Wind farm controller design and testing using LongSim

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Ervin Bossanyi
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Controlling wakes in wind farms

1. What is the optimum\* distribution of power and yaw setpoints 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

Traditional sector management

- Reduced power!
- Increased loading!

Switch this turbine off?

“Induction control”

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

“Wake steering”
Different approaches to control design

- **Quasi-static open-loop control, or “Advanced Sector Management”**
  - Optimised set-points pre-calculated for each wind condition (as a function of wind speed, direction, turbulence, ...)
  - Wind condition defined e.g. by met mast or SCADA data (filtered ⇒ slow response)
  - 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 (more advanced, many possible approaches)**
  - 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’)

**All can be tested in LongSim**
Modelling requirements

- Detailed representation of turbine wakes in different atmospheric conditions
- Realistic, time-varying wind conditions
- Accurate modelling of turbine control dynamics
- Needs time-domain simulations
  - Long enough to capture low-frequency wind variations (hours, days, weeks)
  - Short enough timestep (~1s) to capture principal turbine and wind farm control dynamics
  - Fast enough to run many repeat simulations for design iterations
Time-domain simulation - LongSim

- Choice of engineering wake models, embedded in stochastic flow field
- Wake meandering and advection
- Turbine details, including supervisory control
- Wind farm control algorithm
  - Estimation of wind conditions from turbine signals
  - Setpoint lookup
  - Setpoint implementation

Sedini example with wake steering

- Wind field generated from historical site data (met mast)
- Test & tune control algorithm details
- Test controller against different wake models
- Evaluate power increase, yaw actuator duty etc.
Wind farm control – design process

LongSim

Dynamic simulations

Steady-state setpoint optimisation

Dynamic wind farm control algorithm

LUT

Robustness: Adjustment for uncertainty in wind conditions

Site data: Wind

SCADA

Performance:
- Energy production
- Yaw system duty
- Loads
- Etc.

Compare!
Sedini wind farm, Sardinia

- 43 GE 1.5MW turbines
- Several experiments planned in CL-Windcon project
  - Wake steering tests
  - Wake steering and induction control field tests for a row of 9 turbines (this presentation)
    - Preliminary control design and evaluation for wake steering
    - Final design for induction control tests (which are currently in progress)
    - Preliminary field test results

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 727477
Wake model makes a difference! (wake steering)

Power gain (steady state) with optimised setpoints

Wake model:  A1  E1  A1 but setpoints calculated with E1

Power ratio for WS Results1&2&3, wake A1, TI=0.1

Power ratio for WS Results1&2&3, wake E1, TI=0.1

PowerRatio WakeModel_A1.dat with WFC1&2&3_WS_E1.dat, TI=0.1

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Wake model investigation, using SCADA data

RMS error summed over turbines for each wake model

Wind Direction [°]

Normalised power: A4-34/A4-38

Normalised power: A4-31/A4-38

Period 1

Period 2

Period 3
Wake models

- Standard Ainslie: industry standard for energy calculations
- Standard EPFL: popular for wake studies; several tunable parameters, so can always be made to fit reasonably well

✓ Modified Ainslie (selected):
  - Stability correction to eddy viscosity (using Obukhov length derived from historical mast data)
  - Wake superposition: sum-of-deficits instead of large wind farm corrections
  - Removal of some approximations in the standard model
  - General applicability: no tunable parameters
  - Allows possibility for control to track measured stability (e.g. using sonic anemometer), in addition to wind speed, direction and turbulence.
Need for dynamic simulations

- How do wakes behave dynamically?
  - Meandering, advection

- How do wind conditions vary in practice, and how well can we follow this?
  - Robust (smoothed) setpoints to account for uncertainties in wind condition?

- How do wind conditions vary across the farm at any time?
  - Assume ambient conditions are the same everywhere in the farm at any time?
  - Smoothed setpoints again, or allow variation of estimated wind conditions?

- How to measure the wind condition?
  - Met mast if available?
  - Average of conditions from SCADA at unwaked turbines?
  - Filtering, to be representative of propagation through the farm
  - Variations across the farm?

- How often to update the control?
  - Tracking accuracy vs. smoothness of control action

- How to implement the setpoint changes at the turbine
  - Especially for yaw control. Consider overriding the turbine yaw logic.
  - How to handle ‘flipping’ of yaw offset as wind direction changes?
Induction control for Sedini: Dynamic simulation (5 hour period)

Wind conditions (from met mast)

Setpoint example (#37) (raw, smoothed)

Dynamic result is actually better than steady-state expectation!

Mean increase: Dynamic: 1.58%, QS: 0.94%
Wake steering example – large wind farm

- Yaw setpoints optimised in steady state (whole wind farm)
- Dynamic simulations achieved 25-50% of steady-state expectation
- Can be improved:
  - Better handling of yaw logic
  - Consideration of wind direction variations across farm

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<th>Annual Energy Production increase</th>
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<td>Steady-state</td>
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<tr>
<td>Dynamic</td>
<td>~ 0.7 – 3.3 %</td>
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Wake steering example – Lillgrund wind farm

- Yaw setpoints optimised in steady state (whole wind farm)
- Dynamic simulations actually achieving more than steady-state expectation
  - 6.5% dynamic compared to 2.6% quasi-static in this example

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement no. 727680 (TotalControl, website: www.totalcontrolproject.eu).
FIELD TEST RESULTS

DATA FROM 11TH JULY TO 17TH SEPTEMBER

Sedini_InductionCtrl_test_July11-Sept9.mat, Chunks of 900s after first 300s, increase = 6.2051%
Sedini_InductionCtrl_test_July11-Sept9.mat, Chunks of 900s after first 300s, increase = 3.9424%

- Not enough points yet, but initial results are promising.
- Measurements are continuing
COMPANION SIMULATIONS

USING LONGSIM TO TRY TO REPRODUCE MEASURED BEHAVIOUR

- SCADA measured 1-minute wind data used as wind conditions at the position of turbine #38.
- Use this to generate a wind field covering all the turbines.
- LongSim time-domain simulations run using that wind field.
- Simulated performance of the turbines compared to SCADA measurements.

Invaluable for understanding what’s happening on site!
LongSim to optimise wind farm yaw control

- Each turbine makes use of information from its neighbours
- Spatial averaging (reduces the need for time-averaging)
- Weighted average favouring the turbines nearest to the ‘focal point’
  - Exponential decay of weighting with distance
- Position the focal point further upstream, to provide some useful preview

Tested in LongSim:

- Using the layout of Horns Rev 1
- Correlated wind field generated from met mast data (actually from FINO-1)
- Wakes, with meandering (small uncertainty: is wind direction changed by wake effects?)
Simulation results
Trade-off – power production vs yaw system duty

- Yaw duty represented by total yaw travel (circles) or number of yaw events (crosses).
- Purple: Turbine yaw, Red: Central yaw
- Central yaw slightly increases power production while significantly reducing yaw travel

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<td>Central Yaw: 72.80</td>
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<td>Central Yaw: 72.75</td>
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- Yaw travel: -24%
- Energy: +0.206% (+0.219% with reduced yaw drive power consumption)
Summary – use of LongSim

- Steady-state set-point optimisation for wake steering & induction control
- Time-domain simulation for testing any controllers:
  - Active wake control
  - Wind turbine and wind farm yaw control algorithms
- Sub-second time step, but long simulations (hours → many days)
- Realistic varying wind conditions: site-specific
- Field tests of algorithms designed and tested with LongSim are in progress
- Companion simulations of field tests are proving invaluable to understand what’s going on!
Thanks for listening!

ervin.bossanyi@dnvgl.com

www.dnvgl.com
LongSim model – what is it?

- Range of different engineering wake models available
- Steady-state setpoint optimisation → setpoint LUTs for different wind conditions, for each turbine
- Dynamic time-domain simulation:
  - Long simulations (hours, days or more), fast timestep (~1s)
  - Correlated turbulent wind field across the wind farm, with time-varying mean conditions (e.g. from met mast data)
  - Dynamic model of wakes (superimposed on the ambient flow)
    - Meandering, advection, deflection
  - Turbine dynamics: rotor speed, pitch, speed & power control, supervisory control (including yaw control)
  - Dynamic implementation of wind farm control algorithm
    - Estimation of wind conditions
    - Setpoint lookup
    - Implementation of setpoint changes
  - Output of power, loads (indirectly, from database), supervisory control details (e.g. yaw manoeuvres)
Some next steps

- **Full-scale measurements**
  - Field tests need careful design – need to measure small changes
  - Some tests already reported in literature, beginning to show promise
  - Sedini (in progress, CL-Windcon project)
  - Other field tests in planning

- **Power and loads optimisation**
  - Demonstrated previously in simulation
  - Not easy to define waked loads appropriately
  - Not easy to combine energy and loads into an economic cost function
  - Less immediate commercial interest in loads (but it is starting!)

- **Load equalisation**
  - During curtailment
  - Over lifetime

- **More advanced control algorithms**
  - Closed loop, e.g. MPC
  - AI / machine learning
Conclusions

Can wind farms realistically benefit from active control of turbine wakes?

- **Almost certainly, yes**
  - Still many uncertainties in modelling
  - More field testing required
  - Wake steering may be more effective, but more problematic to implement
  - Induction control: the jury is still out (evidence in favour is beginning to return). More straightforward to implement.
  - Dynamic induction control: still at the research stage – could be promising but still many questions

- **Modest energy gains**
  - Very dependent on the situation (especially wind farm layout and wind rose)
  - Could be several percent – very valuable
  - Even small gains (<0.5%) are valuable if available with confidence
  - Difficult to demonstrate convincingly in the field over a wide range of conditions, but progress is happening

- **Significant loading benefits**
  - Hard to quantify waked loads accurately
  - Reduced O&M costs (but hard to quantify economic benefits)
  - Increased plant lifetime (ideally, all turbines reach end of life simultaneously)

- **More research needed!**
  - Many approaches, no consensus yet
  - Modelling improvements & validations
  - Characterisation of waked turbine loads