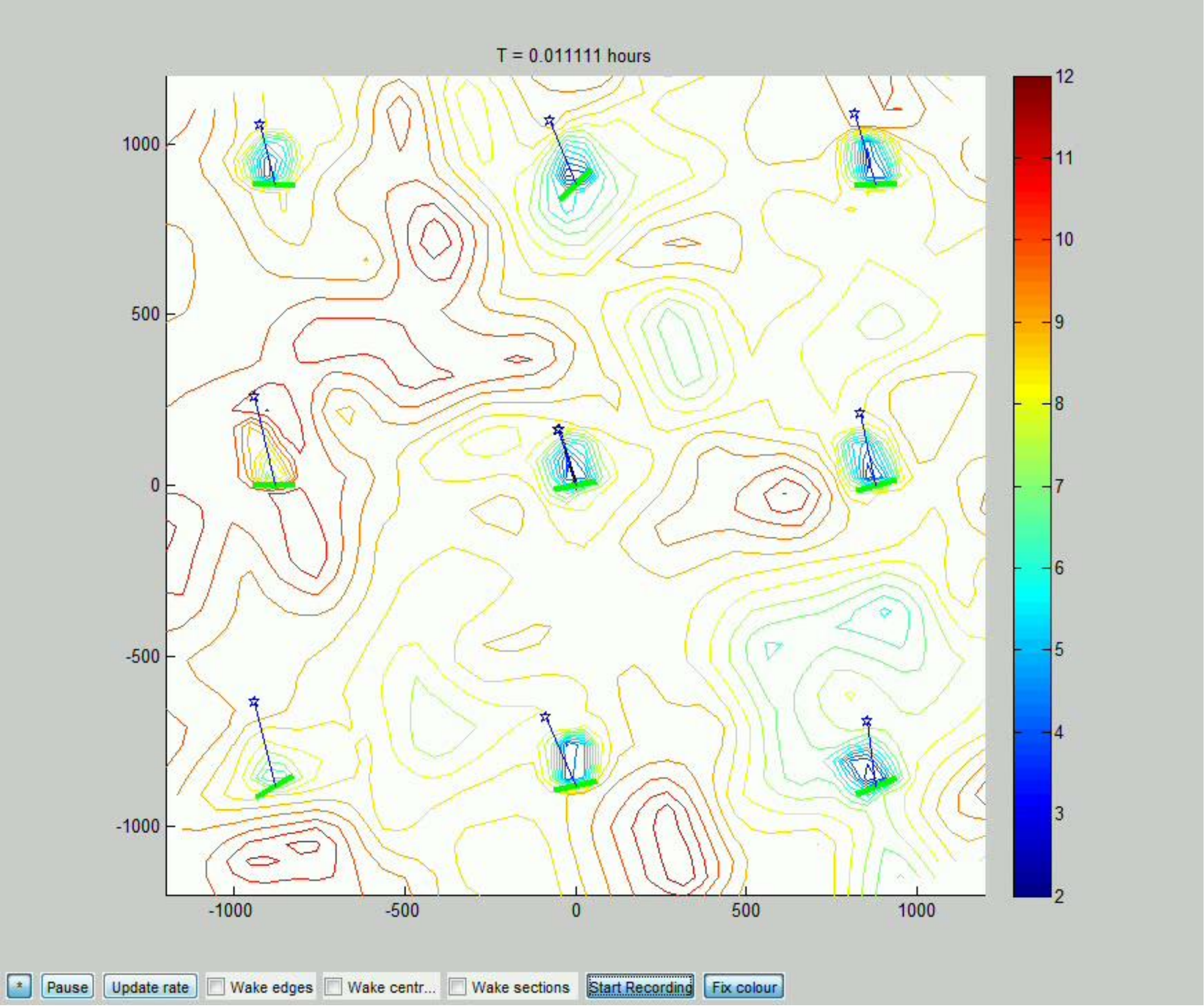
Is it realistic?

Doesn’t obey Navier-Stokes …

… but matches measured statistical properties: spectra & coherence functions

Create correlated turbulence across the wind farm by using correlated phases

Example dynamic simulation: 9 turbines



- Contour plot of wind speed
- Turbines show yaw position and local wind vector

Look out for:

- Turbulence advecting and evolving
- Wakes developing and meandering
- Wind direction changing (SSE to SSW)
- Turbine yaw control follows

One-hour simulation took 4 minutes on a lap-top (using one core)

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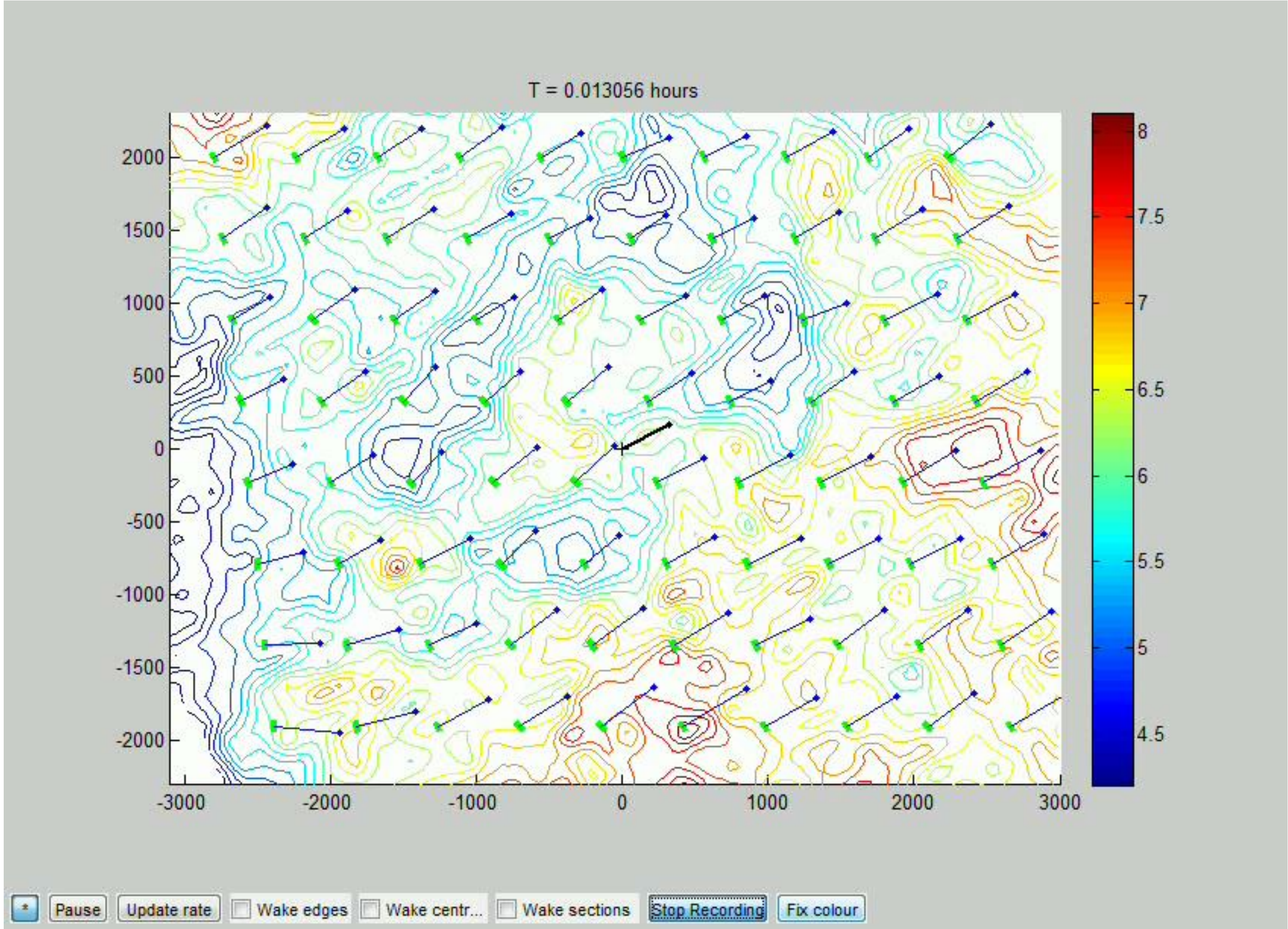
Example dynamic simulation: Horns Rev 1 (80 turbines)



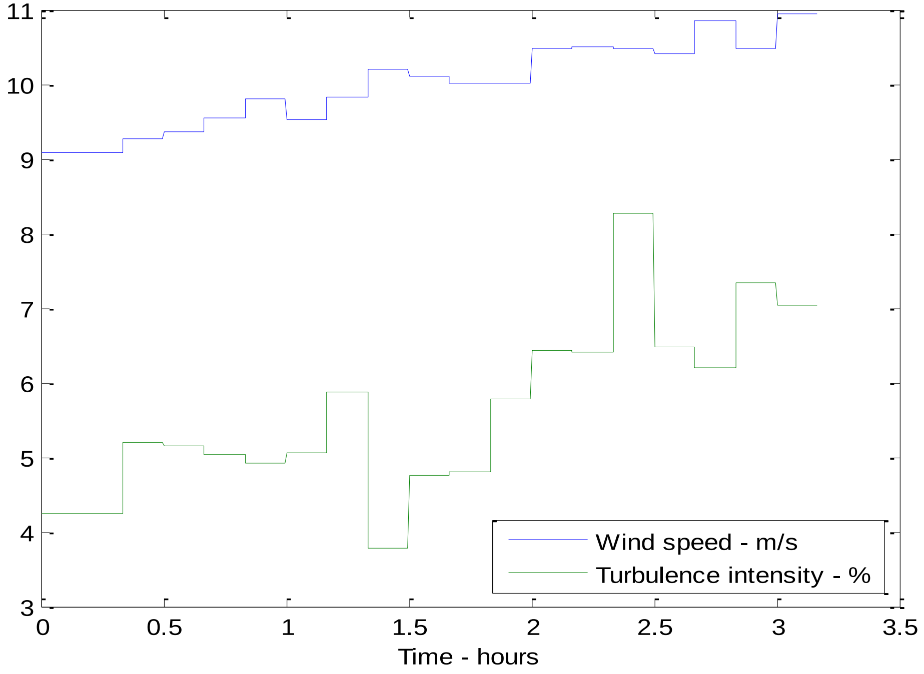
- Low wind speed
- Rapid direction change - ~90º in a few minutes
- Direction change propagates through the farm at mean wind speed
- Faster than real time running on a single core

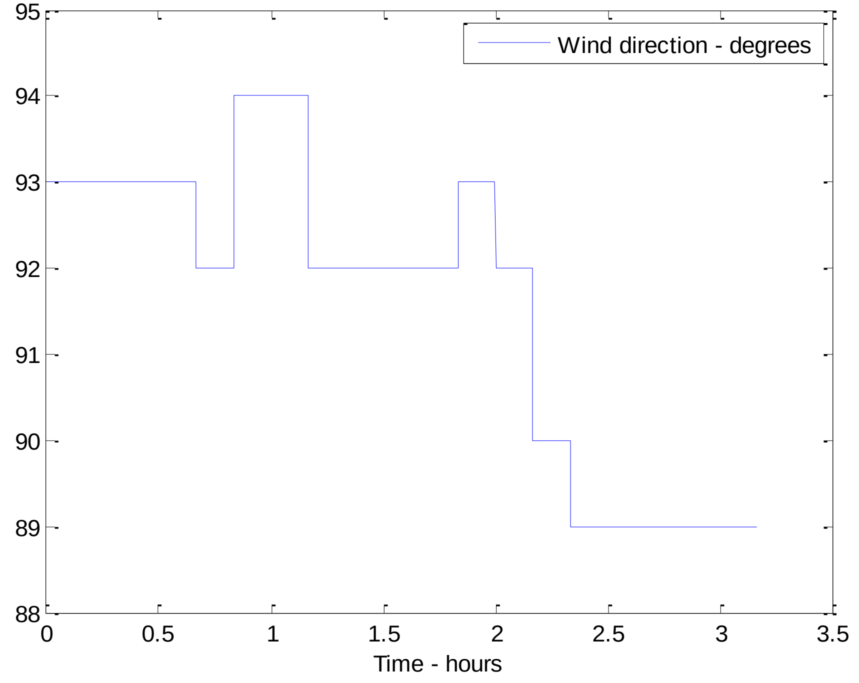
Combining delta control and wake steering

- In general, a combination of delta control and wake steering will be optimal
- Delta and yaw set-points must be optimised together
- Steady state optimiser has now been extended to do this, for a large matrix of wind conditions (wind speed, direction, turbulence intensity)
- Turn into an implementable algorithm: interpolation of set-points for each turbine as wind conditions change
- Dynamic wind farm simulator used to test and evaluate the wind farm controller with changing wind conditions over a period of time.

Dynamic implementation: example 3-hour simulation

FINO-1: 10-minute data

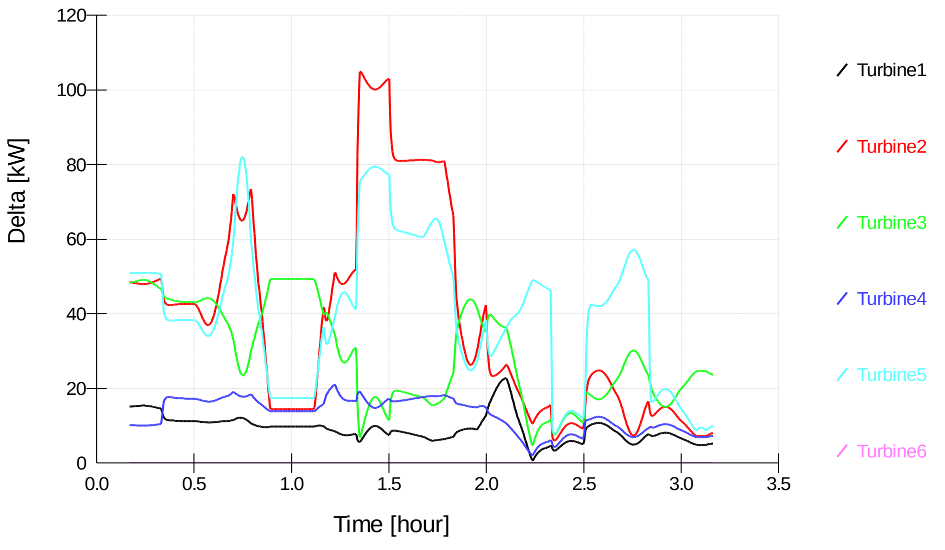


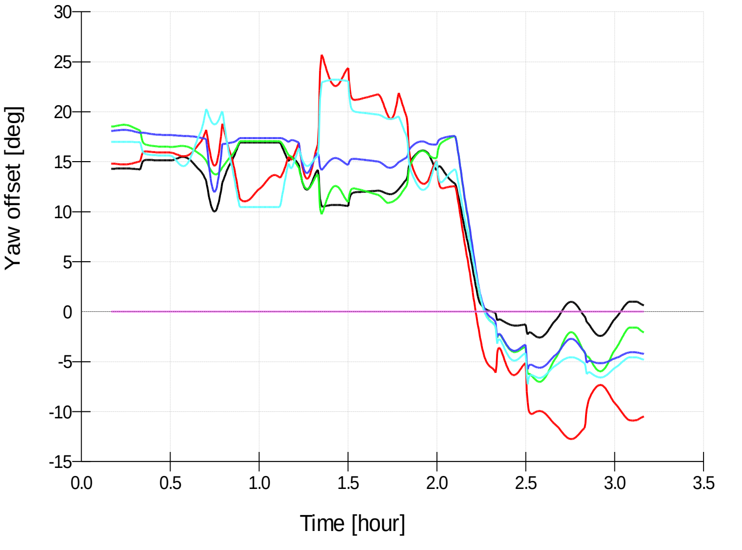


Dynamic implementation: Example results: set-point changes

Power reduction and yaw set-points

- Optimal set-points calculated for each turbine, for a large matrix of wind conditions: combinations of wind speed, direction and turbulence intensity
- Interpolation of set-points as wind conditions change:





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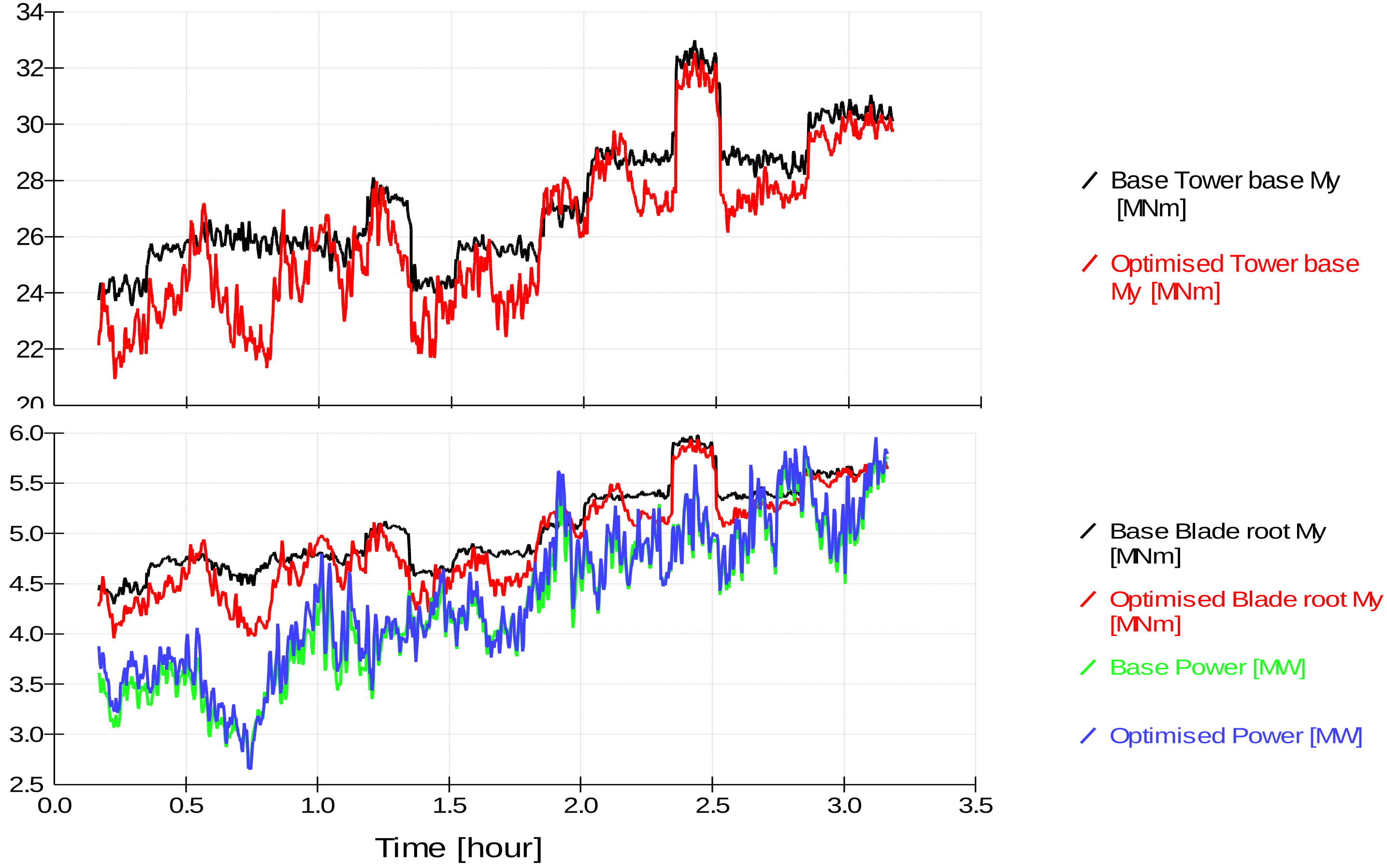
Dynamic implementation: Example results: power and loads



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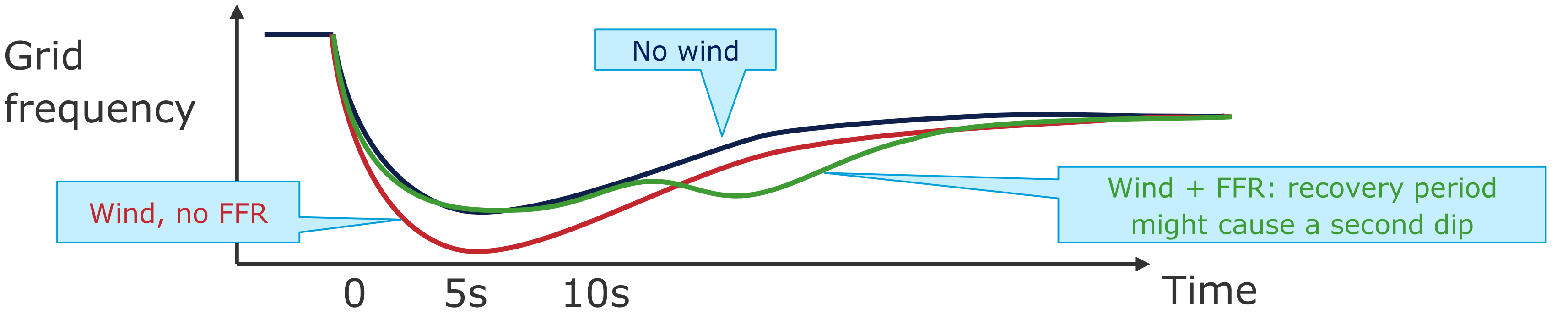
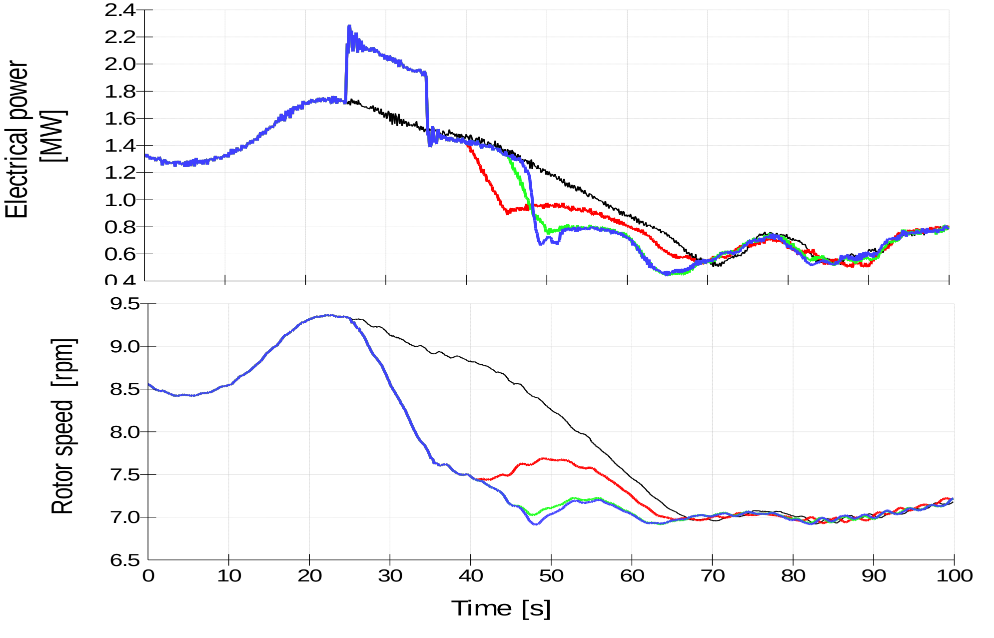
Active power control example - Fast Frequency Response



- Above rated: Reduce blade pitch; extra power limited by (e.g.) power converter. No recovery needed (usually).
- Below rated: use kinetic energy, limited by minimum rotor speed (need to avoid stall). Recovery period can be shaped or delayed.
- Wakes affect how much FFR capability each turbine can offer.



THANK YOU!

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