Control-Oriented Modeling for Wind Farms

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Clipper Liberty, 2012: Modern utility-scale turbine.

- Rosemount, MN.
- Diameter: 96m
- Power: 2.5MW
- Saint Anthony Falls Lab: [http://www.safl.umn.edu/](http://www.safl.umn.edu/)
Trends in Wind Energy

Key Issues:
1. Structural Design
2. Available Wind Resources
3. Improved Efficiency
4. Installation & Maintenance Costs
5. Grid Integration
6. Turbine/Turbine Interactions
Trends in Wind Energy

1. Structural Design
   - Larger turbines
   - New materials for tower / blades
   - Aeroacoustics
   - Passive Films
   - Transportation

Refs: Cotrell, Stehly, Tangler, Moriarty

Image: "Turbine Blade Convoy Passing through Edenfield" by Paul Anderson (From geograph.org.uk.)
Trends in Wind Energy

2. Available Wind Resources
   - Off-shore
   - Vertical axis
   - Airborne (Kites)
   - Inter-annual variability
   - Environmental impacts

Refs: Rotea, Dabiri, Goldstein, Archer

Image: "Alpha Ventus Windmills" by SteKrueBe (From Wikipedia “Offshore Wind Power”)

3. **Improved Efficiency**
   - Advanced controls
   - New sensors (Lidar)
   - Novel actuators (microflaps)

Refs: Schlipf, Johnson, Pao, Balas, Fingersh, Wang, Harris, Hand, Houtzager

Image: Lidar by Dr. Rainer Reuter, University of Oldenburg [http://las.physik.uni-oldenburg.de/](http://las.physik.uni-oldenburg.de/)
Trends in Wind Energy

4. Installation & Maintenance Costs
   • Health Monitoring & Prognostics
   • Fault Detection & Isolation
   • Fault Tolerant Control

Refs: FDI/FTC Competitions, Ozdemir, Lim, Seiler, Rezaei, Johnson, Odgaard

Image: Damaged gear teeth, by Dan Janisch (Mesabi Range Wind Technology Program).
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5. Grid Integration
   • Active Power Control
   • Emulated Inertia
   • Ancillary Services

Refs: Aho, Pao, Johnson, Fleming, Wright, Wang, Buckspan, Jeong

Image: “Hamilton Beach Pylon" by Ibagli (From Wikipedia “Overhead Power Line”)
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6. Turbine/Turbine Interactions
- Maximize power
- Reduce structural loads
- High Fidelity Simulations

Refs: Johnson, Fleming, Gebraad, Seiler, Annoni, Howard, Guala, Yang, Sotiropoulos

Image: Horns Rev 1, by Christian Steiness
Trends in Wind Energy

6. Turbine/Turbine Interactions
   • Maximize power
   • Reduce structural loads
   • High Fidelity Simulations

Refs: Johnson, Fleming, Gebraad, Seiler, Annoni, Howard, Guala, Yang, Sotiropoulos

Saint Anthony Falls Laboratory
Near Wake vs. Far Wake

Mixing/Entrainment

Near Wake
\[ \sim < 3D \]

Far Wake
\[ \sim > 3D \]
Outline

• **Goal**: Construct control-oriented models for wind farms
  • Models need to be low-order but of sufficient fidelity.
  • Use models to design coordinated wind farm controllers

• Individual turbine control
• Coordinated wind farm control
• Wind farm modeling
  • Experimental (black-box) models
  • First-principles, reduced order models
• Conclusions
Individual Turbine Control
Modern Utility-Scale Wind Turbines

Objectives for Individual Turbine Control:
1. Maximize power at low wind speeds.
2. Reduce loads at high wind speeds.

Ref: Johnson, Pao, Balas, Fingersh, IEEE CSM, 2006
Actuator Line Turbine Model

Induction Factor
\[ a := 1 - \frac{v_1}{v} \]

Actuator Line Results: Yang, et. al. The virtual wind simulator (VWiS)
Actuator Disk Turbine Model

Streamwise, \( x \)

\[
P(a,v) = P_{\text{wind}}(v) \ C_p(a)
\]

Turbine
Actuator Disk Turbine Model

Streamwise, $x$

$P(a,v) = P_{\text{wind}}(v) C_p(a)$

Betz Limit: $C_{p_{\text{max}}} = 16/27$ at $a = 1/3$
Park Model (Jensen, 1983)

Streamwise, $x$

$v_2(x) = v (1 - f(x) a)$

$f(x) = 2 \left( \frac{D}{D + 2kx} \right)^2$

$P(a,v)$

$a$

$v$

$v_1$

$X$

Turbine
Coordinated Wind Farm Control
Coordinated Control: Two Turbines

Parameters:
• Rotor Diam=100m
• $v=10\text{m/s}$
• Park and Betz model used

Ref: Johnson & Thomas (2009 ACC)
Coordinated Control: Two Turbines

Parameters:
- Rotor Diam=100m
- \( v = 10 \text{m/s} \)
- \( k = 0.1 \)
- \( x = 4D \)

Ref: Johnson & Thomas (2009 ACC)
Coordinated Control: Two Turbines

Parameters:
- \( D = 100 \text{m} \)
- \( v = 10 \text{m/s} \)
- \( k = 0.1 \)
- \( x = 4D \)

\[ P_{\text{tot}} = P_1 + P_2 \]

Optimal: \( a_1 = 0.25, \ 3.5\% \uparrow \text{Power} \)

Ref: Johnson & Thomas (2009 ACC)
Need for Improved Wake Modeling

• **Issue:** High fidelity simulations show no increased power.
  - ~**10%** compared to the **+3.5%** gain with the Park model

*Simulator for Wind Farm Applications (SOWFA) Churchfield and Lee*
http://wind.nrel.gov/designcodes/simulators/SOWFA
Need for Improved Wake Modeling

- **Summary:** Park model neglects important spatio-temporal dynamics that are relevant for control.

\[ P = P_1 + P_2 \]
Wind Farm Modeling

1. Experimental (black-box) models
2. First-principles, reduced order models
Differences in Modeling Approaches

• Experimental
  • Data driven
  • Site specific
  • Apply to: Existing wind farms

• First-principles
  • General approach
  • Gain insight for farms that are not yet built
  • Apply to: Design of new farms
Wind Farm Modeling

1. **Experimental (black-box) models**

2. **First-principles, reduced order models**
Model Turbines

- Scale → 1:750
- 4.5 m/s
- 10% turbulence intensity

Photo credits: Kevin Howard
SAFL Wind Tunnel

Photo credits: Kevin Howard
Voltage Measurements

• Understand the input/output dynamics

Input voltage $\rightarrow$ generator torque

Output voltage $\rightarrow$ Power

• Square waves with varying frequencies: 0.02Hz to 10Hz
Typical Result

Frequency 0.07 Hz

Turbine 1

Turbine 2
Dynamic Response

Turbine 1 to 2

Magnitude (dB)

Phase (Deg)

TF from Experiments

Experiment
Dynamic Park Model

First Order Dynamics
\[ \dot{\lambda} = A\lambda + B\tau_{g1} \]
\[ a_1 = C\lambda \]

First Order Dynamics
\[ \dot{\lambda} = A\lambda + B\tau_{g2} \]
\[ a_2 = C\lambda \]
Dynamic Park Model

Turbine 1 to 2

Mag (dB)

-100  -80  -60  -40

Freq (Hz)

10^{-2}  10^{-1}  10^{0}  10^{1}

Phase (Deg)

-1000  -800  -600  -400  -200

TF from Experiments
Dynamic Park
Experiment
Wind Farm Modeling

1. Experimental (black-box) models

2. First-principles, reduced order models

Ref: “A low-order model for wind farm control,” by Annoni and Seiler, Submitted to the 2015 ACC.
Flow Snapshot

Figure by: Kevin Howard
Proper Orthogonal Decomposition (POD)

- Technique to compress data in flow $v(x,y,t)$
  - Holmes et. al, “Turbulence, Coherent Structures, Dynamical Systems and Symmetry.” 1996
Proper Orthogonal Decomposition (POD)

- Construct most energetic modes in flow \( \{v_k\} \)

**Snapshot**

- U POD mode 1
- U POD mode 2
- U POD mode 3
- U POD mode 4
Proper Orthogonal Decomposition (POD)

- Construct most energetic modes in flow \( \{v_k\} \)
- Approximate flow by projection onto energetic modes
  \[ v \approx \sum_k c_k v_k \]
Proper Orthogonal Decomposition (POD)

- Construct most energetic modes in flow \( \{v_k\} \)
- Approximate flow by projection onto energetic modes
  
  \[ v \approx \sum_k c_k v_k \]

- Obtain low-order ODE model of PDE by Galerkin projection

![Snapshot 10 Modes](image1)

![Reconstructed U from POD](image2)

![Snapshot 100 Modes](image3)

![Reconstructed U from POD](image4)
Balanced Truncation

- Model reduction technique for state-space systems
  - Controllability Gramian gives input energy to reach a state.
  - Observability Gramian gives output energy from a state.
  - Balancing state transformation to yield equal observability/controllability properties.
  - Truncate less observable/controllable states.

\[ \dot{x} = Ax + Bu \]
\[ y = Cx + Du \]

Refs: Moore, Pernebo & Silverman, Enns
Balanced Truncation

- Model reduction technique for state-space systems
- **Issue**: Gramians obtained via a Lyapunov equation.
  - Computational cost is $O(n^3)$ where $n$ is the state dim.

\[
\dot{x} = Ax + Bu \\
y = Cx + Du
\]

**Refs**: Moore, Pernebo & Silverman, Enns
Balanced POD

• Combination of POD and balanced truncation
  • Scalable numerical implementation

• **Goal:** Obtain model for wind farm feedback control

Rowley et. al. “Model Reduction for fluids, using Balanced Proper Orthogonal Decomposition” 2004
Balanced POD

- Example: Actuator Disk
  - Actuator Disk: 80,000 states
  - Represented with 5 modes
- Fewer BPOD modes needed to obtain low-order model
Reduced Order Models
Conclusions

• **Goal:** Construct control-oriented models for wind farms
  - Models need to be low-order but of sufficient fidelity.
  - Use models to design coordinated wind farm controllers

• **Approaches:**
  - Experimental (black-box) models
  - First-principles, reduced order models via BPOD

• **Next Steps:**
  - Extend BPOD method from actuator disk to higher fidelity models
  - Use models for simple control designs
  - Test controllers in simulation and wind tunnel.
Acknowledgments

• Eolos Consortium and Saint Anthony Falls Laboratory
  • http://www.eolos.umn.edu/
  • http://www.safl.umn.edu/

• Institute for Renewable Energy and the Environment
  • Grant No. RL-0010-12: “Design Tools for Multivariable Control of Large Wind Turbines.”
  • Grant No. RL-0011-13: “Innovating for Sustainable Electricity Systems: Integrating Variable Renewable, Regional Grids, and Distributed Resources.”

• US Department of Energy
  • Grant No. DE-EE0002980: “An Industry/Academe Consortium for Achieving 20% wind by 2030 through Cutting-Edge Research and Workforce Training.”

• US National Science Foundation
  • Grant No. NSF-CMMI-1254129: “CAREER: Probabilistic Tools for High Reliability Monitoring and Control of Wind Farms.”