Simulation of wind power plants

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Ervin Bossanyi
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What?

- **Time domain simulation of a wind farm as a power station**
- **Capability to represent:**
  - All external environmental conditions across the site: wind, wave, current, etc.
  - Flow within the wind farm array accounting for atmospheric and wake effects
  - Performance, loading and control of each individual turbine + support structure
  - Electrical interactions between turbines and with the grid
  - Control of the wind power station as a whole
Why?

- **Improve wind farm design & layout**
  - More detailed understanding of terrain, wake & electrical interaction effects

- **Development and testing of wind farm controls**
  - Minimise wake interactions (induction control, wake steering, sector management)
  - Provide grid ancillary services (curtailment, ramp rate limits, delta control, frequency response)
  - Optimise supervisory control at wind farm level (high wind shutdown / rampdown, low voltage ride-through)

- **Optimisation of O&M strategies**
  - Understanding conditions experienced by individual turbines
  - Planning of scheduled maintenance
How?

✗ Not one tool based on one simulation model, but:
✓ Framework or toolbox within which different models can be linked together into a simulation platform tailored to any specific problem:
  ▪ A database structure containing all the fundamental parameters relevant to the wind power station
  ▪ A set of modelling tools of different levels of sophistication for addressing problems of different complexity
  ▪ A framework containing interfaces to the database and the modelling tools
  ▪ A user interface and workflow management system
Physical components

A wind power station is a complex combination of coupled physical systems that dictate how the entire power station behaves:

- Topographical flow effects (onshore sites)
- Metocean conditions (offshore sites)
- Atmospheric stability and turbulence
- Dynamic wind turbines with individual controllers
- Turbine wake effects (affected by atmospheric turbulence)
- Wind farm electrical systems and interconnections
- Grid connection, and interaction with the external electrical network
Constraints

- **Economic revenues:**
  - From electricity production
  - From providing grid ancillary services

- **Operational costs / loss of revenue**
  - Operation and maintenance costs
  - Environmental conditions imposed on operation (e.g. noise constraints)
  - Curtailment demands imposed by network operators
Examples of typical timescales

- **Timesteps:**
  - <1ms: electrical transients
  - ~10ms: turbine control & loads, electromechanical interactions
  - ~1 sec: turbine supervisory control and wake dynamics
  - 1-10 min: farm level control
  - 10-60 min: energy trading & forecasting
  - ~1 day: O&M planning
  - ∞ (steady-state): Farm layout design

- **Length of simulations:**
  - ~1s: electrical transients
  - ~1 min: grid interaction: LVRT, frequency response
  - 10-60 min: farm control for specific wind conditions, including ancillary services
  - 1hr – 1 year: supervisory control
  - 1 week – 25 years: O&M strategy
Wind field modelling

- **Temporal variation:**
  - Constant conditions, e.g. for simple simulations up to 10 minutes
  - Low frequency variations, e.g. for some supervisory controls, energy trading, etc.
  - Turbulence: 10-60 minute simulations with turbine & wake dynamics
  - Turbulence + low frequencies: supervisory / farm control with turbine & wake dynamics

- **Spatial variation:**
  - None
  - Steady-state: Terrain / topographical effects
  - Dynamic: Correlation of temporal variations across the wind farm
Pre-existing tools, further development and links

**Bladed** (single turbine)
Detailed turbine dynamics and control, turbulent wind
Generates fatigue loads, power etc.
(0.01s for 10 minutes)

**WindFarmer** (wind farm)
Terrain & wakes
Energy calculation
Layout optimisation
(steady state)

**Set-point optimiser** (wind farm)
Power (delta) set-point and yaw offsets
Pre-calculated fatigue look-up
(steady state)

**Cost model**

**LongSim** (single turbine)
Full turbine control with simplified dynamics, pre-calculated fatigue look-up
Low-frequency wind plus turbulence
(1s for hours – weeks – years)

**CFD** (wind farm)
Terrain & wakes
RANS
(steady state)

**Dynamic wind farm simulator**
Turbine model as LongSim
Wind field correlated across wind farm
(low frequency + turbulence)
Wakes with wake dynamics, meandering
Wind farm control
(1s for hours – weeks – years)
Dynamic wind farm simulator: 9-turbine example

- 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)
Dynamic wind farm simulator: Horns Rev 1 (80 turbines)

- Low wind speed
- Rapid direction change - ~90° in a few minutes
- Direction change propagates through the farm at mean wind speed

- Faster than real time running on a single core
Toolbox vision – other interconnections

- More direct integration
  - CFD for higher-fidelity terrain & wake flow calculations
  - Site layout optimisation
  - Turbine aeroelastic model (Bladed)
  - Cost models

- Other components
  - Electrical models such as DigSILENT, PSCAD etc.
  - Grid operational models (e.g. KERMIT)
  - O&M planning models
  - Market models
  - Forecasting
  - Etc.
Example application: control of wind farm wakes

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

• 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?
Control of wind farm wakes: Process

- Bladed: pre-calculate performance and fatigue loads
- Cost model: Define cost function for optimisation
- Steady-state optimiser: calculate set-points
- Dynamic wind farm simulator: simulate performance with realistically changing dynamic conditions
**Example results**

**Row of 6 turbines, 3-hour simulation with changing wind conditions**

FINO-1 data:

![Graph showing wind speed, turbulence intensity, and wind direction over time.](image)

**Optimal set-point matrix calculated for turbulence levels 4%, 7%, 10%**

- **4% turbulence**
- **7% turbulence**

![Graphs showing the optimal set-point matrix for different wind speeds and turbulence levels.](image)
Example results: simulation output

- Set-points change with wind conditions
- Large reduction in fatigue loading
- Slight increase in energy production
Conclusions

- A basic (usable) toolset has been created, by extending several existing codes, and linking them (in ad-hoc fashion, so far...)
- Many components already validated up to a point, but more detailed validation is needed (interaction of sub-models, wider range of conditions, etc.). This will undoubtedly lead to improved or better-calibrated sub-models
- Improved or alternative sub-models can be easily plugged in as they become available
- Integration framework does not yet exist formally, and some components have not yet been linked at all (e.g. grid model)

Next steps

- Validation → improvement of sub-models
- Further component integration and software structure design
Thank you

ervin.bossanyi@dnvgl.com

www.dnvgl.com

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