A Holistic View of Wind Farm Control

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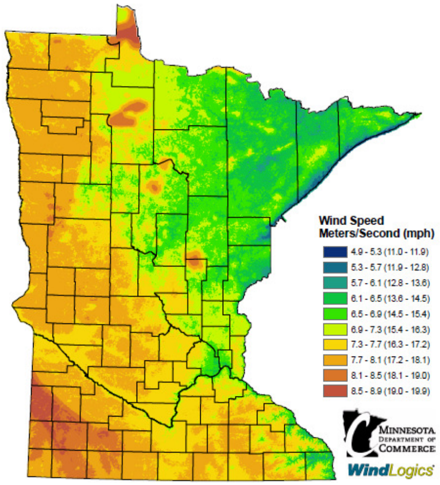
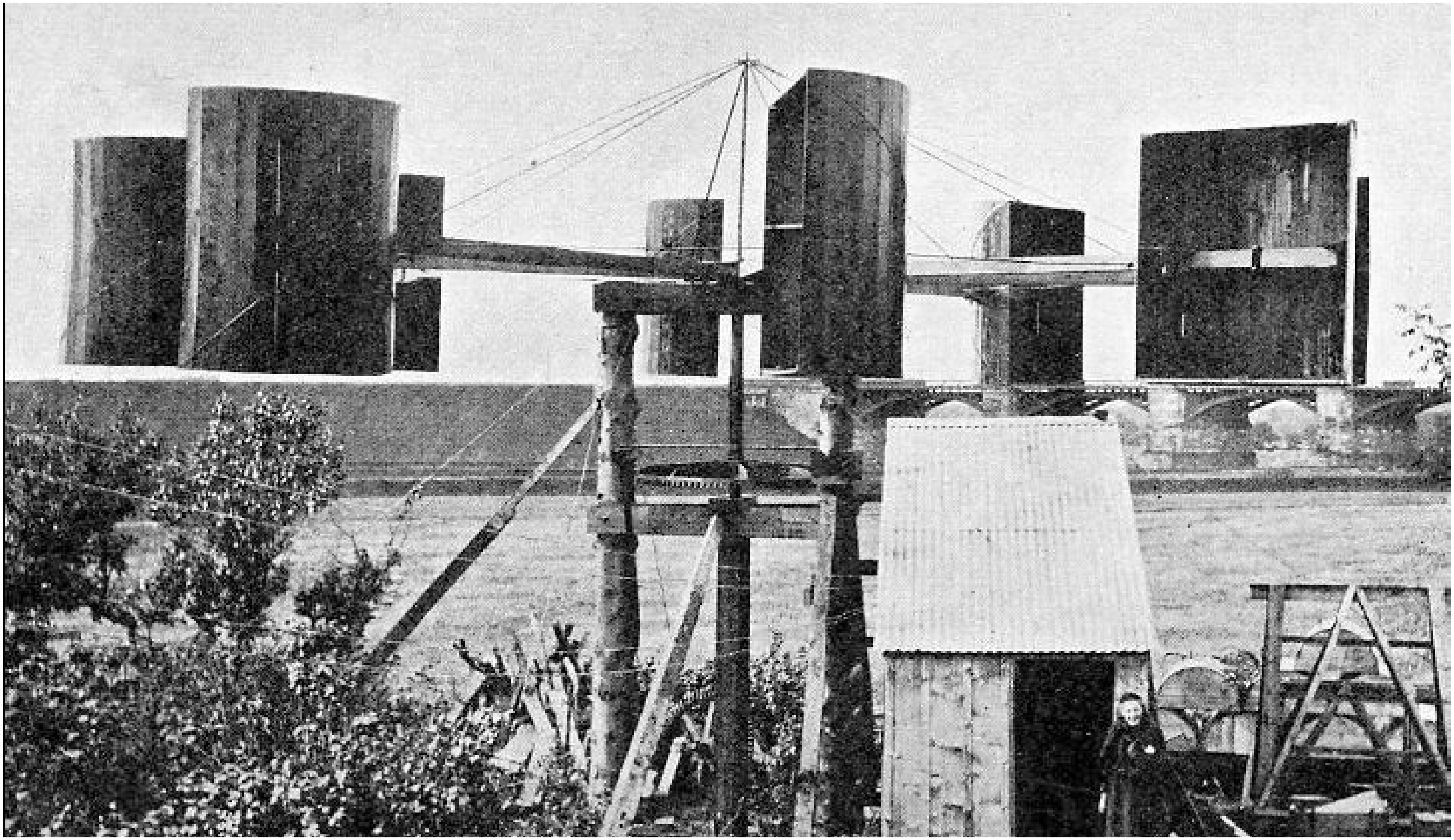
February 11, 2014

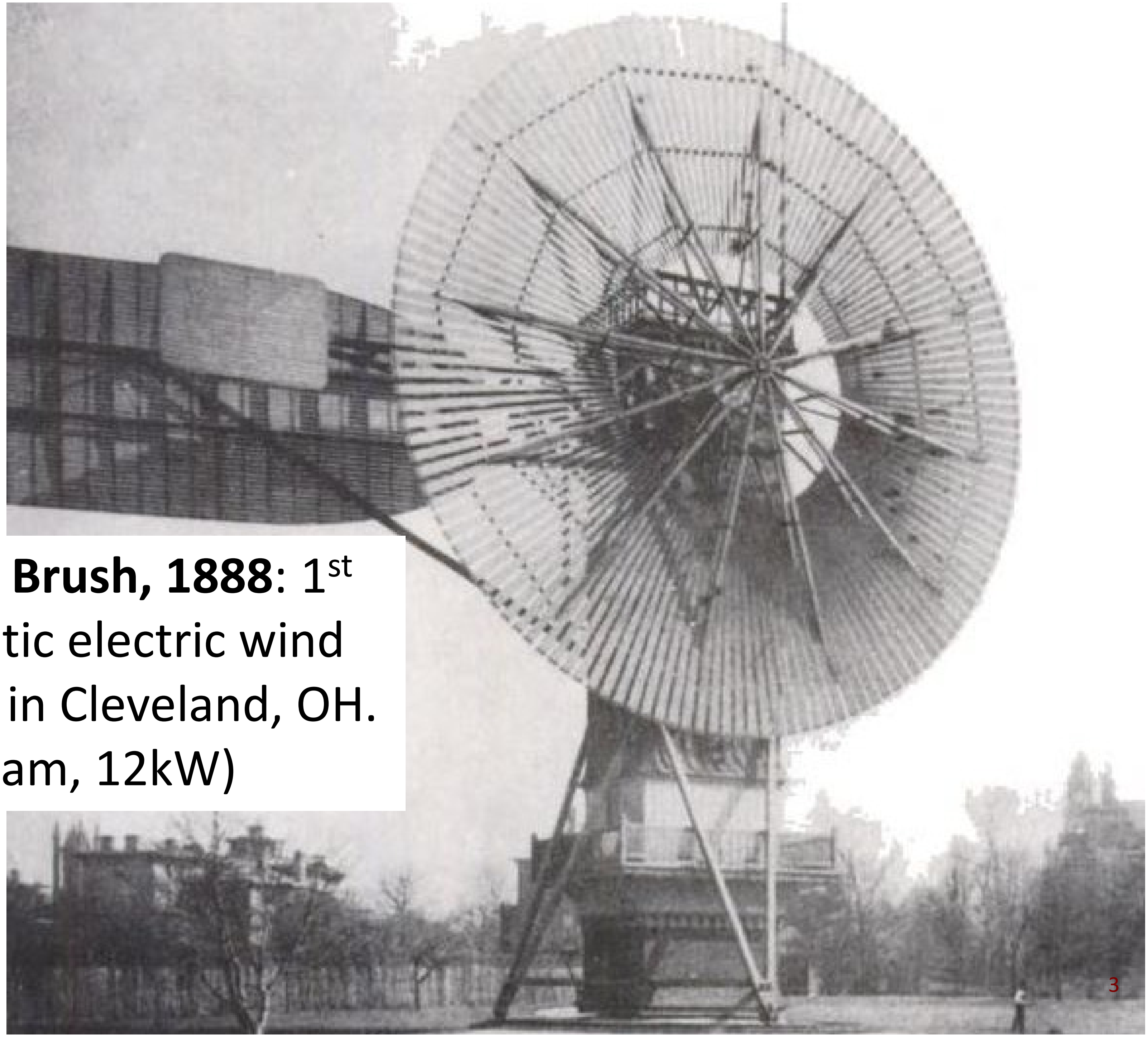
Seminar: Saint Anthony Falls Laboratory





- **James Blyth, 1887**: 1st electric wind turbine in Marykirk, Scotland. (Not Shown)
- **Turbine Shown, ~1890**: Enough power "to light ten 25-volt bulbs." [Ref: Hardy, 2010]

* **Charles Brush, 1888**: 1st automatic electric wind turbine in Cleveland, OH. (17m diam, 12kW)



- **Clipper Liberty, 2012**: Modern utility scale turbine in Rosemount, MN. (96m diam, 2.5MW)
- $C_{p,Liberty}/C_{p,Brush}=6.5$

Outline

- Individual Turbine Control
- Modeling and Control of a Wind Farm
- Conclusions

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Performance Objectives

1. Maximize captured power

$$P = \boxed{\frac{1}{2}\rho A v^3} \boxed{C_p}$$

Power in Wind *Power Coefficient: Function of turbine design, wind conditions, and control*

2. Minimize structural loads
3. Reduce operational downtime

Turbine Components

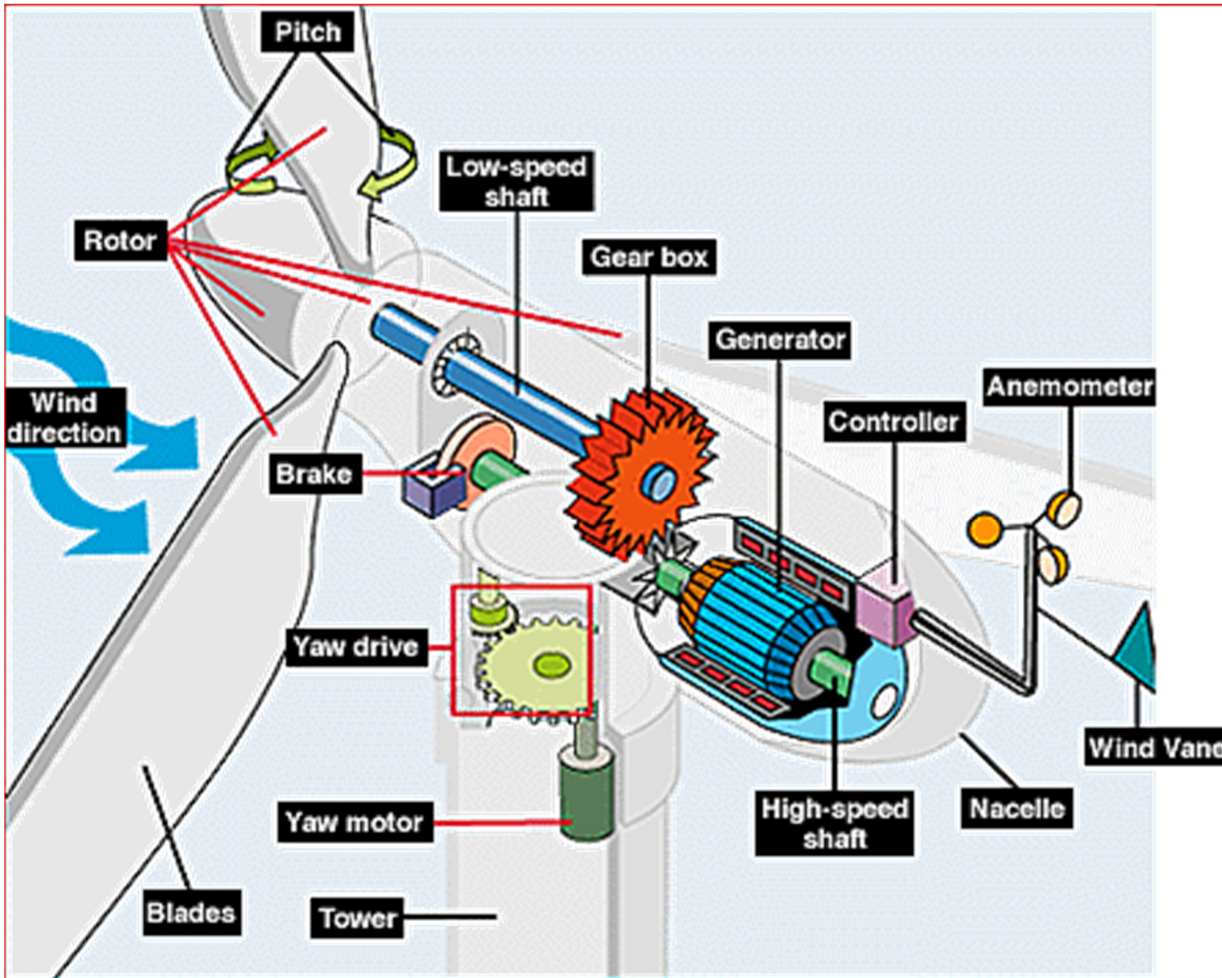


Figure from the US DOE

Simple Rigid Body Model

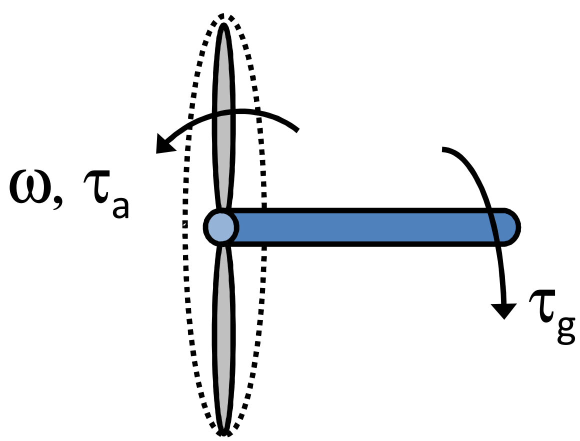
Newton's second law for rotational systems

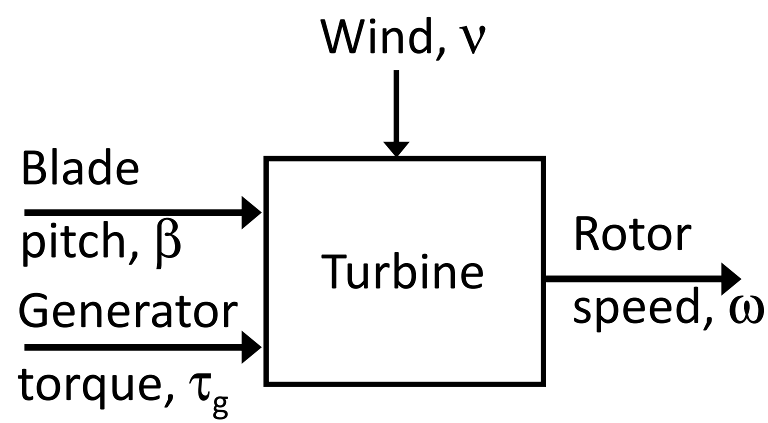
Control inputs are the generator torque (τ_g) and blade pitch (β)

$$J\dot{\omega} = \tau_a(\omega, v, \beta) - \tau_g$$

Rotational inertia of blades, rotor and drivetrain

Aerodynamic torque depends on rotor speed (ω), wind speed (v), and blade pitch angles (β).





Power Coefficient, C_p

- $C_p := \dfrac{P_{captured}}{P_{wind}} = C_p(\beta, \lambda)$
  - β= Collective blade pitch
  - λ= Tip speed ratio $= \omega R / v$
- Aerodynamic torque

$$\tau_a = \frac{P_{captured}}{\omega} = \frac{\rho A v^3 C_p(\beta, \lambda)}{2\omega}$$

Cp for NREL CART 600kW, 21.7m turbine

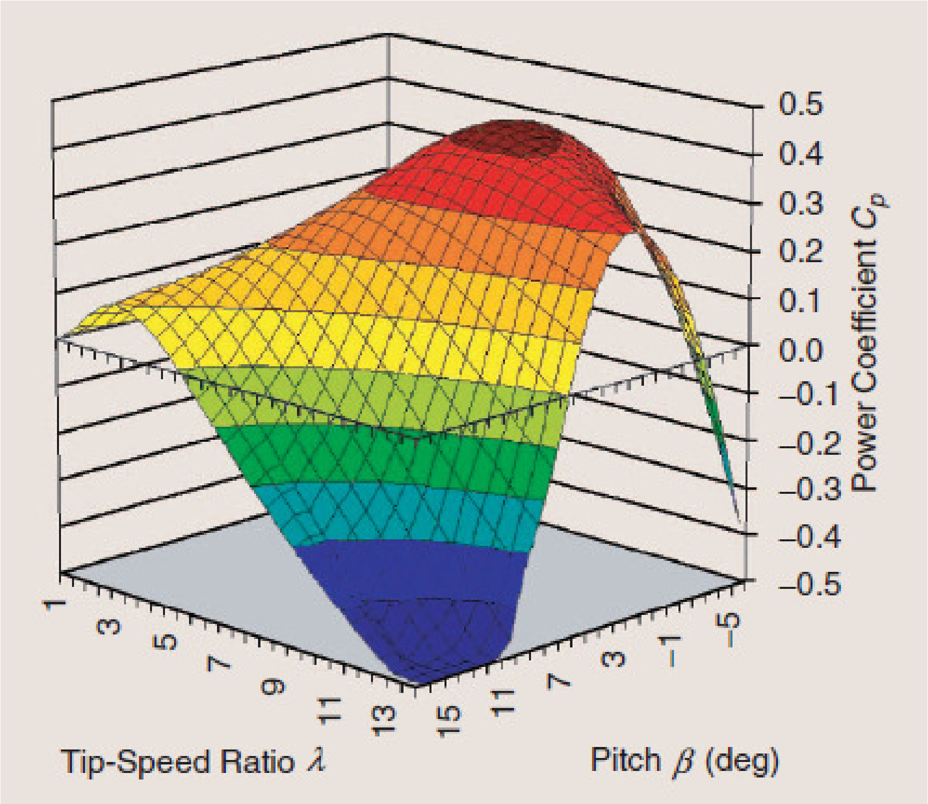


Figure from:
K. Johnson, L. Pao, M. Balas, and L. Fingersh, Control of Variable Speed Wind Turbines, IEEE Control Systems Magazine, June 2006

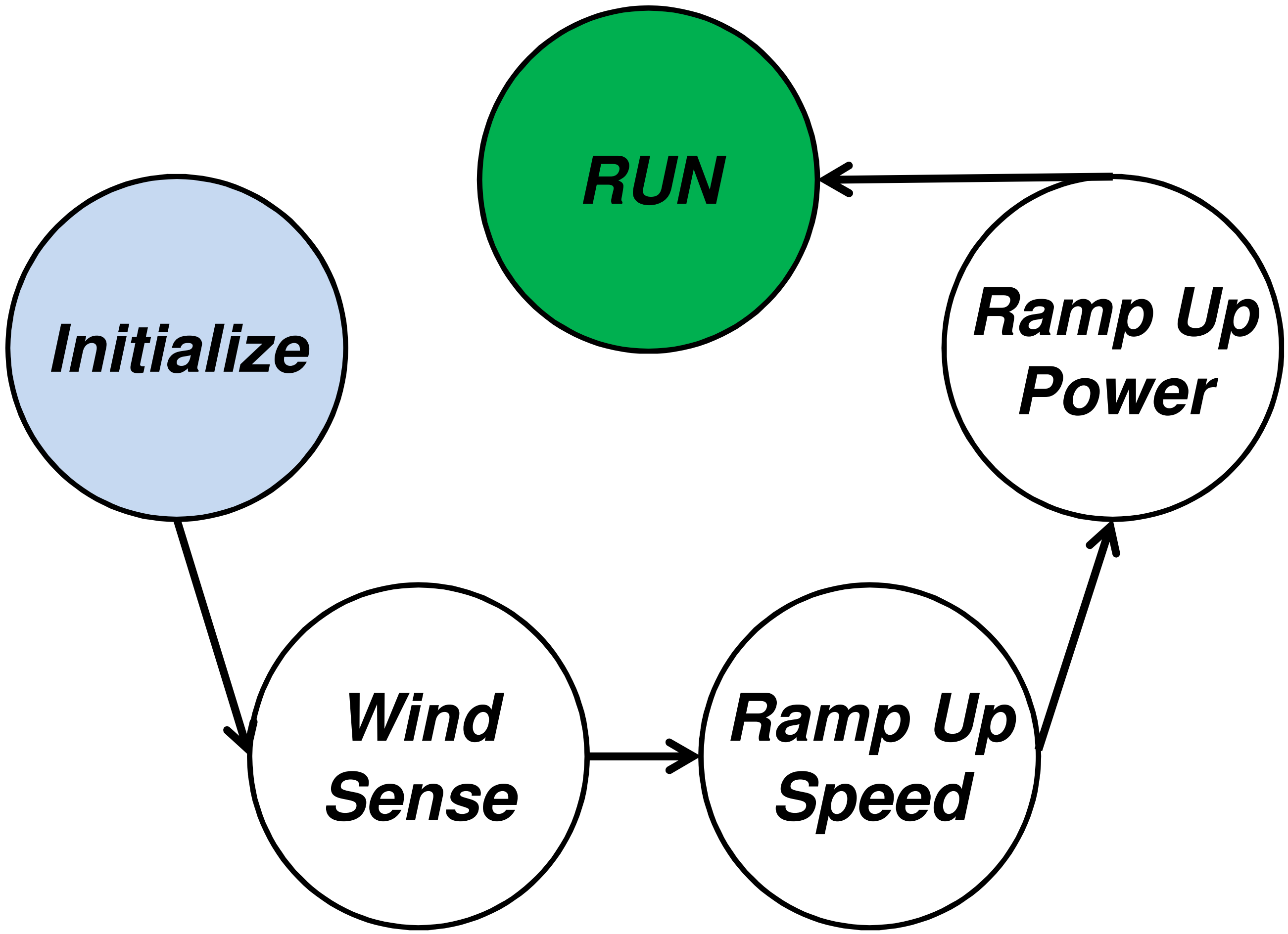
Wind Turbine Control

- Control strategies depend on the wind conditions
  - Supervisory control and mode logic
  - Yaw control
  - Power capture at low wind speeds
  - Rated power + load reduction at high wind speeds

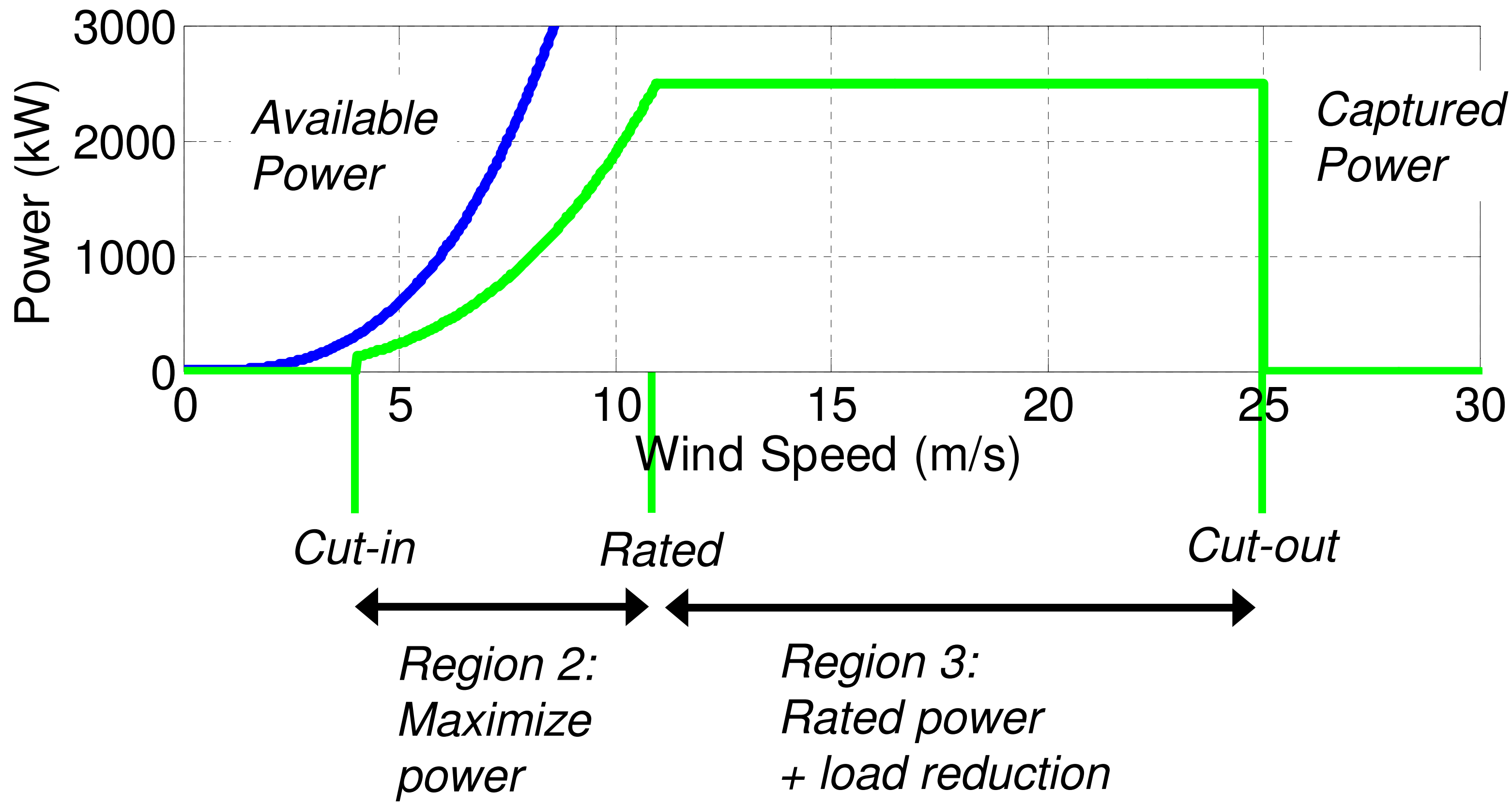
- Good Survey References

  - K. Johnson, L. Pao, M. Balas, and L. Fingersh, Control of Variable Speed Wind Turbines, IEEE Control Systems Magazine, June 2006.
  - T. Burton, D. Sharpe, N. Jenkins, E. Bossanyi, Wind Energy Handbook, Chapter 8: The Controller, 2001.
  - J. Laks, L. Pao, and A. Wright, Control of Wind Turbines: Past, Present and Future, American Control Conference, 2009.

Simplified Turbine Operating States

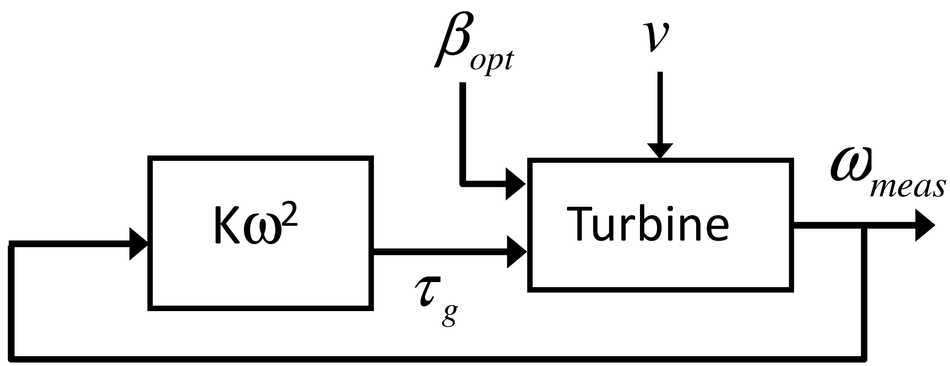


Typical Operating ("Run") Modes



Plot based on Clipper Liberty C100 2.5MW turbine assuming $C_{p,max} = 0.4$
(Theoretical bound for power capture given by Betz Limit: $C_{p,Betz} = 0.59$)

Region 2: Standard Controller



$$\tau_g = K\omega^2 \quad \text{where} \quad K = \tfrac{1}{2}\rho A R^3 \frac{C_{p,\max}}{\lambda_{\max}^3}$$

Convergence to optimal power capture (λ converges to λ_{max}) in steady wind. [Ref: Johnson, et al, Control System Mag., 2006]

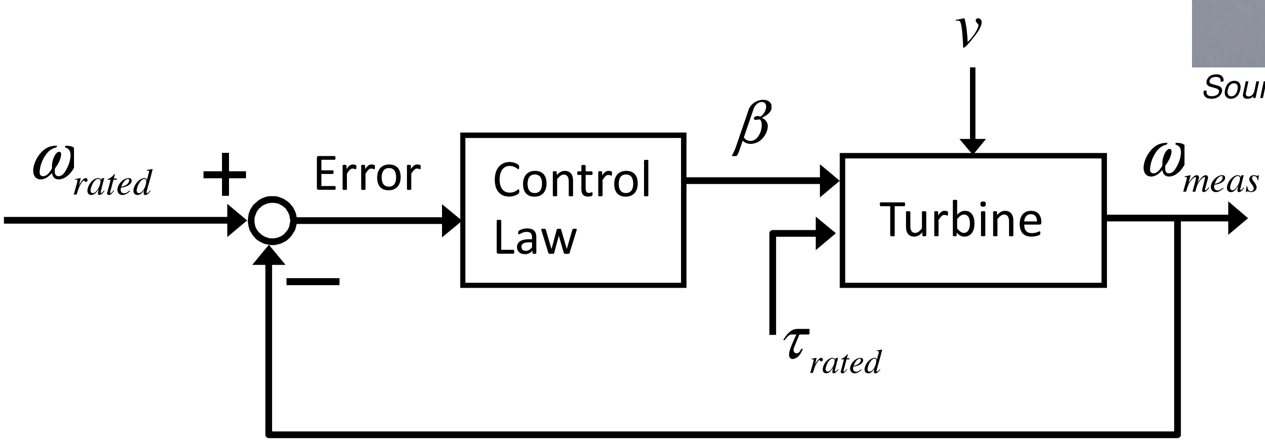
Region 3: Blade Pitch Control

$$\beta(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \dot{e}(t)$$

where $e(t) = \omega_{rated}(t) - \omega(t)$

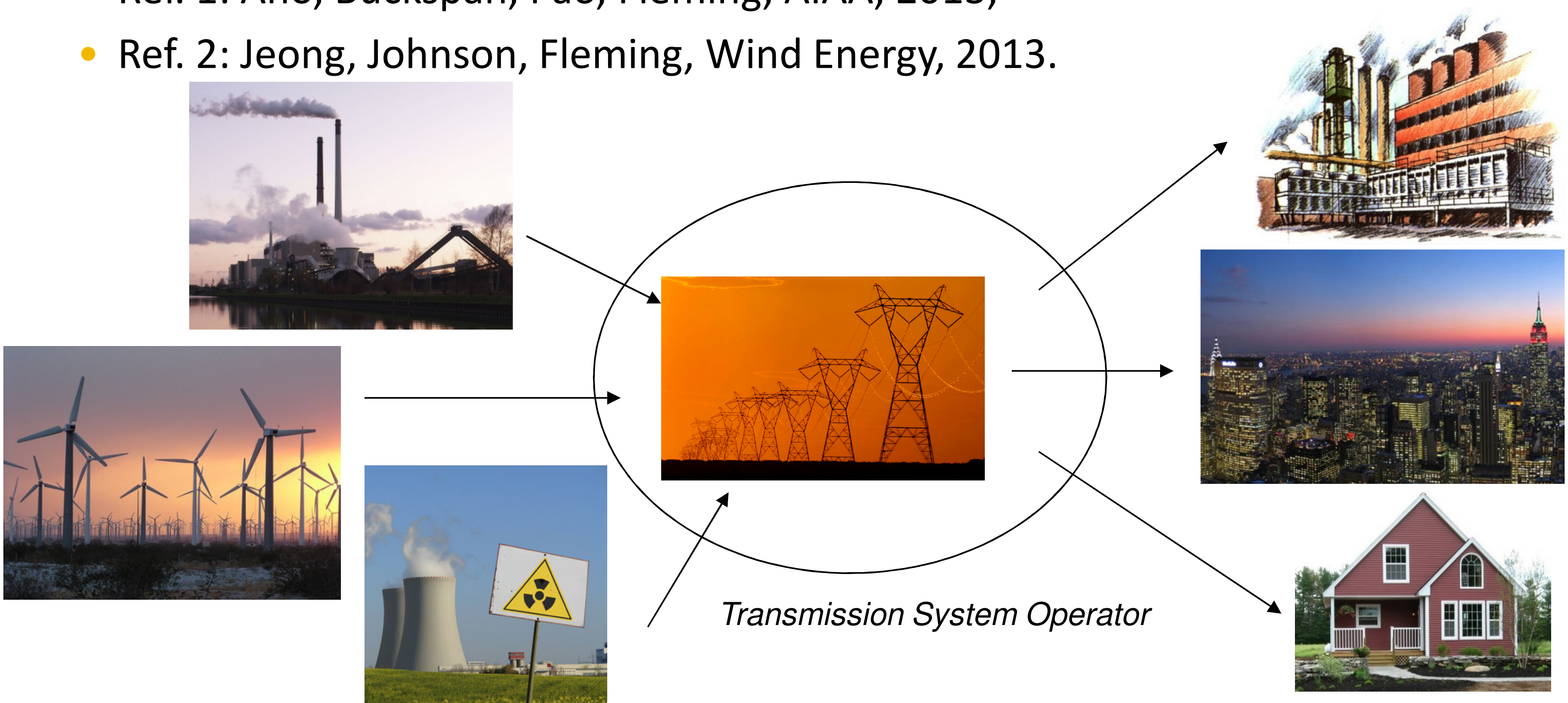
Ref: Laks, et. al., ACC, 2009

Source: http://www.windurance.com/pitch.html

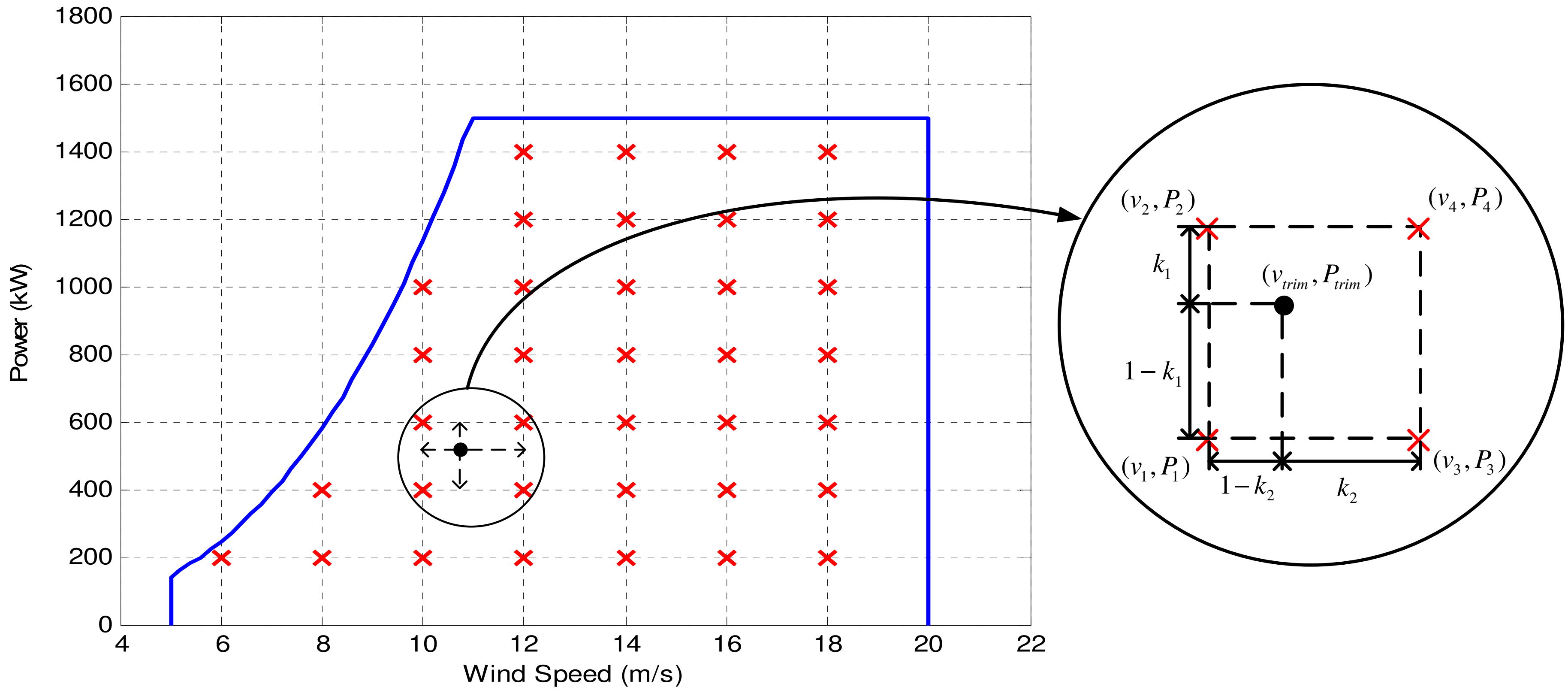


Active Power Control

- Operate turbine to follow power commands
  - Uses: First Response (Frequency Control), Secondary response (automatic generation control), Ancillary Services.
  - Ref. 1: Aho, Buckspan, Pao, Fleming, AIAA, 2013,
  - Ref. 2: Jeong, Johnson, Fleming, Wind Energy, 2013.



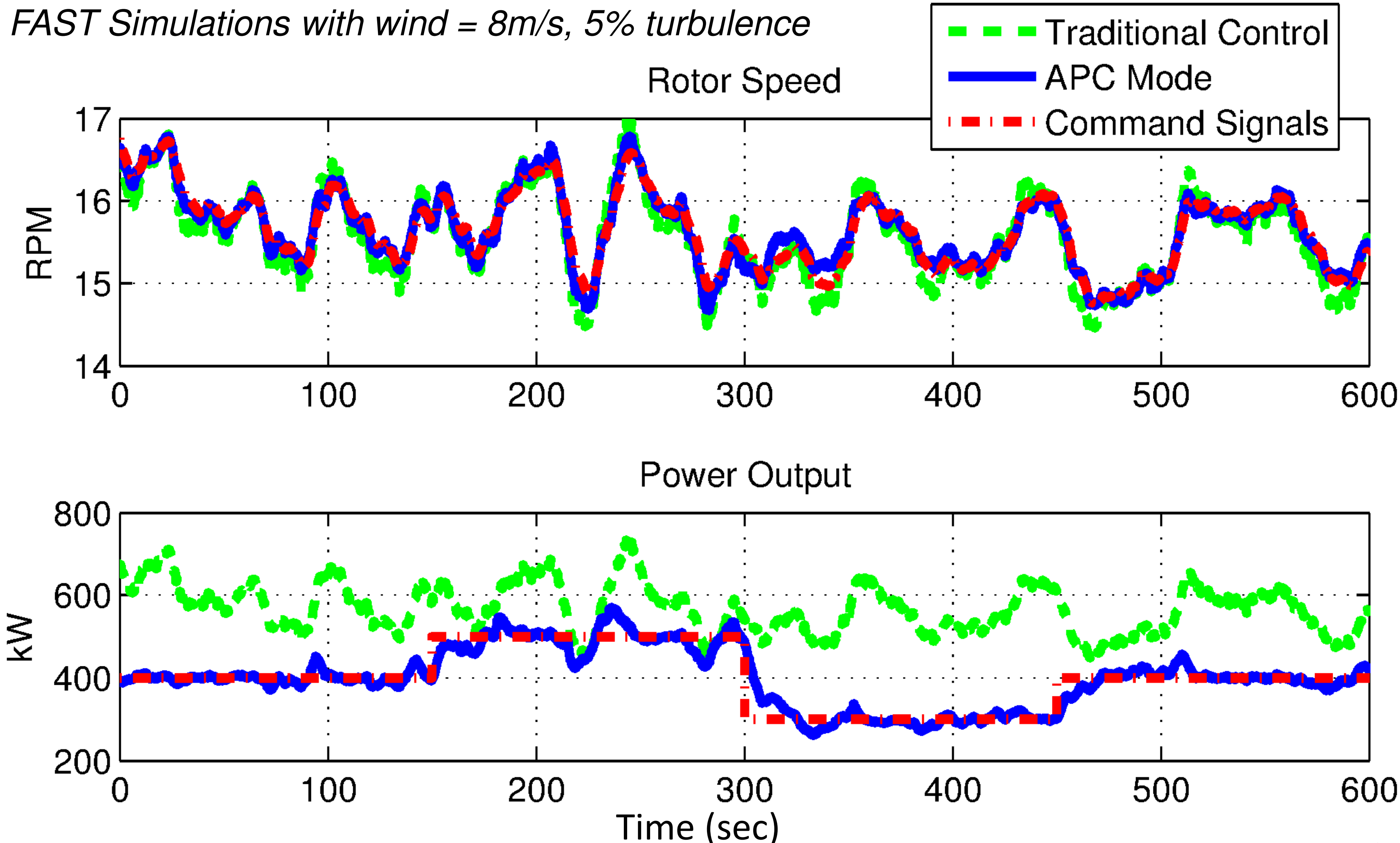
Gain-Scheduled Active Power Control



- Ref: Wang and Seiler, AIAA 2014.

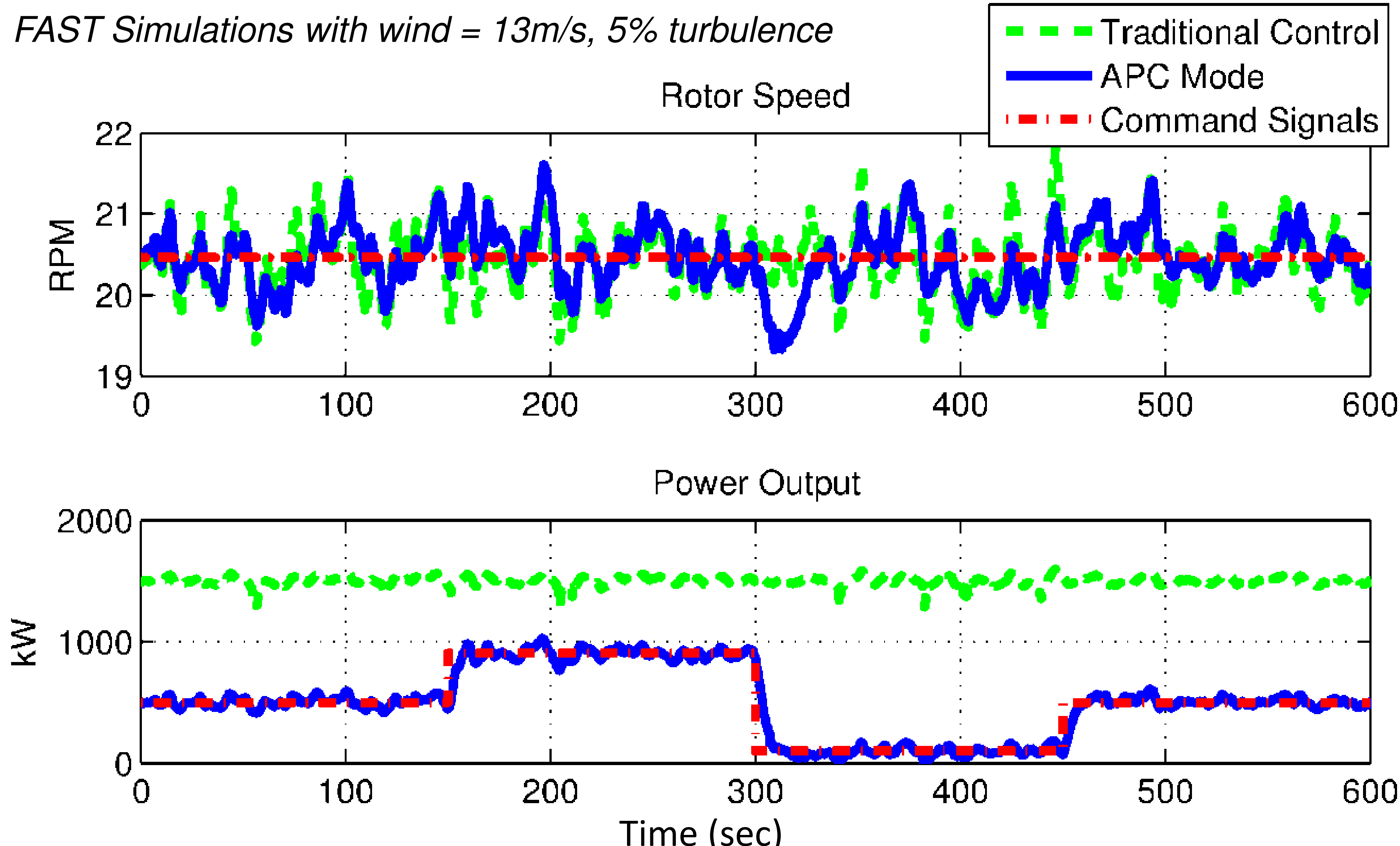
Active Power Control: Low Wind Speeds

FAST Simulations with wind = 8m/s, 5% turbulence



Active Power Control: High Wind Speeds

FAST Simulations with wind = 13m/s, 5% turbulence



Outline

- Individual Turbine Control
- **Modeling and Control of a Wind Farm**
- Conclusions

Wind Farm Control

- Wind Farm Control
  - Maximize Power
  - Mitigate Loads
  - Enable operation similar to conventional power plants
- Understand aerodynamic interactions in a wind farm

Horns Rev 1 (Photographer: Christian Steiness)

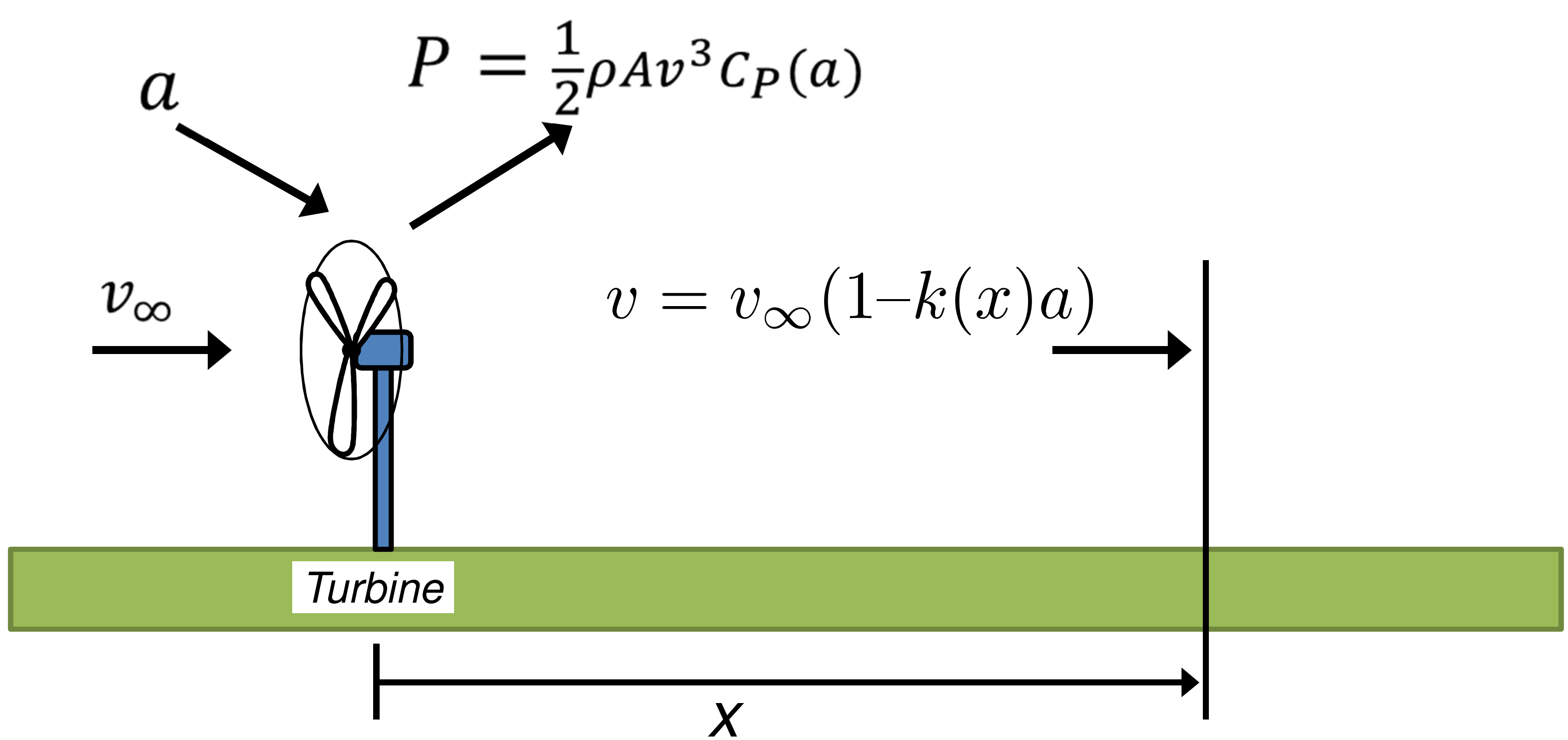
Turbine Model: Actuator Disk + Park Model

Turbine Efficiency:

$$C_P(a) = 4a(1-a)^2$$

Velocity Deficit (Jensen, 83):

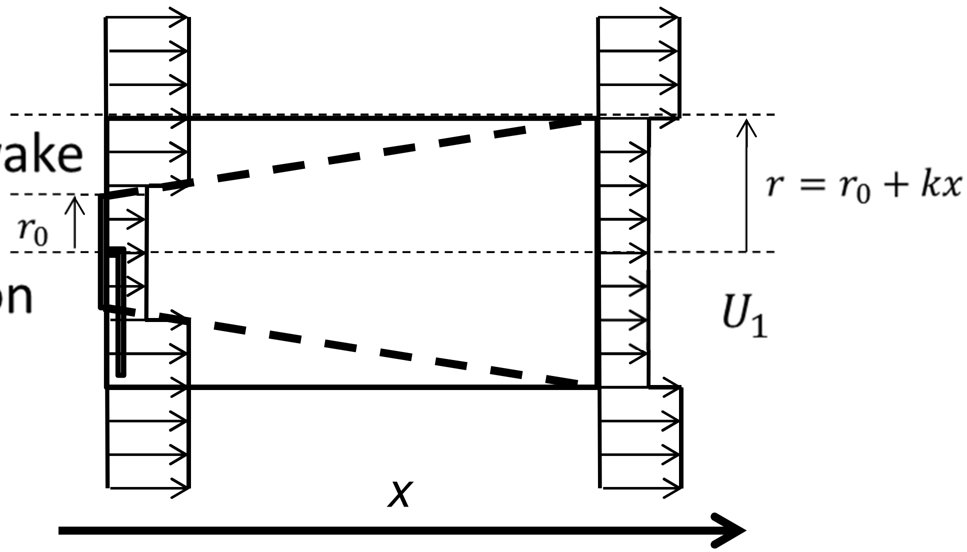
$$k(x) = 2\left(\frac{D}{D+2k_r x}\right)^2$$



Derivation of Park Model

<u>Assumptions</u>

1. Steady Inflow
2. Uniform velocity in wake cross-section
3. Linear wake expansion
4. Betz $U_0 = {}^{U_\infty}/_3$



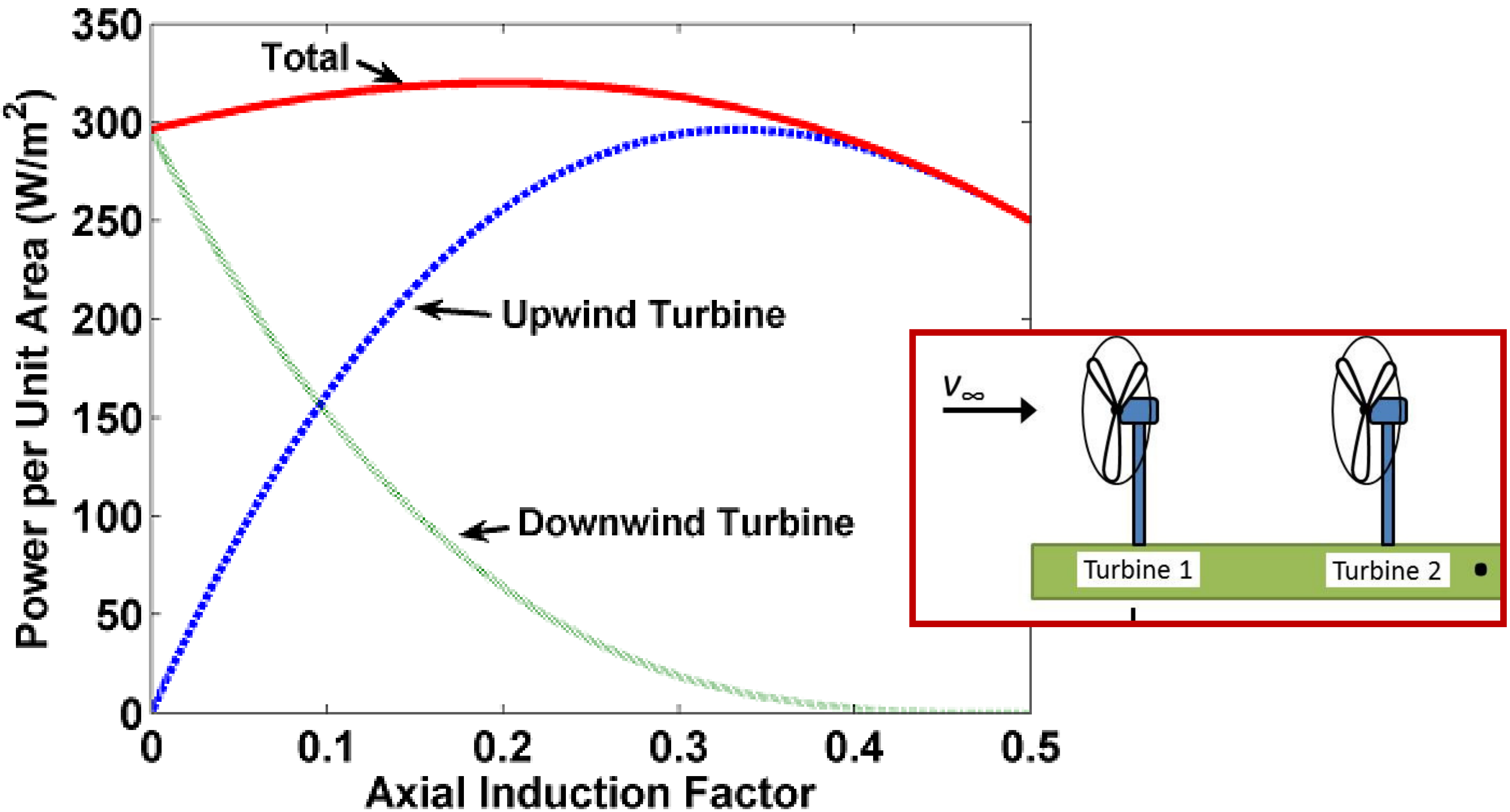
<u>Conservation of Mass</u>

$$-\pi r_0^2 U_0 - \pi(r^2 - r_0^2)U_0 + \pi r^2 U_1 = 0$$

$$U_1 = \left(1 - \frac{2}{3}\left(\frac{r_0}{r_0 + \boxed{k}x}\right)^2\right)U_\infty$$

Wake Expansion Coefficient

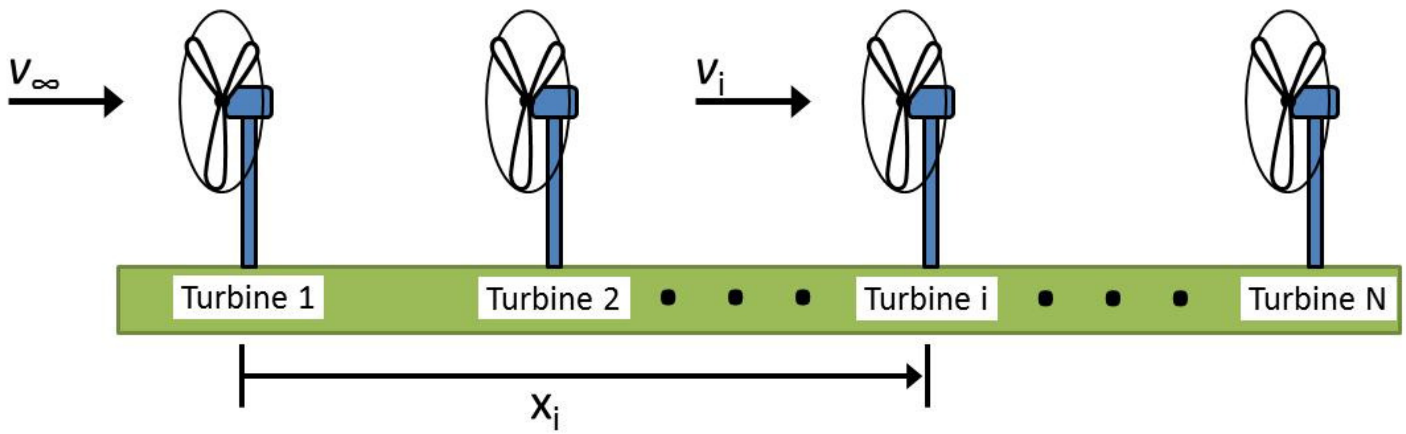
Coordinated Control: Two Turbines



Johnson & Thomas, ACC, 2009

N-turbine Linear Array

- **Objective:** Determine (quasi-steady) control inputs to maximize power produced by an array of turbines



Ref: Bitar and Seiler, ACC, 2013

Power Maximization: Near Field

- Problem: Determine joint induction factor $a = (a_1, a_2, \cdots, a_N)$ to maximize total power $J(a, v_\infty) = \sum_{i=1}^{N} P_i(a_i, v_i)$.
- Optimal induction factors obtained via Dynamic Programming

Bellman Equation: Solve backwards iteration for value function (power produced by turbines i,…,N with inlet velocity *v*)

$$J_i^\circ(v) = \max_{a \in \mathcal{A}_i} \left\{ \; P_i(a, v) \; + \; J_{i+1}^\circ(v(1 - a \; \kappa_{i,i+1})) \; \right\}$$

Boundary Condition:

$$J_N^\circ(v) = \max_{a \in \mathcal{A}_N} \; P_N(a, v)$$

Power Maximization: Near Field

- Problem: Determine joint induction factor $a = (a_1, a_2, \cdots, a_N)$ to maximize total power $J(a, v_\infty) = \sum_{i=1}^{N} P_i(a_i, v_i)$.
- Dynamic Programming Results

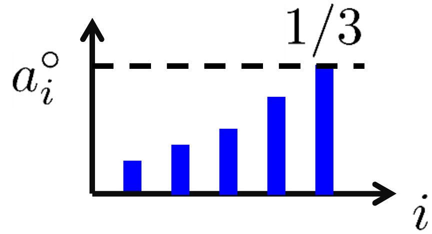
Optimal Induction Factors: Obtained via backwards iteration

$$a_i^\circ = \frac{1}{3}\left(\frac{2 - 3\phi\kappa^2 - \sqrt{1 - 12\phi\kappa^2 + 9\phi\kappa + 3\phi\kappa^3}}{1 - \phi\kappa^3}\right)$$

$$\phi_i = (1 - a_i^\circ \kappa_{i,i+1})^3 \phi_{i+1} \;+\; a_i^\circ (1 - a_i^\circ)^2 \qquad \text{(BC: } \phi_{N+1} = 0 \text{)}$$

For $k_r = 0$

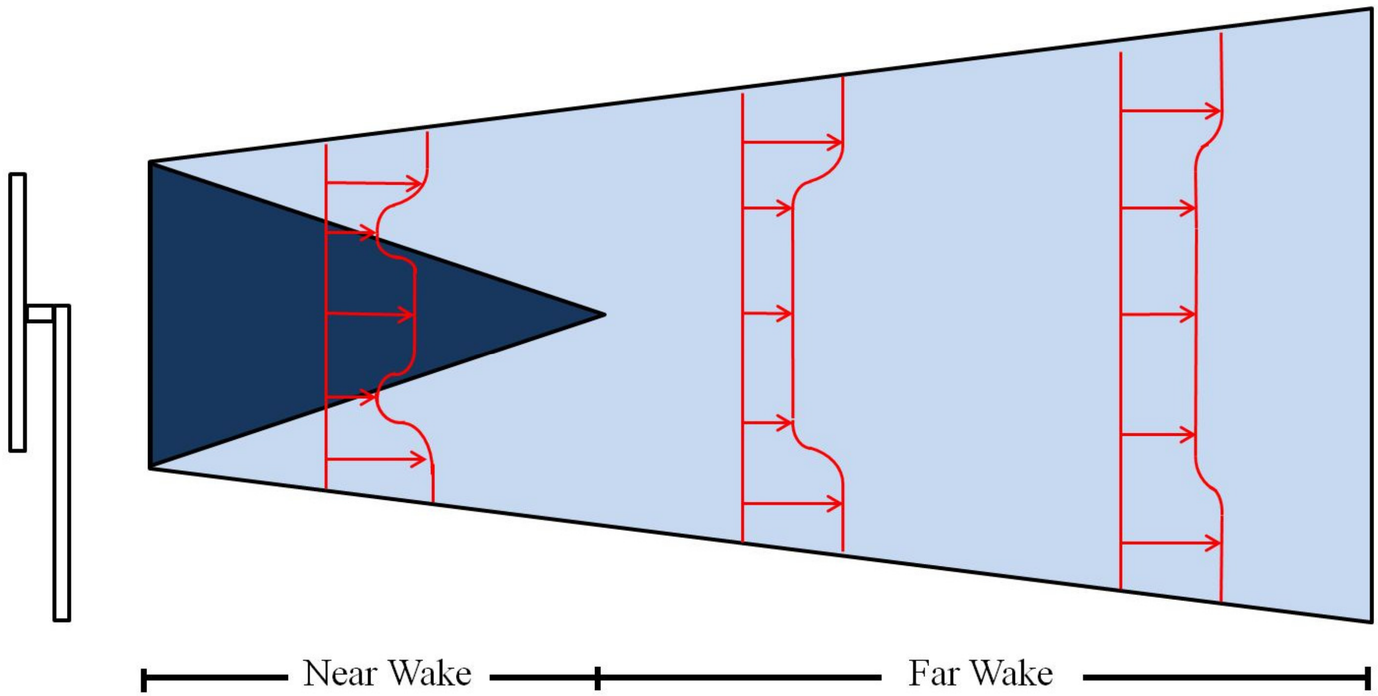
$$a_i^\circ = \frac{1}{2(N-i)+3}$$



For uniformly spaced infinite arrays

$$\frac{C_P^\circ - \overline{C}_P}{\overline{C}_P} = 8.33\%$$

Issue: Limited Fidelity of Park Model

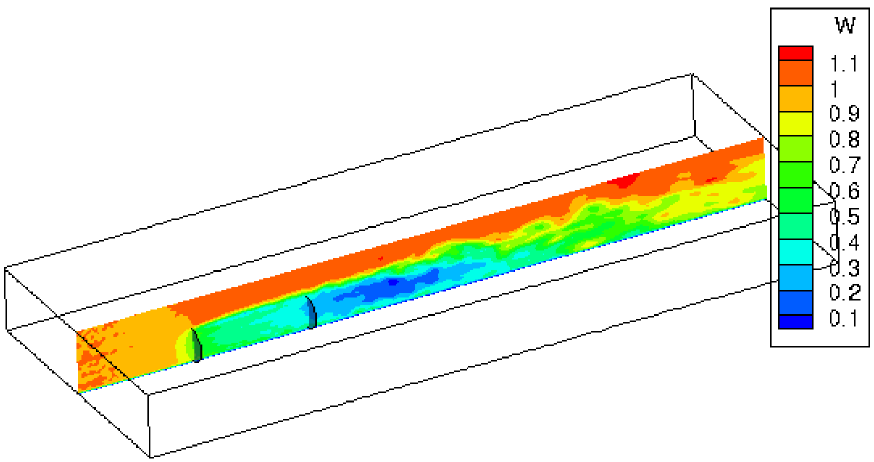


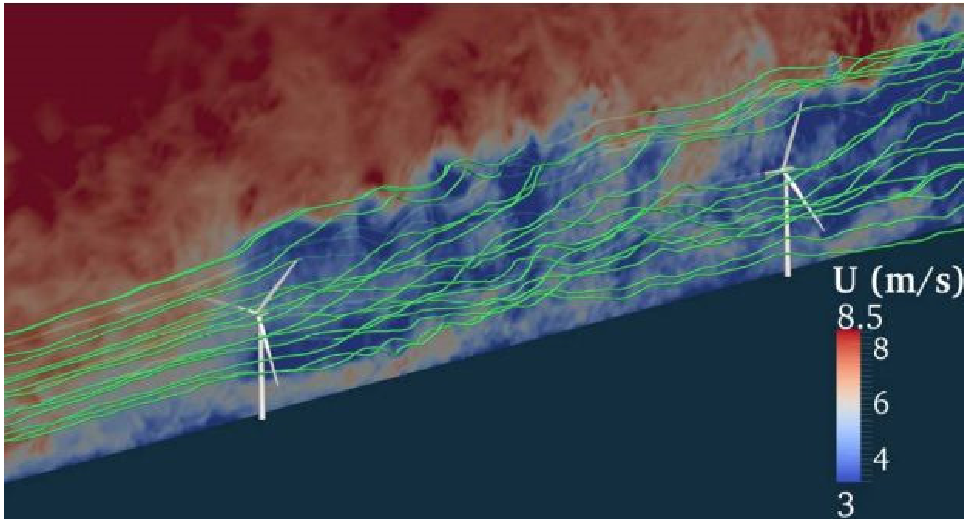
Key Questions

1. What is the impact of the control law on the trailing wake?
2. What is appropriate level of model fidelity required for coordinated wind turbine control?
3. Can we take advantage of wake interactions to better integrate wind into the energy system?

SAFL Large Eddy Simulation

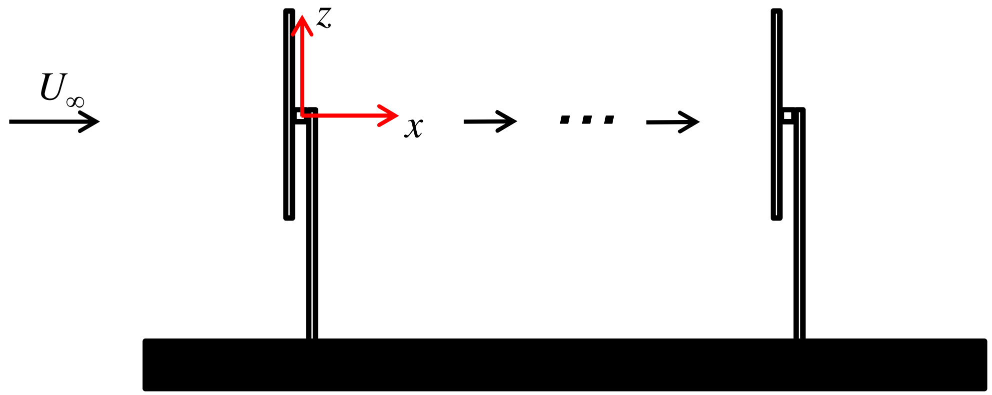
- **Approach:** Use high fidelity simulations
  - Flow: 3-D incompressible Navier-Stokes equations
  - Turbine: Fixed speed or tip speed ratio
- **Opportunity:** Integrate Clipper dynamics/control law
  - Joint work with Yang, Annoni, and Sotiropoulos

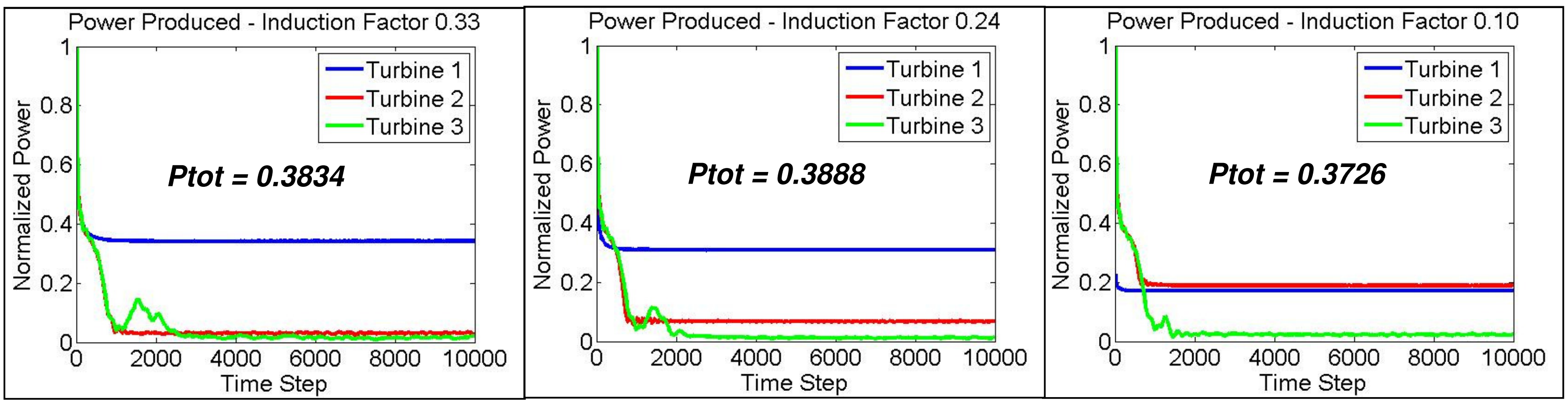




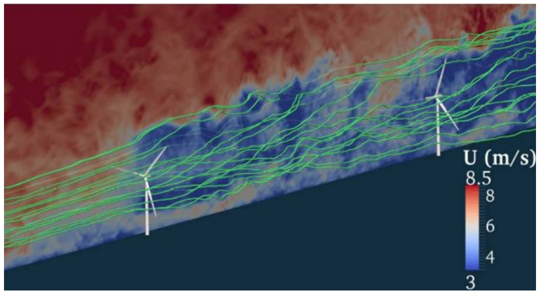
Axial Induction Control

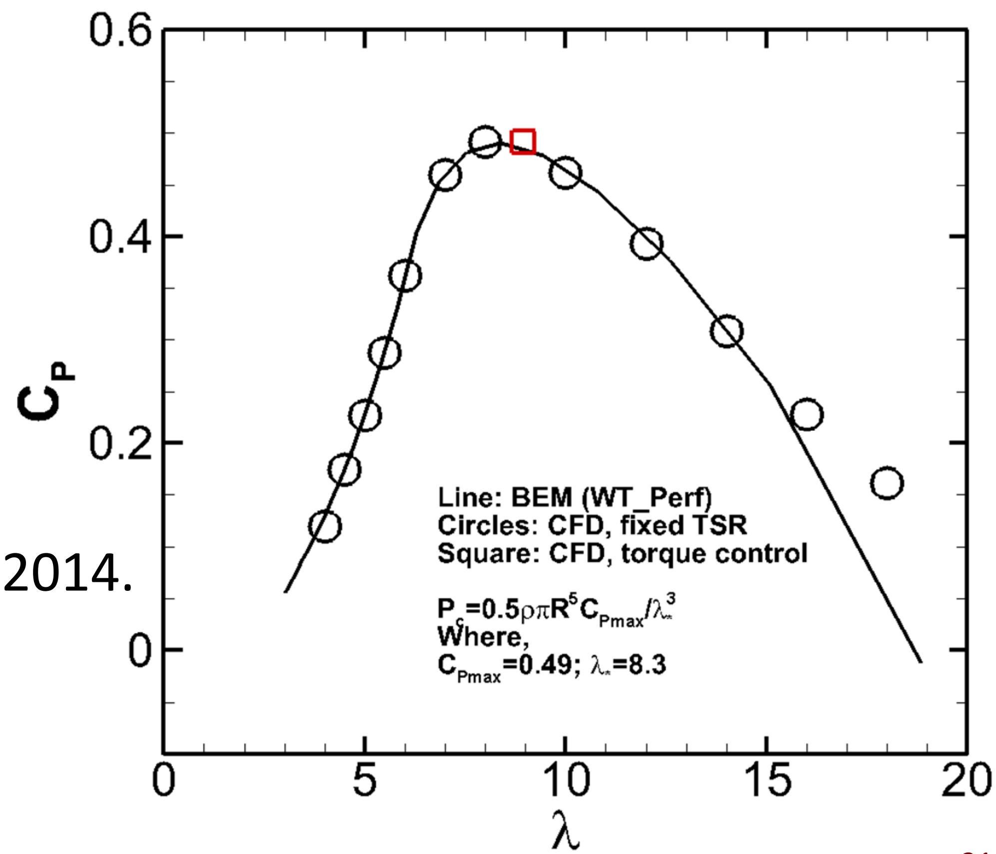
- De-rate 1st turbine → Maximize Power in Turbine Array





LES With Clipper Controller





Preliminary results

- Clipper Region 2 Torque Control
- Yang, Annoni, Seiler, Sotiropoulos, 2014.

Wind Tunnel and Field Tests

- **Approach:** Use LIDAR measurements of wake
  - Clipper Turbine: Measurements made at 1.5D, 2D, 2.5D, and 3D
- **Opportunity:** Integrate Clipper dynamics/control law
  - Joint work with Howard, Annoni, and Guala

LIDAR at UMore Park

Clipper Turbine

Wind Tunnel and Field Tests

- **Approach:** Wind tunnel tests using a 3 turbine array
  - Experiments with turbine spacing by fixing 1st and 3rd turbine
  - De-rating first turbine
- **Opportunity:** Understand wake interactions and potential gains from coordinated turbine control
  - Joint work with Howard, Annoni, and Guala

Wind Farm in Wind Tunnel

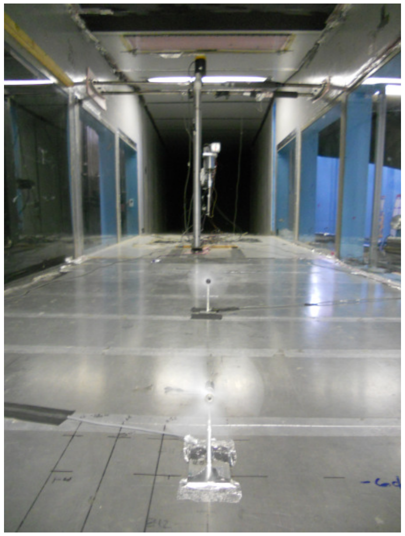


Photo Credits: Kevin Howard

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- **Conclusions**

Conclusions

- Control systems increase power capture and reduce structural loads on utility-scale wind turbines.
- Performance and reliability trade-offs are becoming more difficult with trends to larger / off-shore turbines.
- Potential to coordinate all turbines in a wind farm in order to increase power and reduce overall loads
    - Requires a better understanding of trailing wakes and how these are affected by the control algorithms.

Acknowledgments

- 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”