Studying wind farm frequency regulation using high fidelity wind farm simulations

Carl R. Shapiro, Luis A. Martínez-Tossas, Charles Meneveau, and Dennice F. Gayme

Department of Mechanical Engineering
Johns Hopkins University
Baltimore, Maryland

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Outline

1 Introduction

2 Prior work

3 Simulation framework

4 Preliminary results

5 Addressing transient overshoot

6 Conclusions and future work
Introduction

Why is this an interesting topic?

- Increasing wind generation has profound implications for grid operations

Current practice:

- Ancillary services are used to maintain grid stability
- Traditional generators have most responsibility to take part in ancillary services
- Wind power has not been part of these vital grid services, except for active curtailment

Where we’re headed:

- As wind power production increases, grid operators are considering requiring wind farms to be capable of providing many of these services

Research goals:

- Leverage large eddy simulations of wind farms to allow wind farms to provide secondary frequency regulation (one type of ancillary service)
**Frequency regulation**

- Power grid frequency is maintained by matching active (real) power generation and load.
- Particularly important after a major grid disturbance (e.g. generator or transmission line failure).
- Frequency regulation occurs over many timescales.

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<th>Primary</th>
<th>Secondary</th>
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<td>Restore system to nominal frequency</td>
<td>Manual balancing of system after failure</td>
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<td>Duration</td>
<td>$\sim 15\text{ min}$</td>
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Secondary frequency regulation

- Participating generators are required to track a regulation signal.
- Reference signal may be:
  - Balance control (Absolute power reference signal)
  - Delta control (Percentage of available wind power)

![Diagram showing PJM Regulation Test Signal A and PJM Regulation Test Signal D](image-url)
Prior work (traditional control)

Many studies have looked at using wind turbines for secondary frequency regulation.

- Power is controlled by using the power coefficient curve.
- The operating power production is derated from the maximum value.
- Tip speed ratio and blade pitch are controlled to regulate power production.

Shortcomings:

- Does not consider unsteady aerodynamic effects.
- Cannot be easily applied to an entire wind farm because of wake interactions.
Large eddy simulations

Incompressible filtered Navier Stokes equations:

\[
\partial_t \tilde{u}_i + \partial_j (\tilde{u}_i \tilde{u}_j) = - \partial_i \tilde{p}^* - \partial_j \tau_{ij} + f_i
\]

\[
\partial_i \tilde{u}_i = 0
\]

24 Turbines:

Domain Size:
9 × 3 × 1 km

Grid Size:
576 × 192 × 64

Pseudo-spectral concurrent precursor simulation

Turbines added as forcing term
Actuator line model

- Blade sections represented by point forces in computational domain
- Lift and drag found by sampling local velocity
- Calculated forces applied on LES domain through gaussian filter
Power and thrust coefficients

- Accurate power and thrust coefficient curves are needed to implement frequency regulation controller.
- Curves are usually found using blade element momentum (BEM) theory.
- Simplicity of BEM and coarse resolution of simulations mean curves will not match.

Simulation curves generated:
- Uniform inflow at 8 m/s.
- Grid resolution of \( \Delta x = \Delta y = \Delta z = 16 \) m.
- On \( 2.048 \times 1.024 \times 1.024 \) km domain.
Power and thrust coefficients

- Normalized by optimal power coefficient
- Gives correct trends
Testing traditional control

- Traditional control tested on a 24-turbine wind (4 rows of 6 turbines)
- Blade pitch angle changed from $\beta = 4^\circ$ to $\beta = 0^\circ$
Testing traditional control

Comparing to power output with no change in pitch angle:

Transient overshoot in all rows

Steady-state error in first row

Drop in power after one inter-turbine flow through time
Addressing the transient overshoot

Response of pitch change in uniform inflow:

- Overshoot caused by inertial effects
- Wind does not slow down instantaneously to change in thrust
- Results in large initial change in power production
Addressing the transient overshoot

- A linear model is developed from simulated step changes in pitch
- Curve fits used to identify coefficients for model
- Model used to determine needed pitch angle to track curve

Uniform inflow results:
Addressing the transient overshoot

Turbulent inflow results:

![Graphs showing power vs time for different rows.
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Row 1
- Power (MW)
- Time (min)
- Traditional Control
- Dynamic Control
- No Control
- Reference

Row 2
- Power (MW)
- Time (min)
- Traditional Control
- Dynamic Control
- No Control
- Reference

Row 3
- Power (MW)
- Time (min)
- Traditional Control
- Dynamic Control
- No Control
- Reference

Row 4
- Power (MW)
- Time (min)
- Traditional Control
- Dynamic Control
- No Control
- Reference

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Conclusions and future work

Conclusions:
- Wind farms can provide ancillary services, such as secondary frequency regulation
- Current traditional controls that use power coefficient curves do not consider transient aerodynamic effects or turbine interactions
- Large-eddy simulations combined with actuator line model provide test bed to develop more advanced controls
- Transient overshoot can be overcome by using a simple linear plant model

Future work:
- Adjust expected power based on turbulent inflow
- Control farm power by accounting for turbine wake interactions
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