A Tutorial on the Dynamics and Control of Wind Turbines and Wind Farms

9:20-10:20 A Tutorial on the Dynamics and Control Wind Turbines and Wind Farms, Lucy Pao and Katie Johnson

10:20-10:40 Wind Turbine Modeling Overview for Control Engineers, Pat Moriarty and Sandy Butterfield

10:40-11:00 Control of Wind Turbines: Past, Present, and Future, Jason Laks, Lucy Pao, and Alan Wright

11:00-11:20 Wind Farm Control: Addressing the Aerodynamic Interaction Among Wind Turbines, Katie Johnson and Naveen Thomas

A Tutorial on the Dynamics and Control of Wind Turbines and Wind Farms

Partners in the Colorado Renewable Energy Collaboratory's Center for Research and Education in Wind

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SCHOOL OF MINES 1874 COLORADO

American Control Conference St. Louis, MO June 2009

Wind Energy

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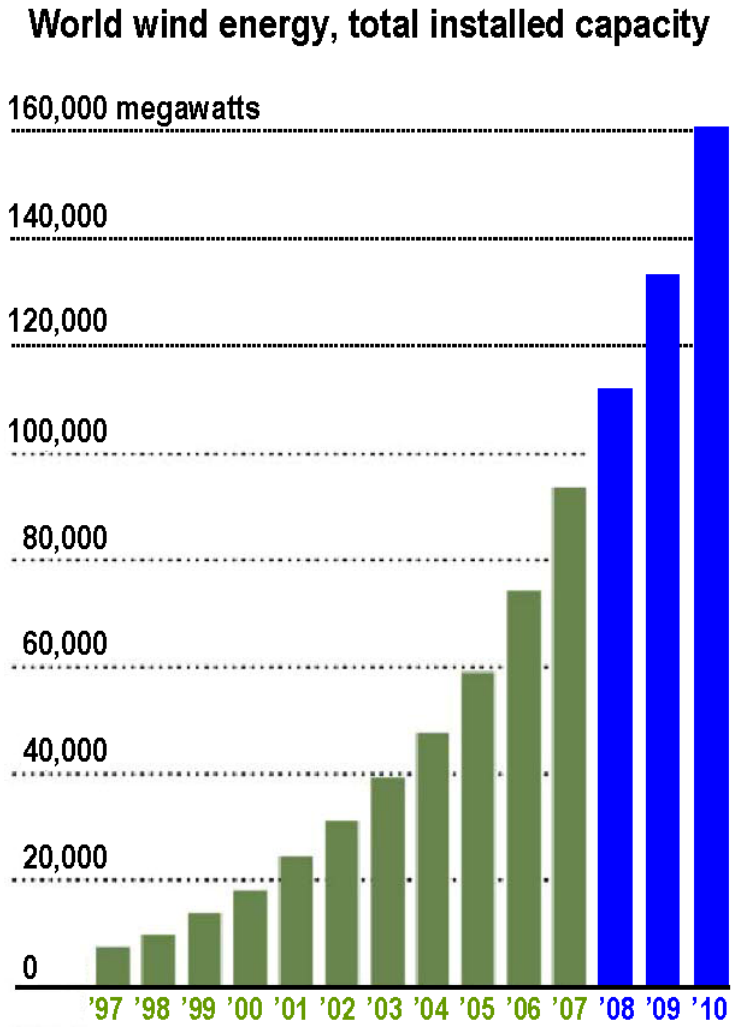
- Fastest growing energy source in the world
- Current global installed capacity exceeds 100,000 MW, with a projected growth of more than 20% per year for the next five years
- Wind farms today produce electrical power at a Cost-of-Energy of approximately $0.03/kWh, comparable to that of coal and natural gas based power plants



[data from www.wwindea.org]

Increasing Turbine Size

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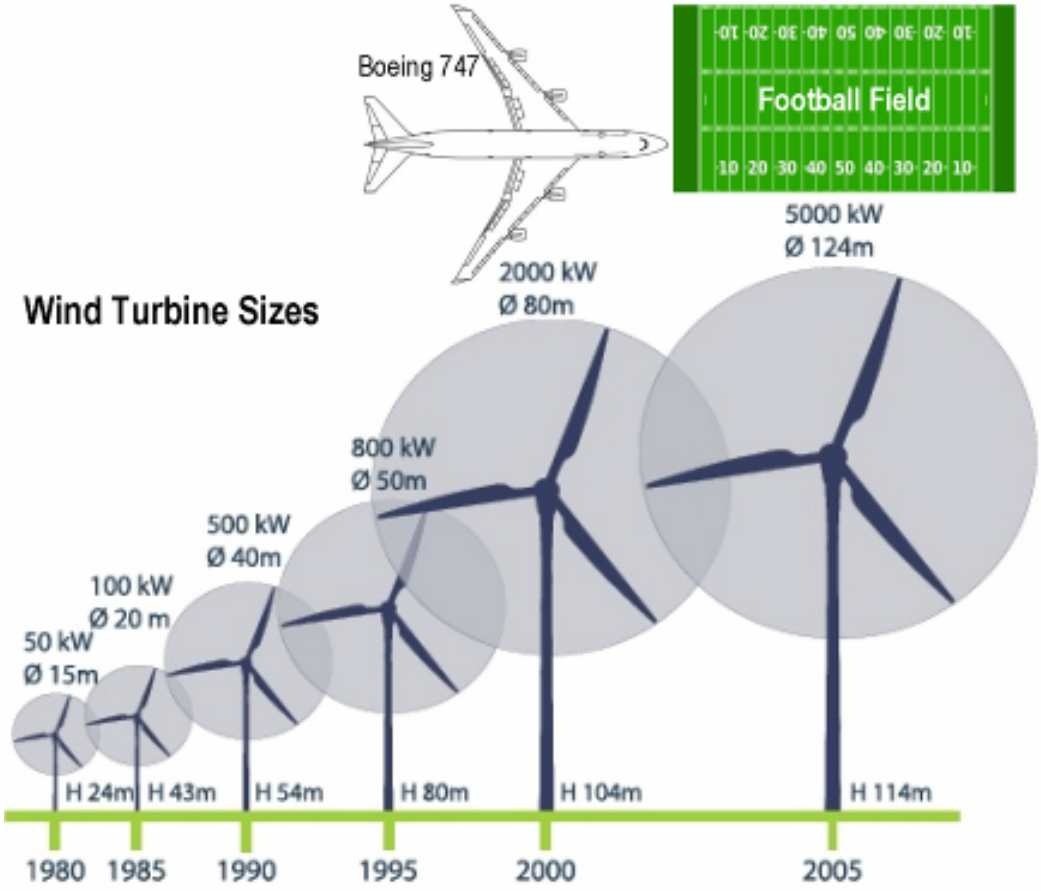
- Typical size of utility-scale wind turbines has grown dramatically
- Large flexible structures operating in uncertain environments [video]
- Advanced controllers can help increase energy capture efficiency and reduce structural loading
  - → Decrease the cost of wind energy



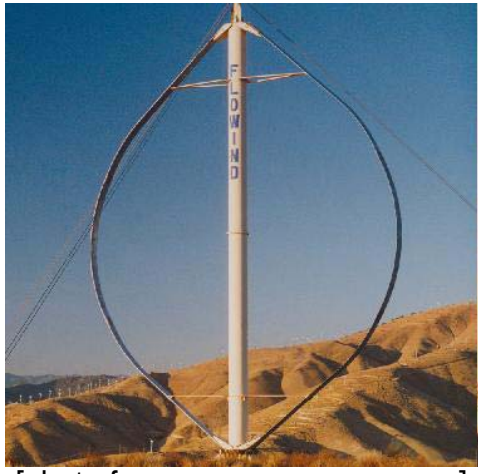
[diagrams and schematic from www.renewableenergy.no, www.aerospaceweb.org/aircraft/jetliner/b747, and en.wikipedia.org/wiki/American_football]

Outline

- Motivation and Wind Turbine Basics
- Wind Turbine Control Loops
- Issues in Turbine Control
- Advanced Turbine Control
- Wind Farms
- Offshore Wind
- Conclusions

Vertical vs. Horizontal Axis Wind Turbines

- Vertical-axis wind turbines (VAWTs) more common among smaller turbines
- HAWTs are the most commonly produced utility-scale wind turbines
- Advantages of horizontal-axis wind turbines (HAWTs)
  - Improved power capture capabilities
  - Pitchable blades
  - Improved structural performance



[photo from www.symscape.com]

[photo courtesy of L. J. Fingersh, NREL]

Vertical vs. Horizontal Axis Wind Turbines

- Vertical-axis wind turbines (VAWTs) more common among smaller turbines
- HAWTs are the most commonly produced utility-scale wind turbines
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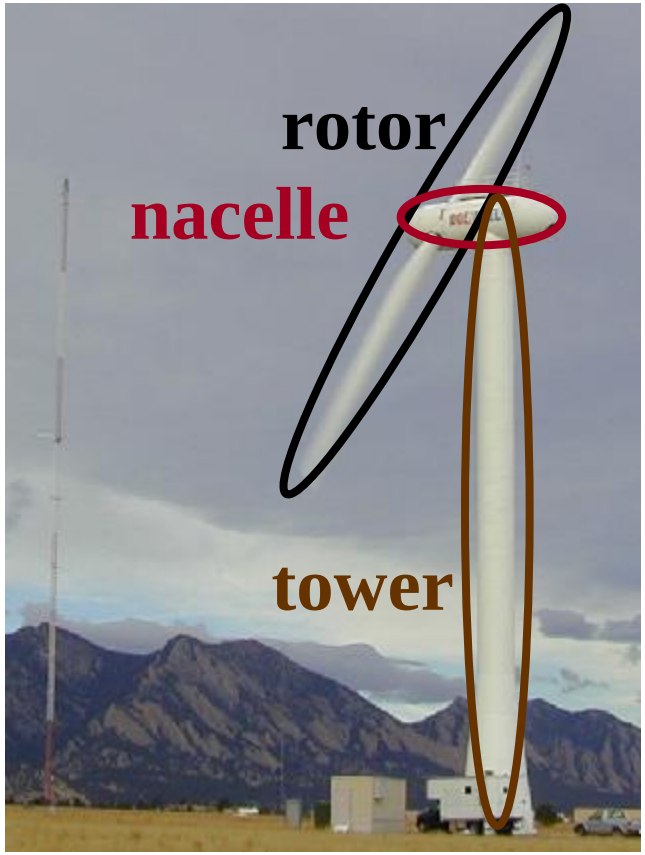
Horizontal Axis Wind Turbine



NREL's Control Advanced Research Turbine (CART2)

Wind Turbine Components

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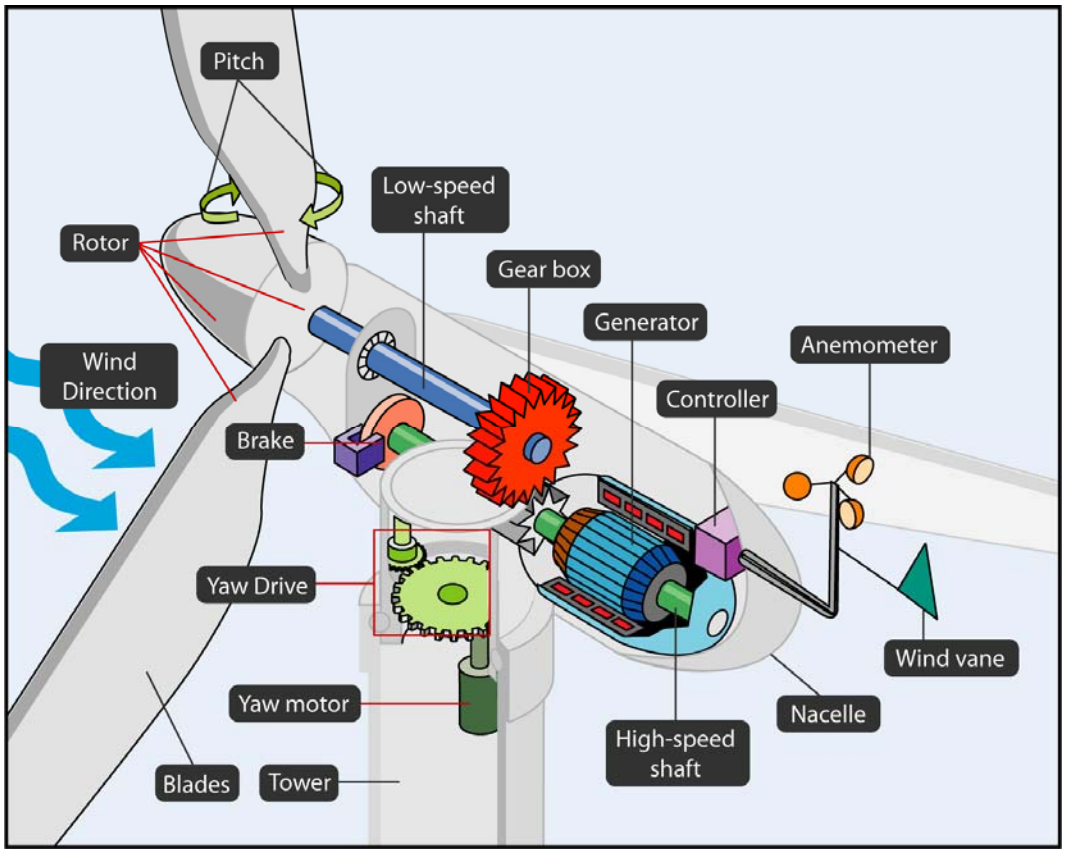
- Wind encounters rotor, causing it to spin
- Low-speed shaft transfers energy to the gear box
  - Steps up speed
  - Spins high-speed shaft
- High-speed shaft causes generator to spin, producing electricity
- Yaw system turns nacelle so that rotor faces into the wind

Upwind HAWT



[figure courtesy of US Dept. of Energy]

Wind Turbine Design Considerations

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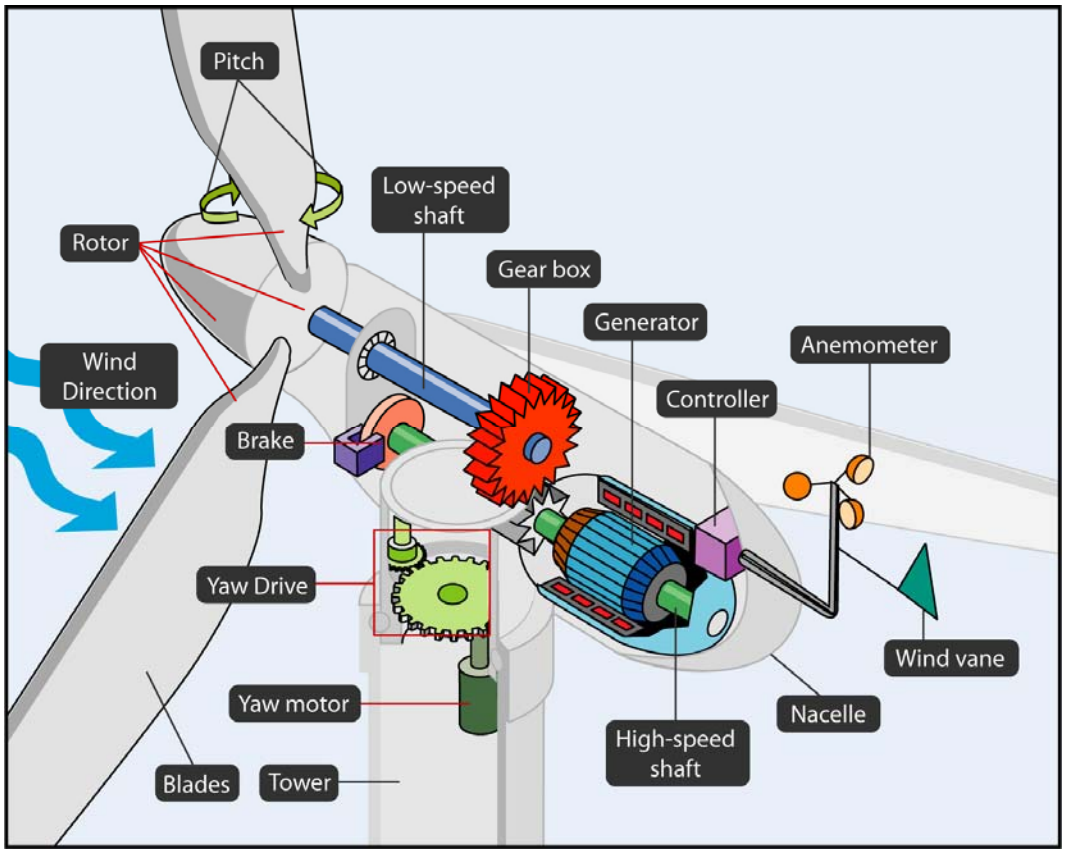
- Upwind vs. downwind
  - Tower shadow
- Variable or fixed pitch
  - Initial cost
  - Ability to control loads and change aerodynamic torque
- Variable or fixed speed
  - Aerodynamic efficiency
  - Electrical power processing
- Number of blades

Upwind HAWT



[figure courtesy of US Dept. of Energy]

Operating Regions

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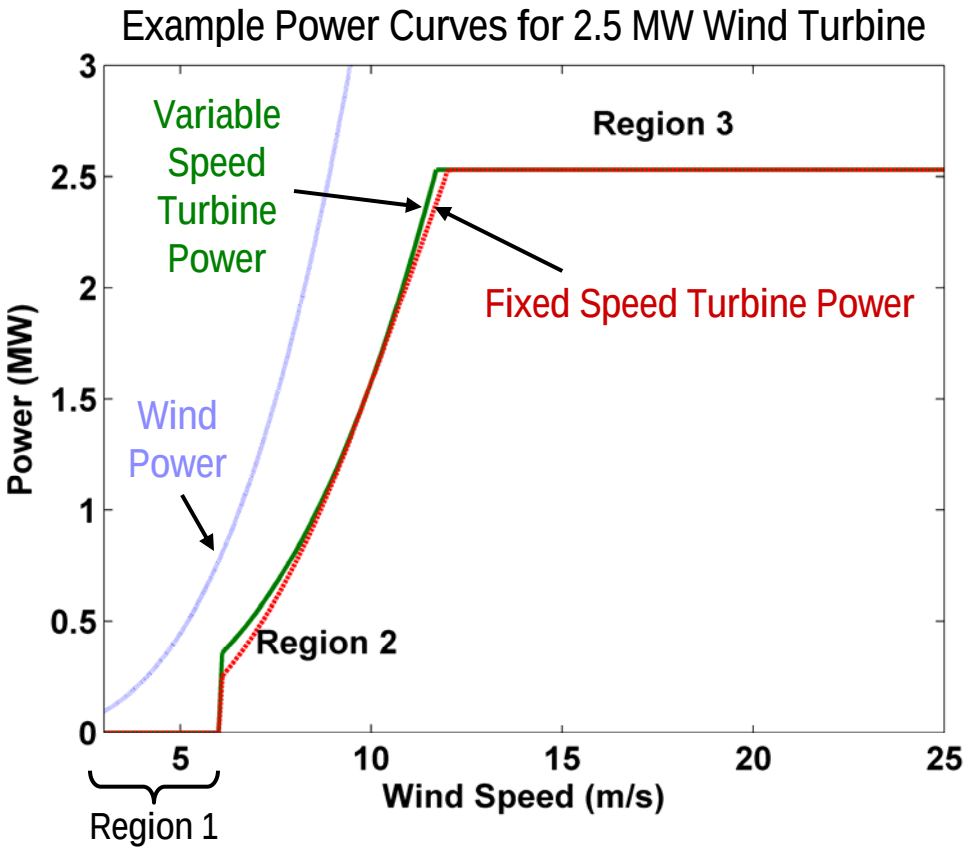
- Region 1: Low wind speed (below 6 m/s)
  - Wind turbines not run, because power available in wind is low compared to losses in turbine system
- Region 2: Medium wind speeds (6 m/s to 11.7 m/s)
  - Variable-speed turbine captures more power
  - Fixed-speed turbine optimized for one wind speed (10 m/s)
    - Max difference in example curves is 150 kW.
  - For typical wind speed distributions, in this example, variable-speed turbine captures 2.3% more energy than constant-speed turbine



- Region 3: High wind speeds (above 11.7 m/s)
  - Power is limited to avoid exceeding safe electrical and mechanical load limits

Outline

- Motivation and Wind Turbine Basics
- Wind Turbine Control Loops
  - Wind Inflow
  - Sensors
  - Actuators
  - Torque Control
  - Pitch Control
- Issues in Turbine Control
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Wind Turbine Control Loops

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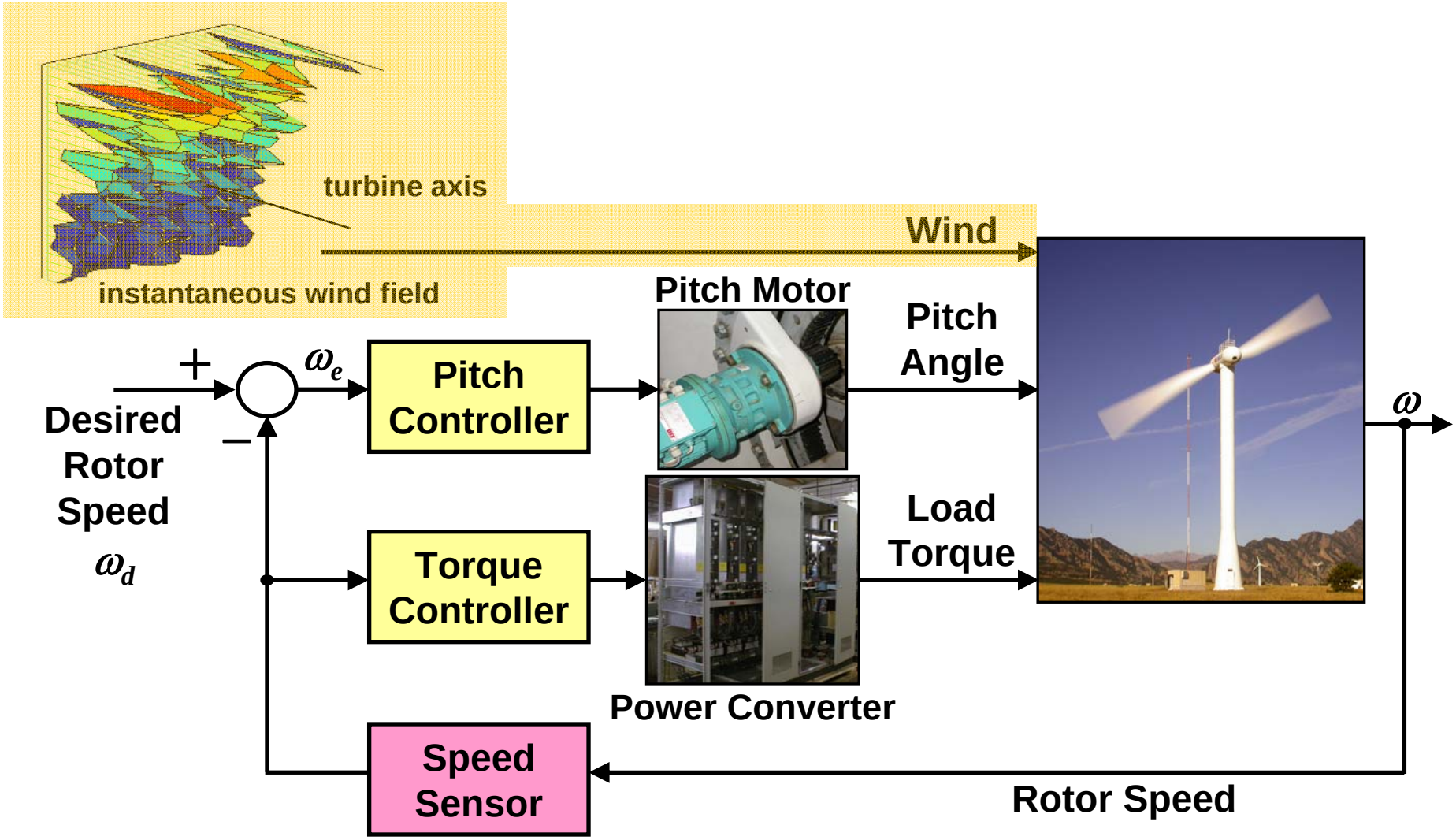

Wind Inflow

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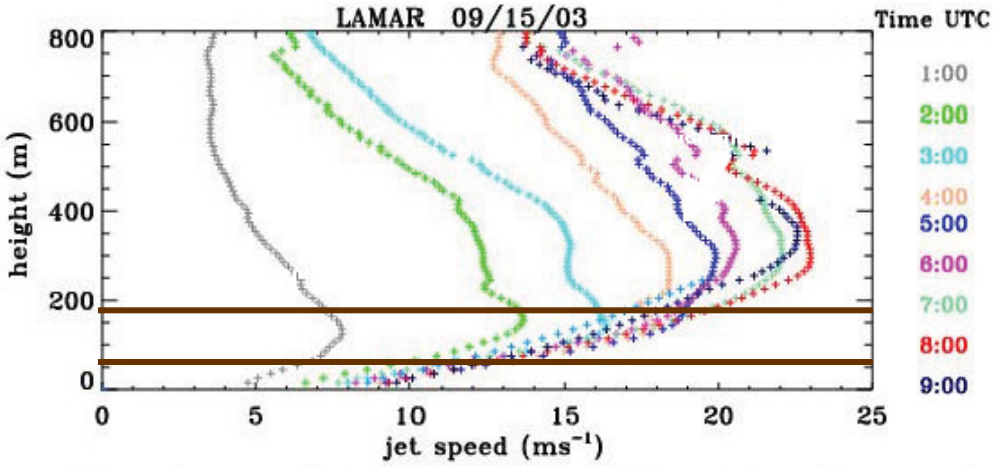
- Differential heating of atmosphere is driving mechanism for earth's winds
- Numerous phenomena affect wind inflow across a wind turbine's rotor plane
  - Sea breezes
  - Frontal passages
  - Mountain and valley flows
  - Nocturnal low-level jet
- Rotor plane of MW utility-scale turbines span from 60m to 180m above the ground
- Virtually impossible to obtain a good measurement of the wind speed encountering the entire span of blades



Hourly profiles of mean wind speed after sunset on 15 Sept 2003

[Figure courtesy of R. Banta, Y. Pichugina, N. Kelley, B. Jonkman, and W. Brewer]

Characterizing the Wind

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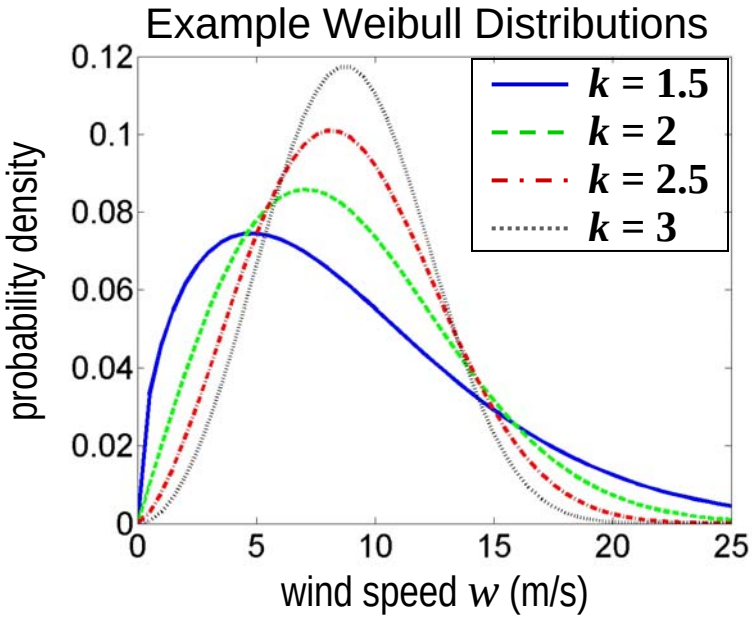
- Average wind speed
  - Spatial
  - Temporal
- Frequency distribution of wind speeds
  - Spatial
  - Temporal
- Prevailing wind direction
  - Frequency of other wind directions
- Capacity Factor



$$f(w) = k\frac{w^{k-1}}{c^k}\exp\left(-\left(\frac{w}{c}\right)^k\right)$$

c : scale parameter k : shape parameter

$$\text{CF} = \frac{\text{actual energy output over time period}}{\text{energy output if turbine operated at max output over same time period}}$$

Wind Turbine Control Loops

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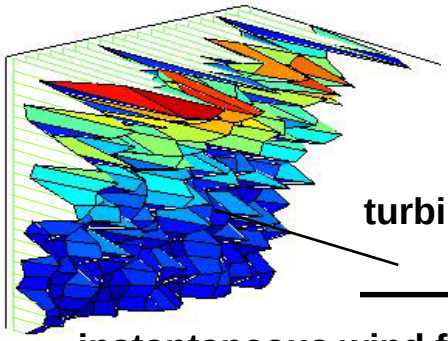


turbine axis

instantaneous wind field

Wind

Pitch Motor

Pitch Angle

+

ω_e

Desired Rotor Speed ω_d

−

Pitch Controller

ω

Torque Controller

Load Torque

Power Converter

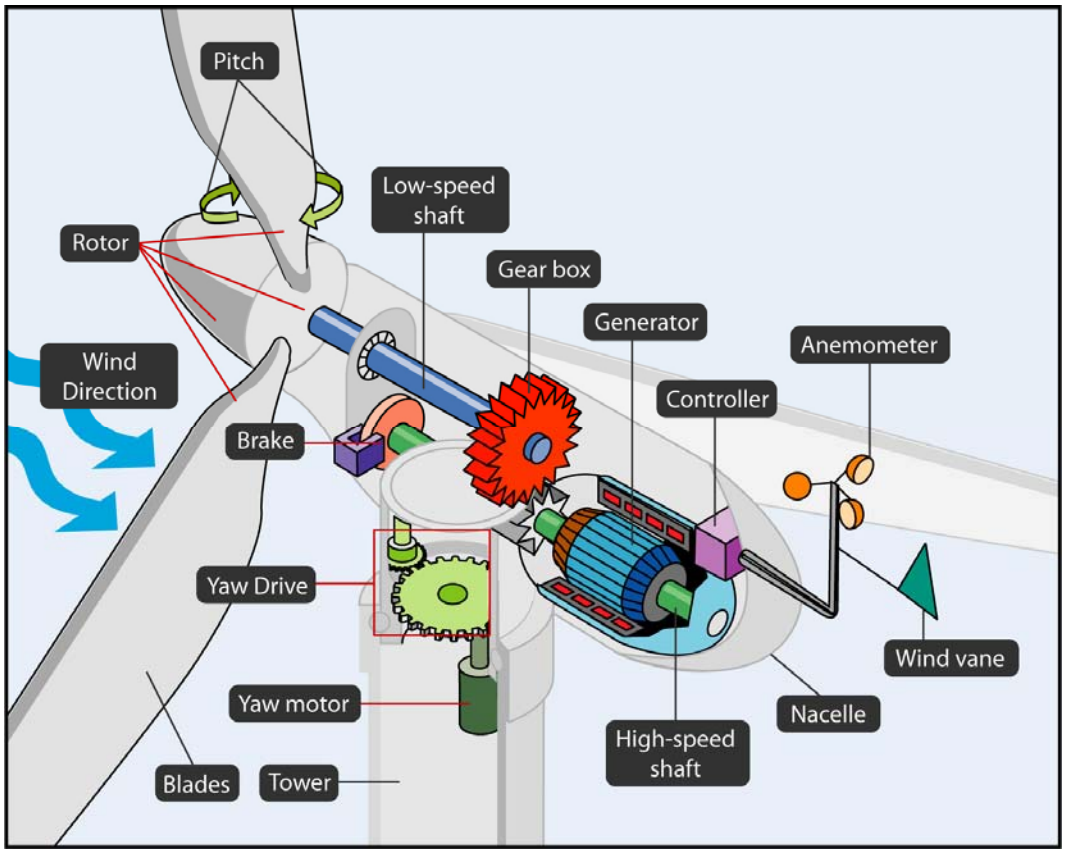
Speed Sensor

Rotor Speed

Sensors

- Rotor speed measured on either high-speed (generator) or low-speed (rotor) shafts
  - Gear box ratio known
- Anemometers used for supervisory control purposes
  - Usually located on nacelle behind rotor plane
    - → poor measurement of wind

Upwind HAWT

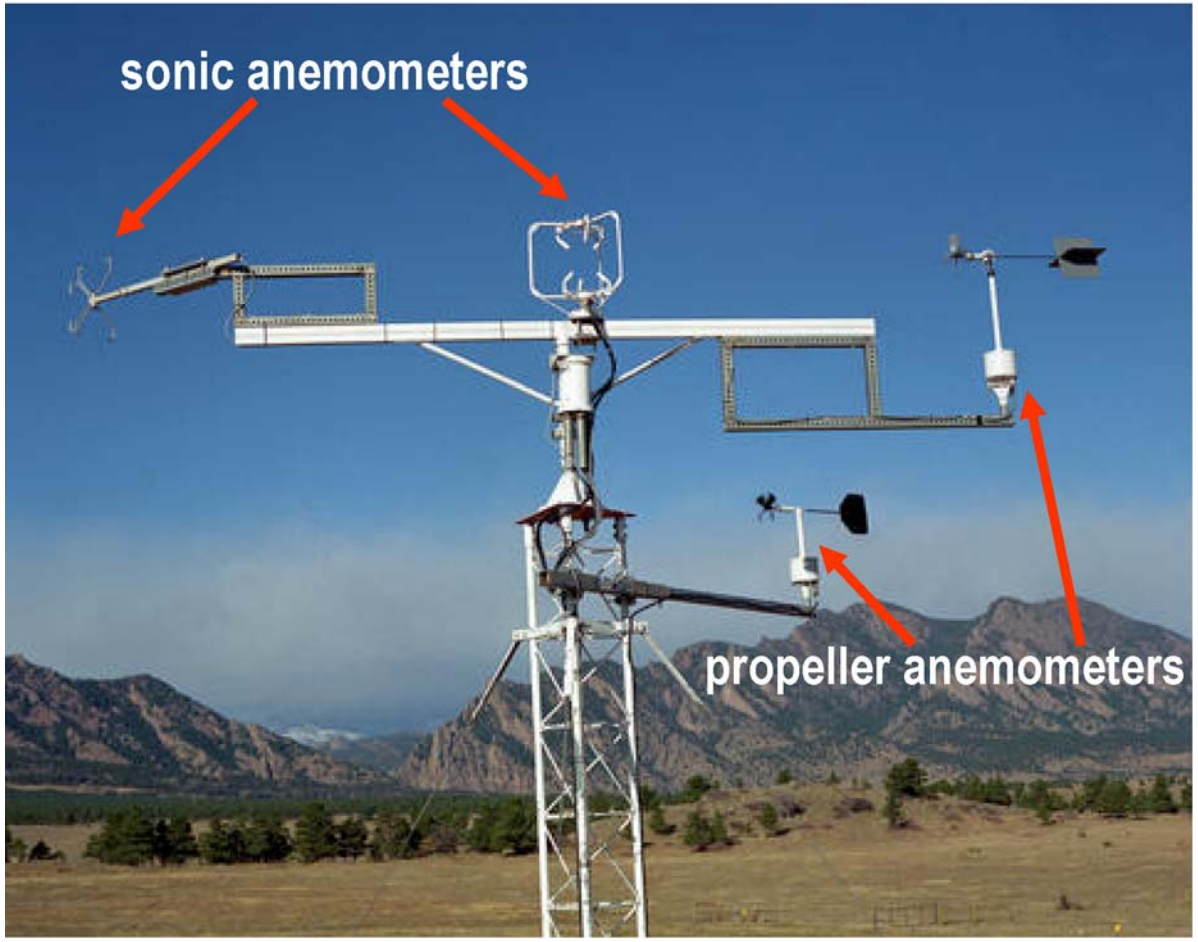


[figure courtesy of US Dept. of Energy]

Sensors

- Rotor speed measured on either high-speed (generator) or low-speed (rotor) shafts
  - Gear box ratio known
- Anemometers used for supervisory control purposes
  - Usually located on nacelle behind rotor plane
    - → poor measurement of wind
- Power measurement devices

Several types of sonic and propeller anemometers on a meteorological tower at NREL's NWTC

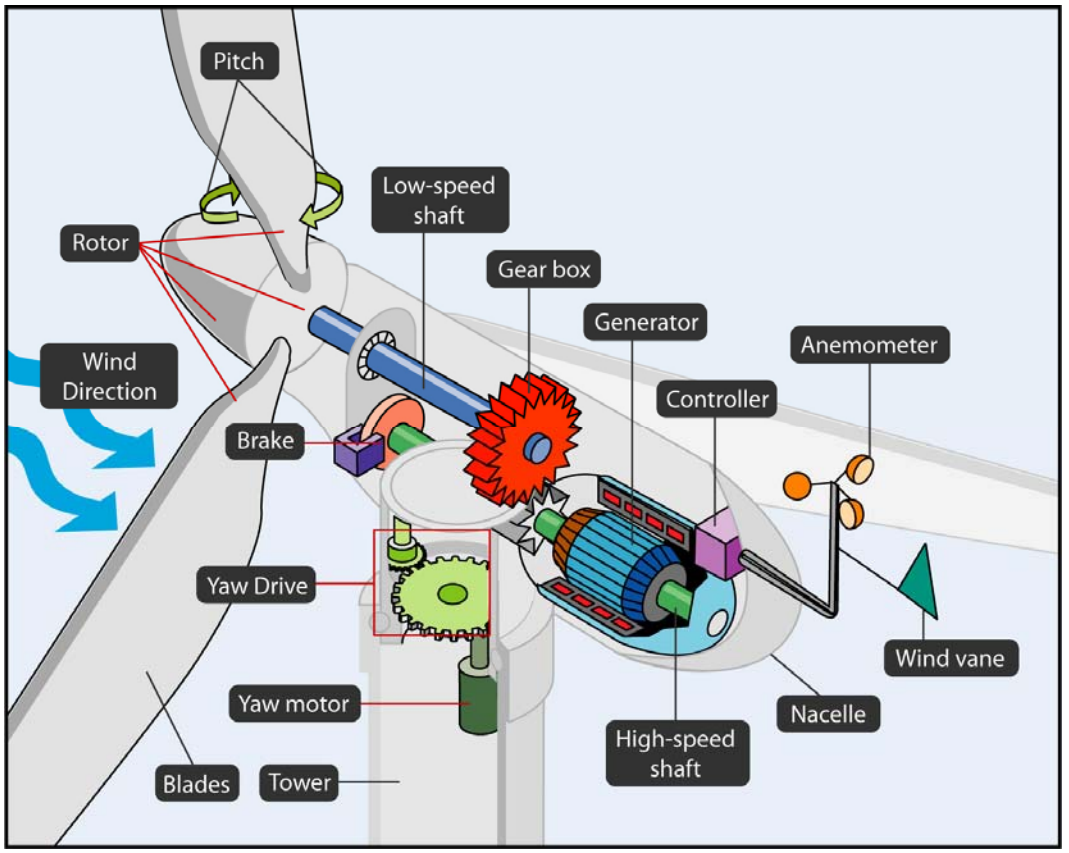


[Photo courtesy of L. J. Fingersh, NREL]

Additional Sensors

- Strain gauges
  - Tower
  - Blades
- Accelerometers
- Position encoders
  - Drive shaft
  - Blade pitch actuation systems
- Torque transducers

Upwind HAWT



[figure courtesy of US Dept. of Energy]

Wind Turbine Control Loops

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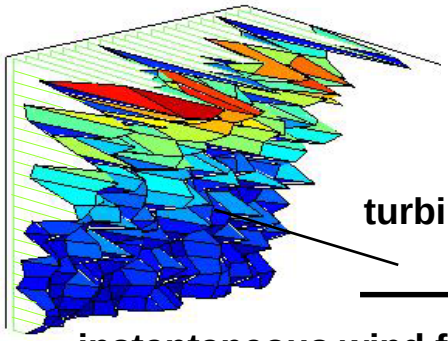


turbine axis

instantaneous wind field

Wind

Pitch Motor

Pitch Angle

Desired Rotor Speed ω_d

$+$

$-$

ω_e

Pitch Controller

Torque Controller

Load Torque

Power Converter

ω

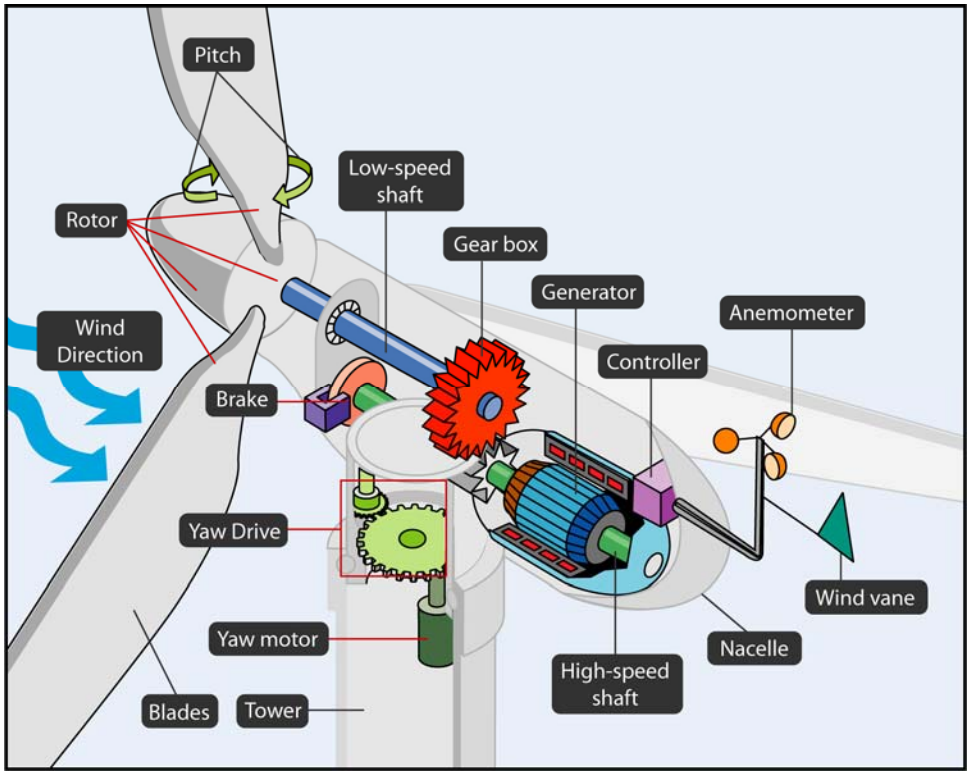
Speed Sensor

Rotor Speed

Actuators

- Yaw motor
  - Slow (usually < 1 deg/s)
- Generator
  - Fast (time constant usually > 10x that of rotor speed)

Upwind HAWT

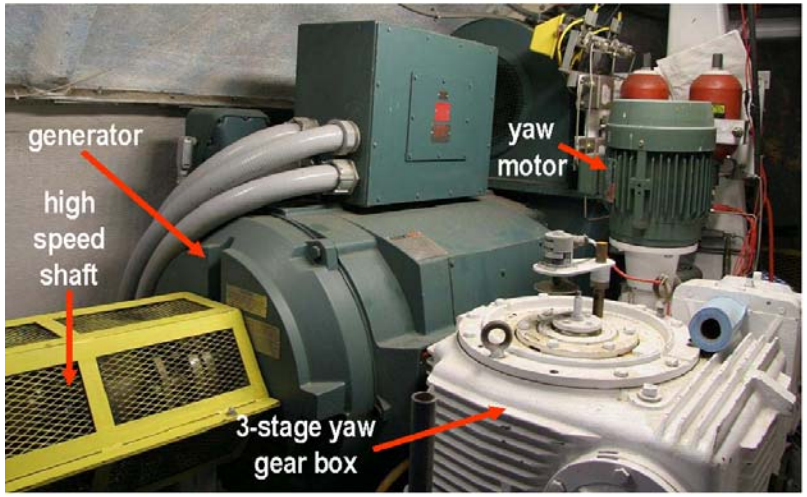


[figure courtesy of US Dept. of Energy]

Actuators

- Yaw motor
  - Slow (usually < 1 deg/s)
- Generator
  - Fast (time constant usually > 10x that of rotor speed)

Inside the Nacelle of the 3-Bladed Controls Advanced Research Turbine (CART3) at NREL's National Wind Technology Center (NWTC)



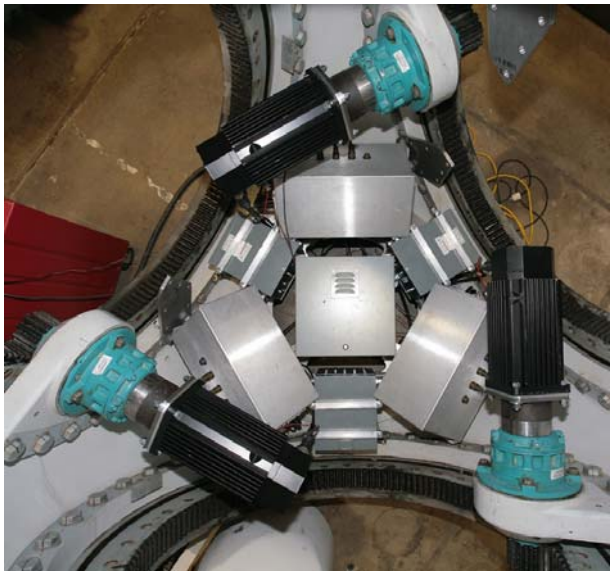
[Photo courtesy of L. J. Fingersh, NREL]

CART3 is a 600 kW wind turbine with a 40 m rotor diameter that is used at NREL's NWTC as an experimental test bed for advanced controllers.

Actuators

- Yaw motor
  - Slow (usually < 1 deg/s)
- Generator
  - Fast (time constant usually > 10x that of rotor speed)
- Blade pitch motor
  - Fast
    - Up to 18 deg/s for 600 kW turbines
    - Up to 8 deg/s for 5 MW turbines
  - Collective vs. Individual Pitch

Three pitch motors on the CART3

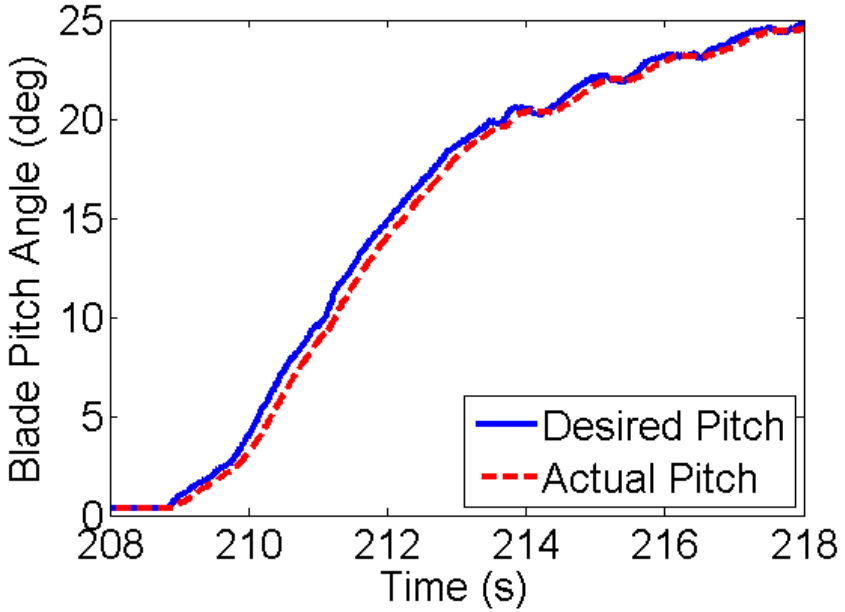


[Photo courtesy of L. J. Fingersh, NREL]

CART3 is equipped with independent blade pitch capability.

More on Actuators

- Operational blade pitch angle data from CART2:
  - CART2 is a 2-bladed, 600 kW wind turbine with a 43 m diameter rotor at NREL's NWTC
  - Data from a normal shut-down event caused by the wind speed decreasing into Region 1
    - Pitch rate limited to approx 5 deg/s
    - Lag between commanded and actual pitch can be represented by a 1st-order filter



- Teetering hinge on 2-bladed turbines
  - Allows rotor to respond to differential loads when blades in vertical position

Torque Control

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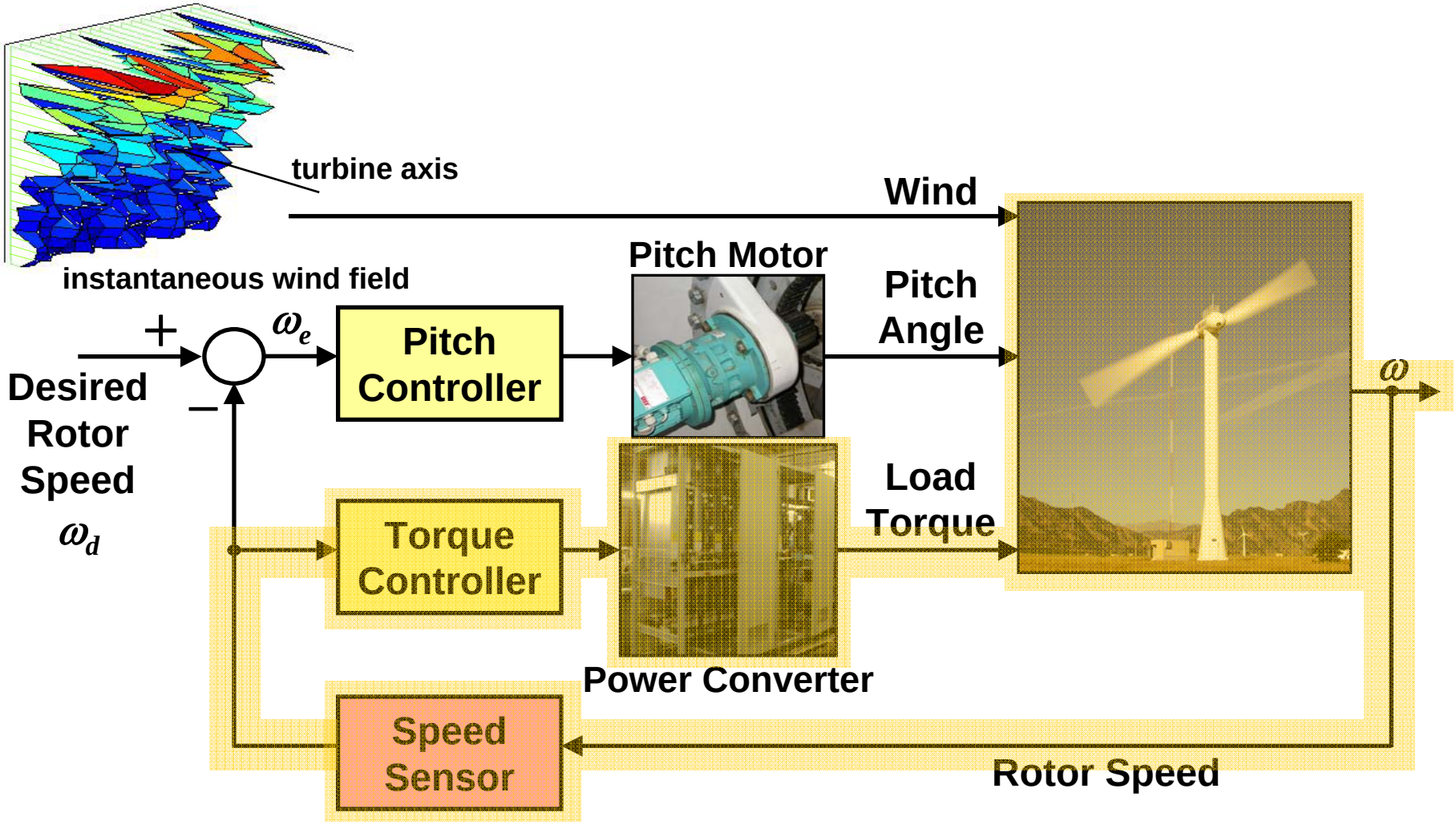

“Standard” Torque Control

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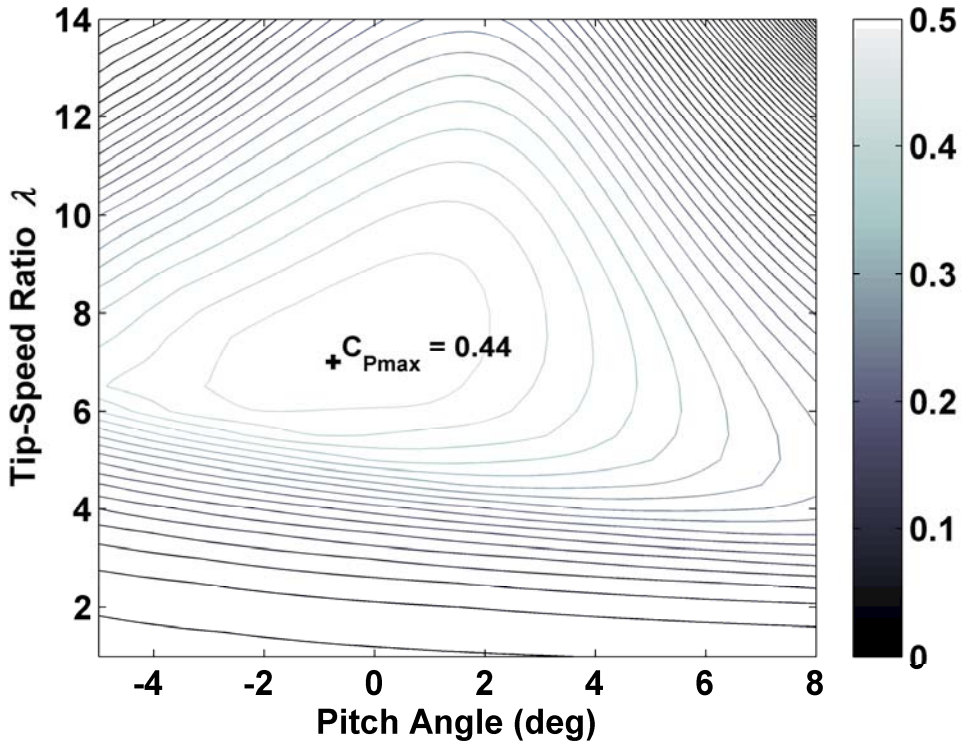
Tip-speed ratio: $\lambda = \dfrac{\omega R}{w}$

$$\tau_c = K\hat{\omega}^2$$

$$K = \frac{1}{2}\rho\pi R^5 \frac{C_{p_{\max}}}{\lambda_*^3}$$



- τ_c = generator (control) torque
- $\hat{\omega}$= measured rotor speed
- ρ = air density
- R = rotor radius
- C_{Pmax} = maximum power coefficient
- λ_* = optimum tip-speed ratio

Torque Control: Perfect Measurements

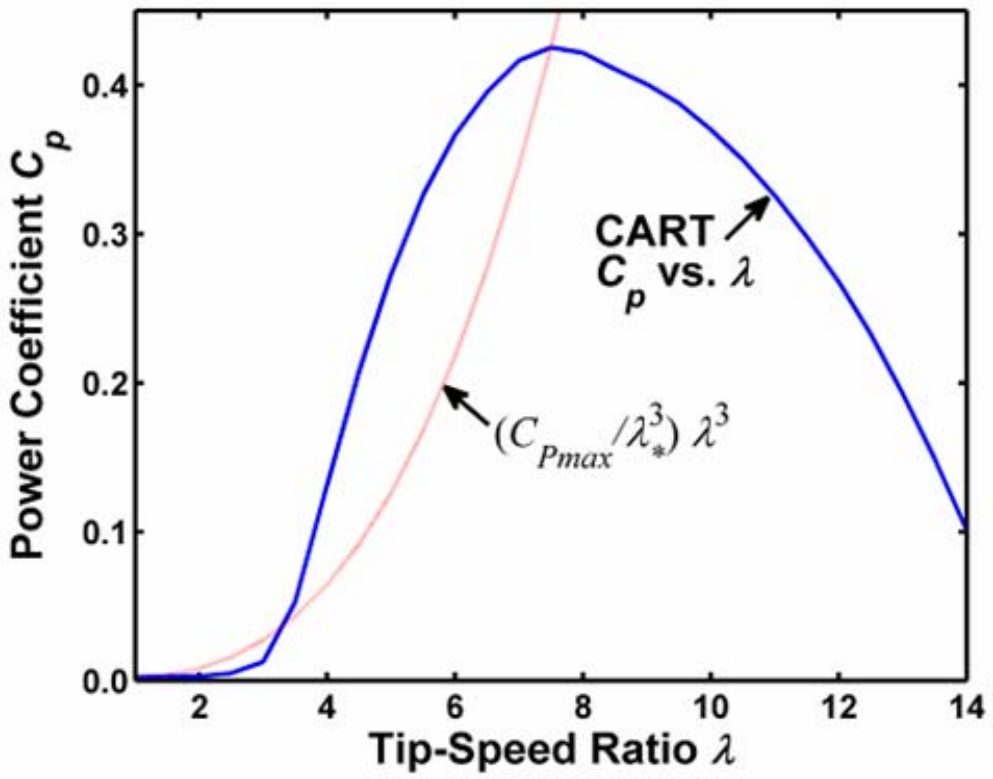
- When measurements are perfect and turbine is perfectly modeled, "standard" torque control leads to optimal operation in the steady-state

$$\dot{\omega} = \frac{1}{J}\left(\tau_{aero} - \tau_c\right)$$

$$\dot{\omega} = \frac{1}{2J}\rho\pi R^5 \omega^2 \left(\frac{C_p}{\lambda^3} - \frac{C_{p_{\max}}}{\lambda_*^3}\right)$$

$$C_p < \frac{C_{p_{\max}}}{\lambda_*^3}\lambda^3 \quad \Rightarrow \quad \dot{\omega} < 0$$

$$C_p > \frac{C_{p_{\max}}}{\lambda_*^3}\lambda^3 \quad \Rightarrow \quad \dot{\omega} > 0$$



Torque Control Summary

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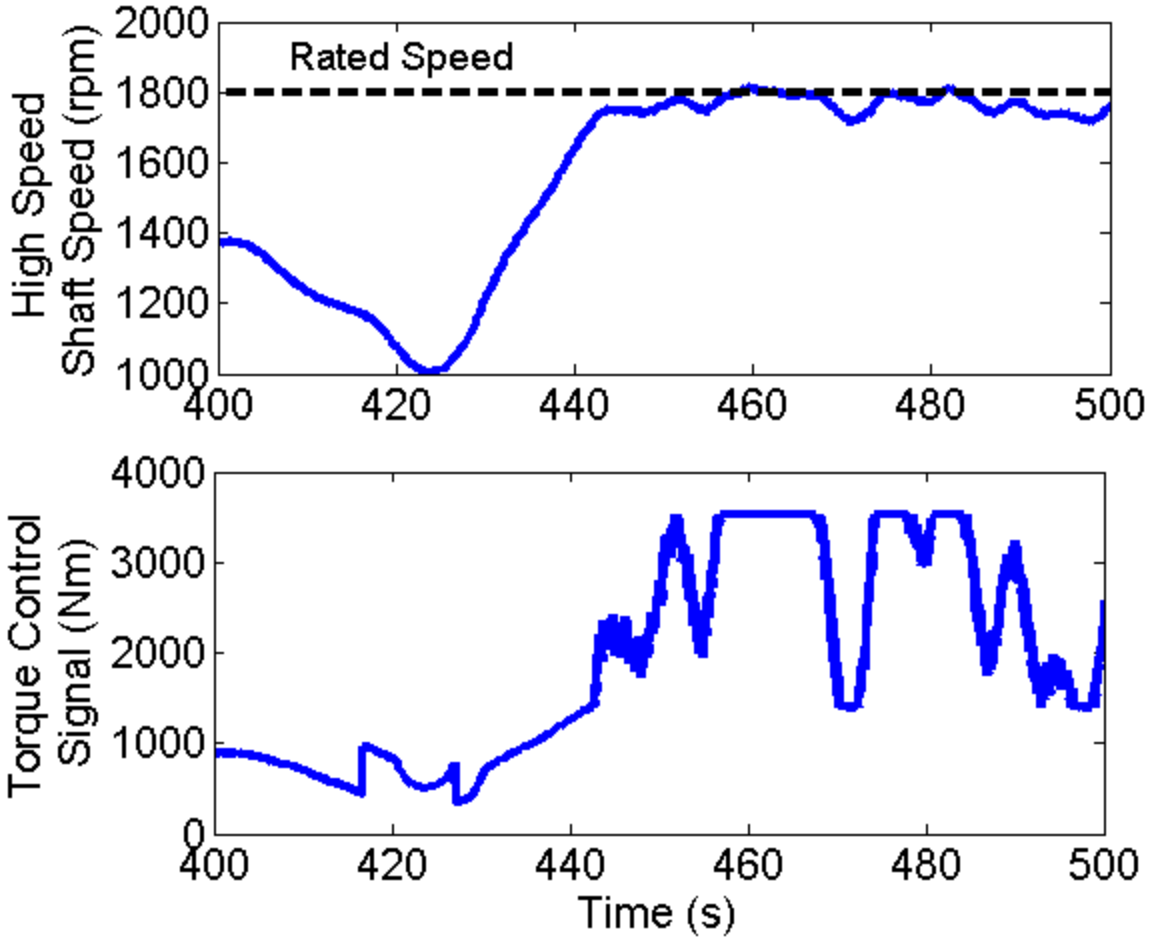
- Data from CART2
- Key features of standard torque control
  - Nonlinear
  - Only required measurement is rotor speed
  - Saturates at rotor speeds near rated
- Speed regulation achieved via pitch control



Pitch Control

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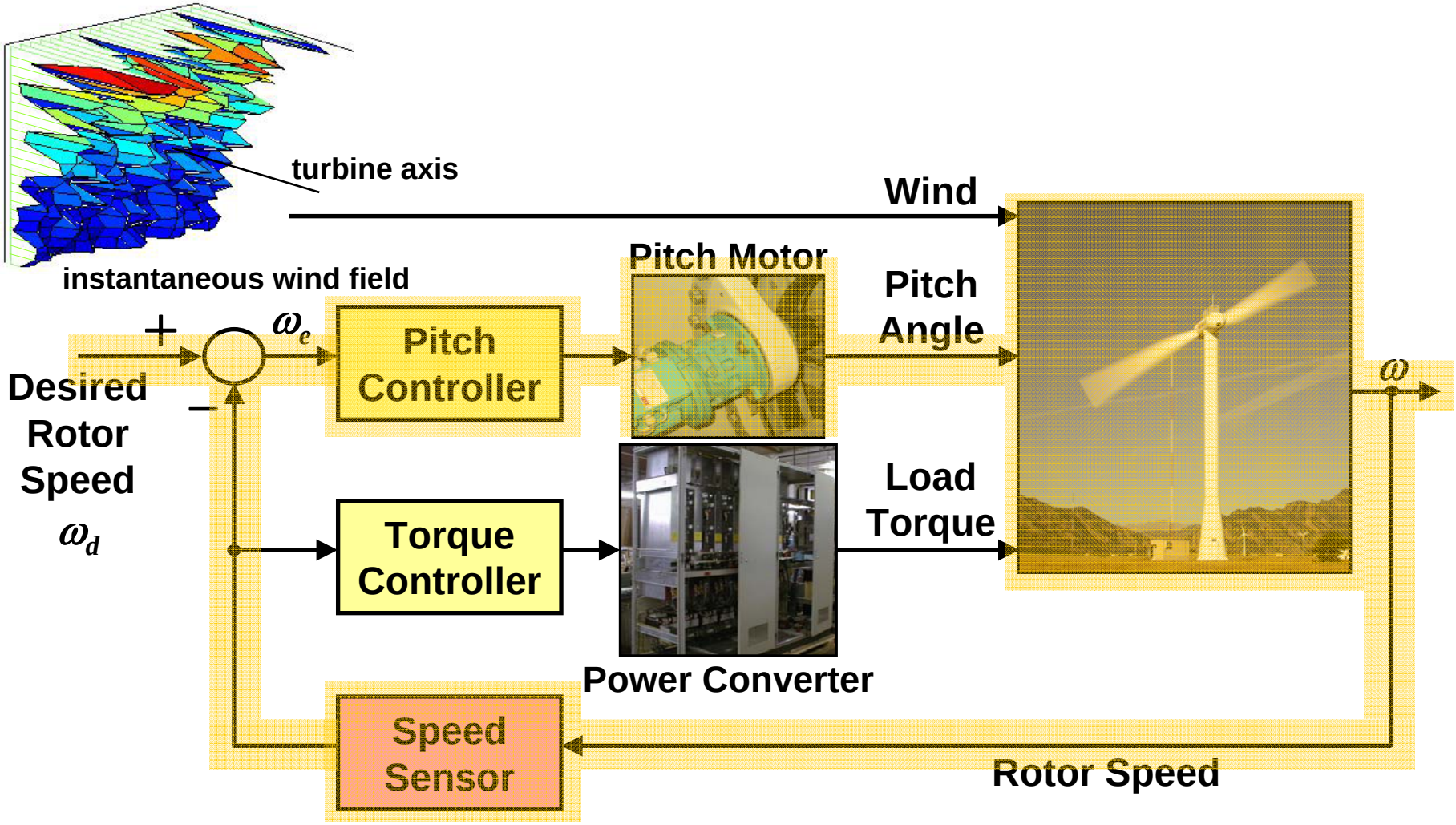
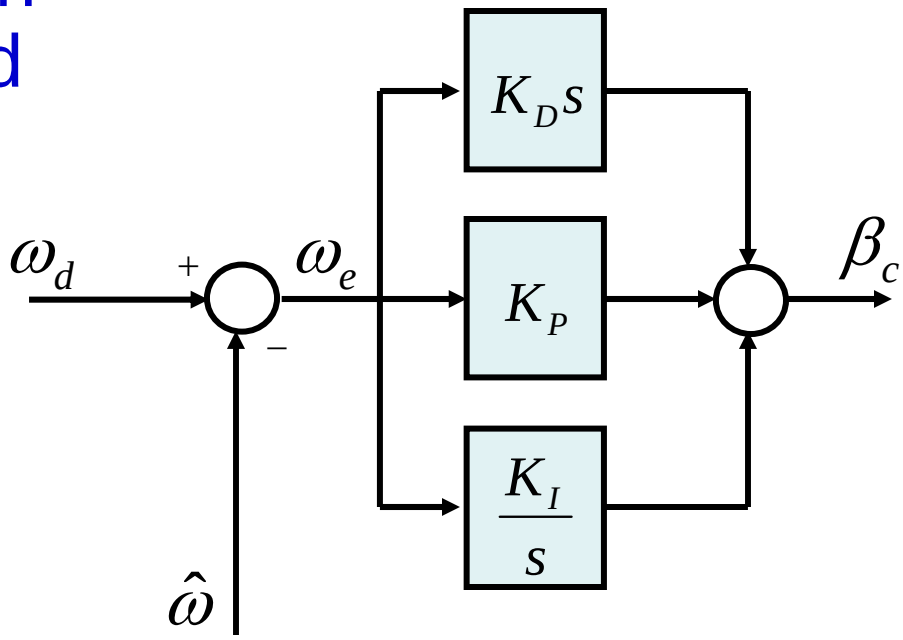


PID Pitch Control

- Speed regulation at high winds typically achieved using PID pitch control

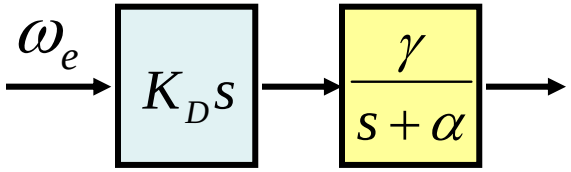


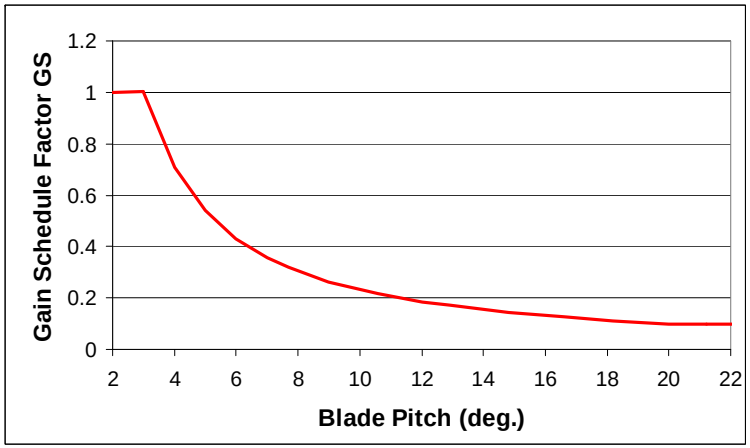
  - ω_e = error in rotor speed
  - ω_d = desired rotor speed
  - β_c = control pitch angle

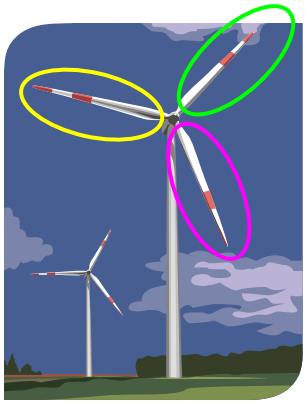
- Pitch rate actuation limits may be up to 8 deg/s

Pitch Control Variations

- Derivative term may be filtered to reduce measurement noise errors
- K_P, K_I, and K_D may be gain scheduled due to system nonlinearities
- Pitch control signal can be given as angle or rate of change
- Pitch control may be collective or independent
  - MIMO control options available







Pitch and Torque Control

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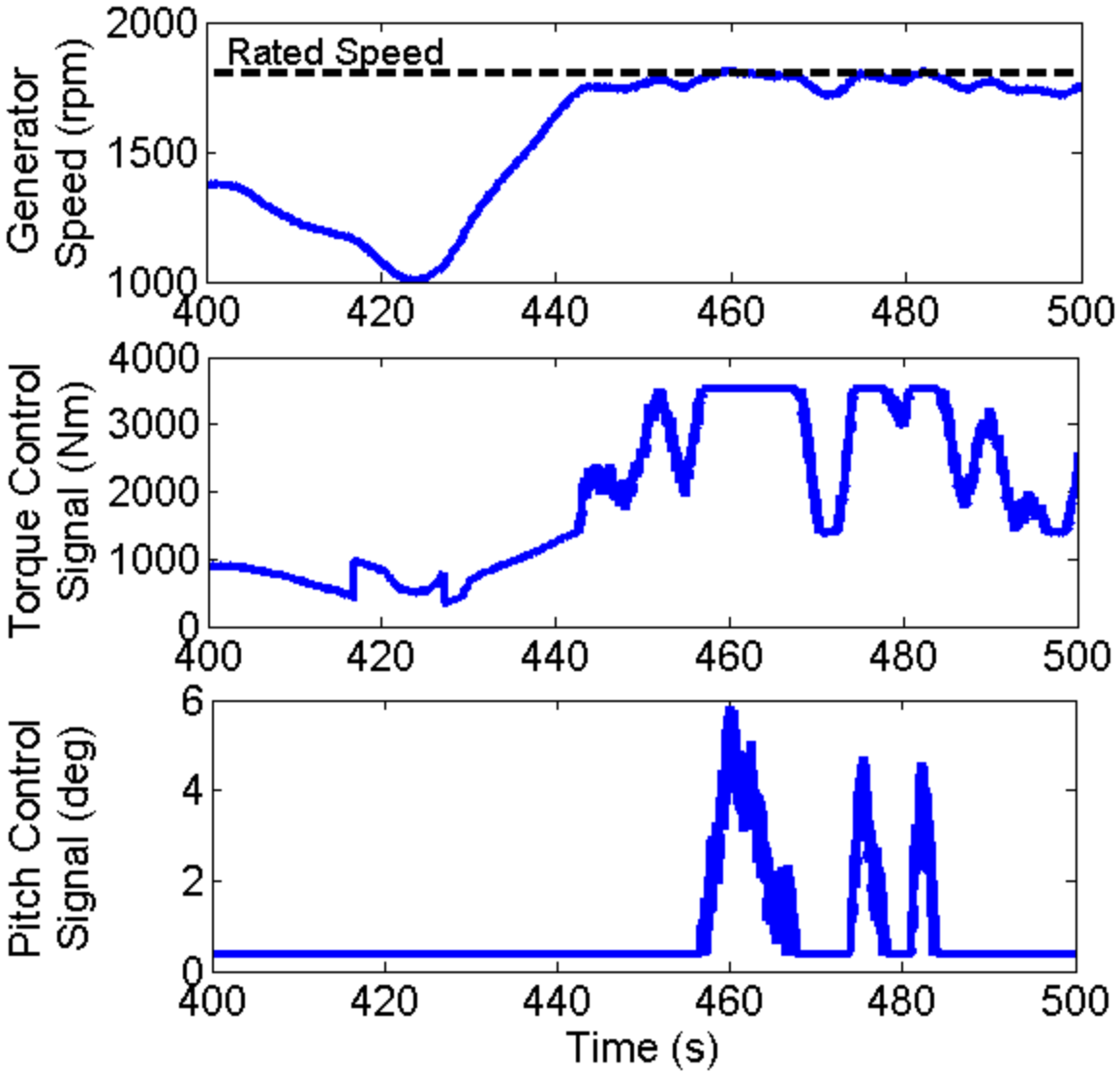
- Pitch control saturated below rated
  - Saturation value chosen to optimize energy capture
- Pitch and torque control loops complement each other



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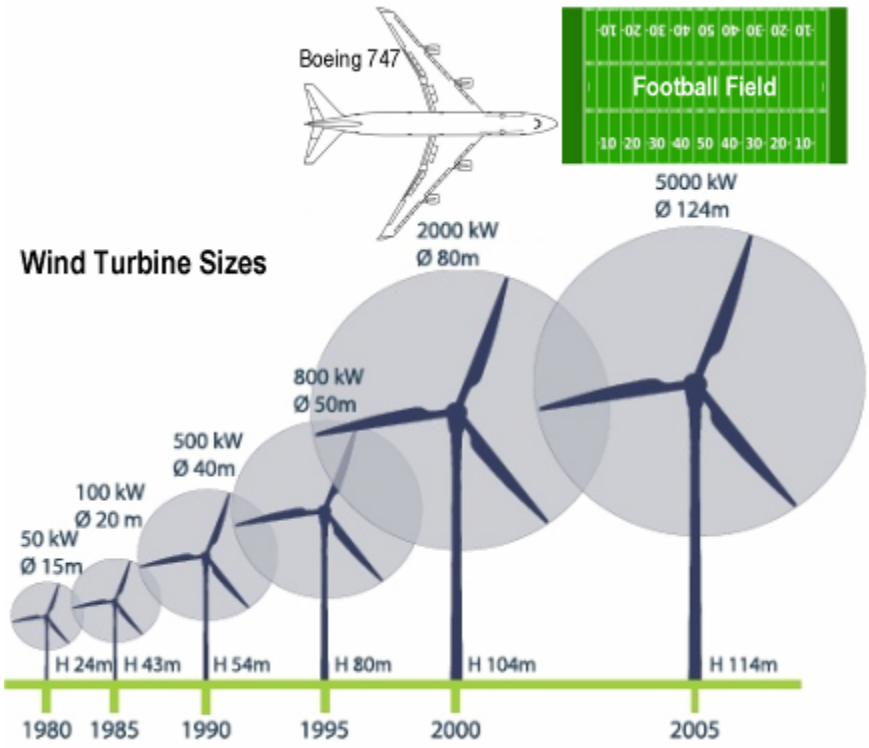
- Issues in Turbine Control
  - Size
  - Multiple control loops
  - Control while stopped
  - Modeling inaccuracies
- Advanced Turbine Control
- Wind Farms
- Offshore Wind
- Conclusions

Increasing Turbine Size

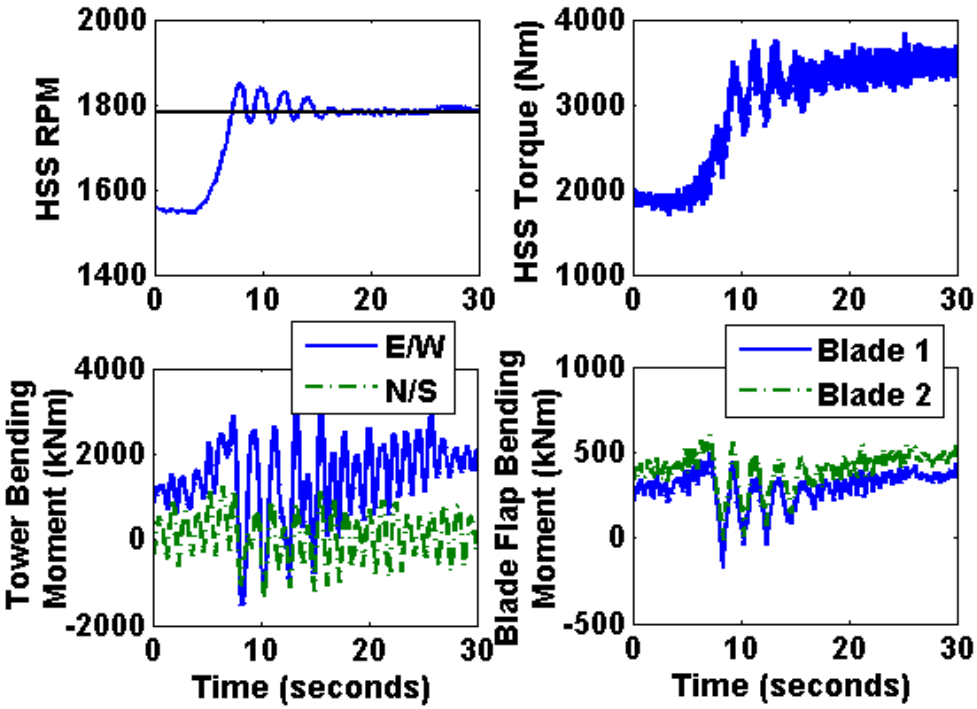
- Increased flexibility may lead to structural vibrations
  - Tower motion (fore-aft and side-to-side)
  - Drive train torsion
  - Blade bending and twisting
- Rotor is larger than some "coherent" wind turbulence structures
  - Requires individual blade pitch control



[diagrams and schematic from www.renewableenergy.no, www.aerospaceweb.org/aircraft/jetliner/b747, and en.wikipedia.org/wiki/American_football]

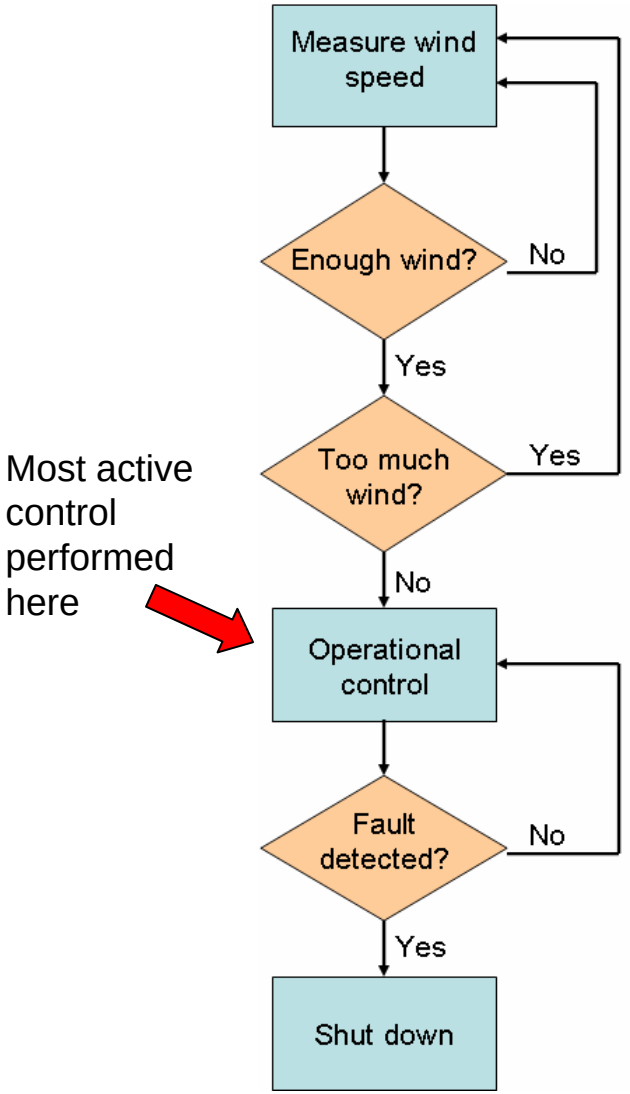
Multiple Control Loops

- Transition between regions 2 and 3 sometimes leads to maximum turbine loads
- Switching between torque and pitch control may exacerbate problem
- CART2 field data during a bad transition:



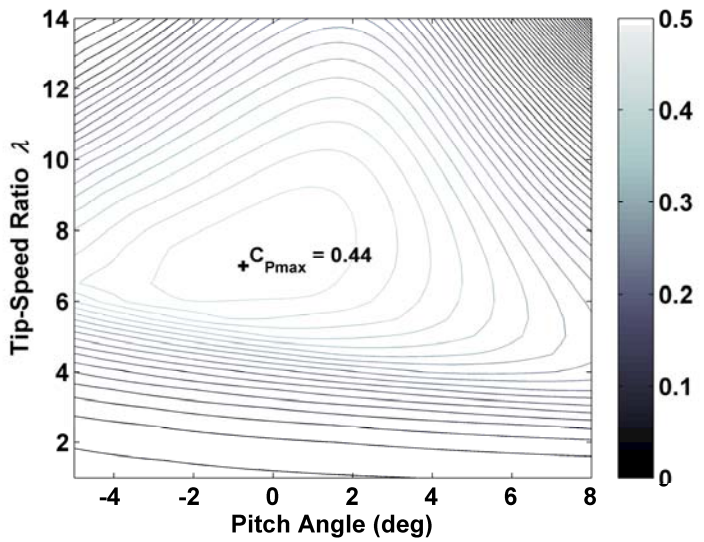
Control while Stopped

- Supervisory control may stop turbines due to faults or high winds
- Little active control usually performed while stopped
  - Yaw control may still be performed to point turbine into the wind
- Extreme loads may occur during "parked" conditions, usually in high winds
- Fault detection and health monitoring are also of interest



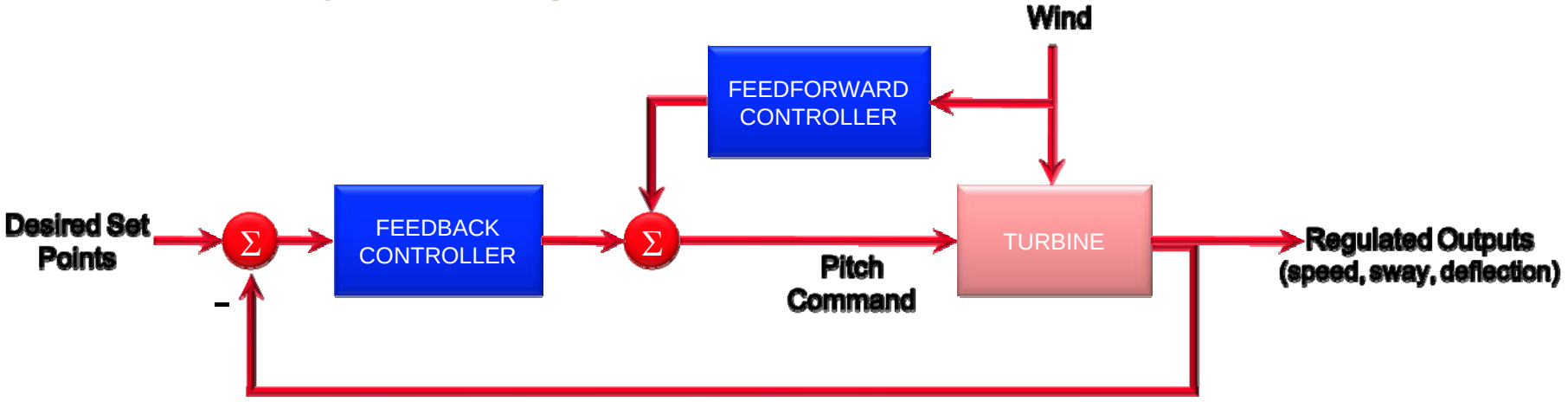
Modeling Inaccuracies

- Torque control assumes perfect knowledge of the turbine's C_p surface
  - Errors can be costly
- Effect of a 5% modeling error in the optimal tip speed ratio
  - Energy loss of around 1% - 3% in Region 2
  - Assume we reach DOE's 20% Wind Energy by 2030 goal
    - requires ~300 GW of installed capacity
  - Assume the cost of energy is $0.03 per kilowatt-hour (kWh)
  - Thus, a 1% loss of energy is equivalent to a loss of $630 million per year



Advanced Control Strategies

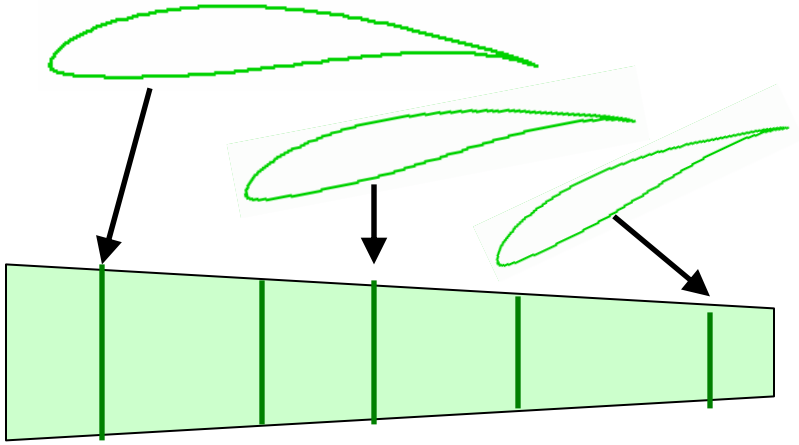
- Adaptive control
- Feedforward control
  - Using wind speed estimates
  - Using wind speed measurements



- Lots of others under development

Advanced Blades

- New configurations and actuators under development
  - Multiple pitch actuators per blade
    - Will allow different pitch angles at different radial positions
  - Microtabs
    - Will change aerodynamic forces
  - Air valves
    - Will change aerodynamic forces
- Advanced blade concepts will likely require new control systems



Multiple pitch actuators per blade

Microtabs (not to scale)

Outline

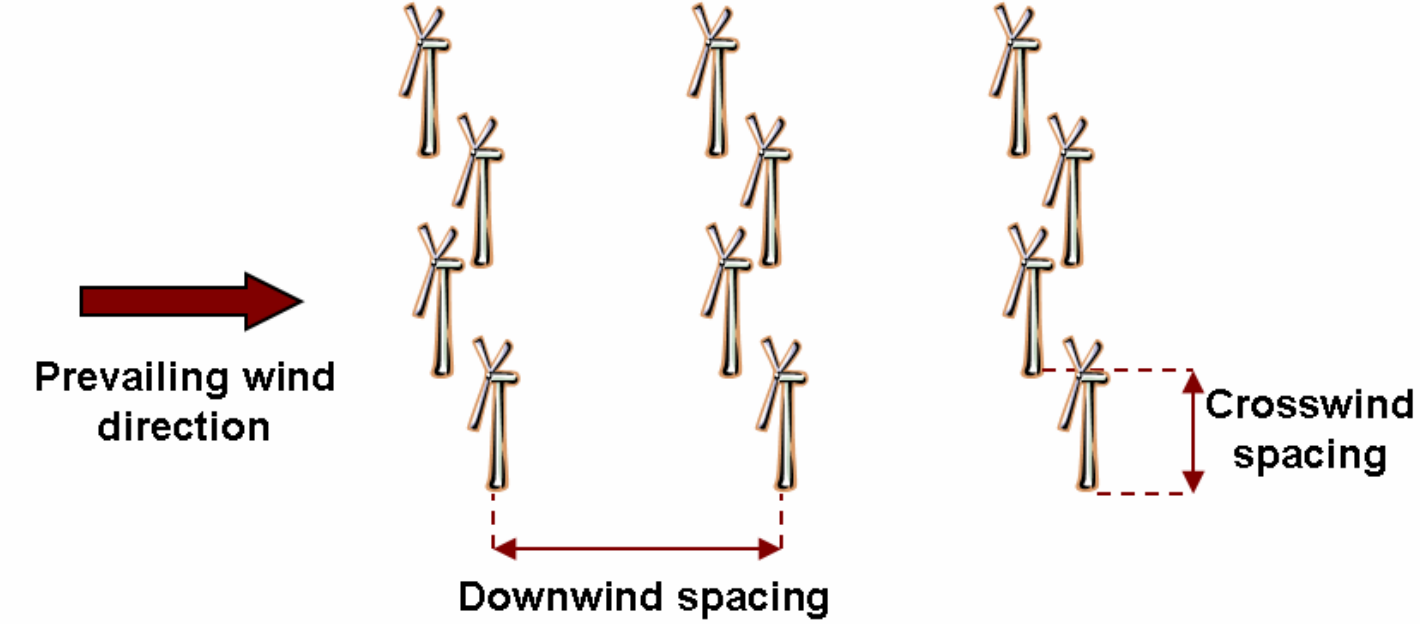
- Motivation and Wind Turbine Basics
- Wind Turbine Control Loops
- Issues in Turbine Control
- Advanced Turbine Control
- Wind Farms
- Offshore Wind
- Conclusions

Wind Farm Considerations

- Wind farms can take advantage of economies of scale
- May differ from individual turbines in
  - noise
  - safety
  - visual
  - environmental effects

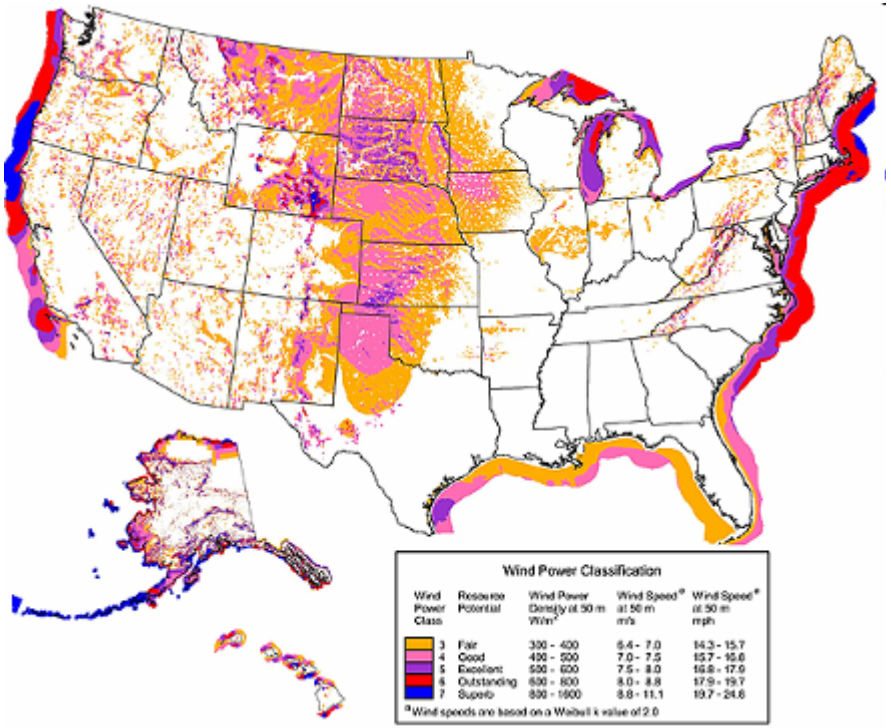
Wind Farm Layouts and Control

- Control focuses
  - Electricity
  - Aerodynamics
- Control goal is to maximize "array efficiency" given existing configuration



Offshore Wind Motivation

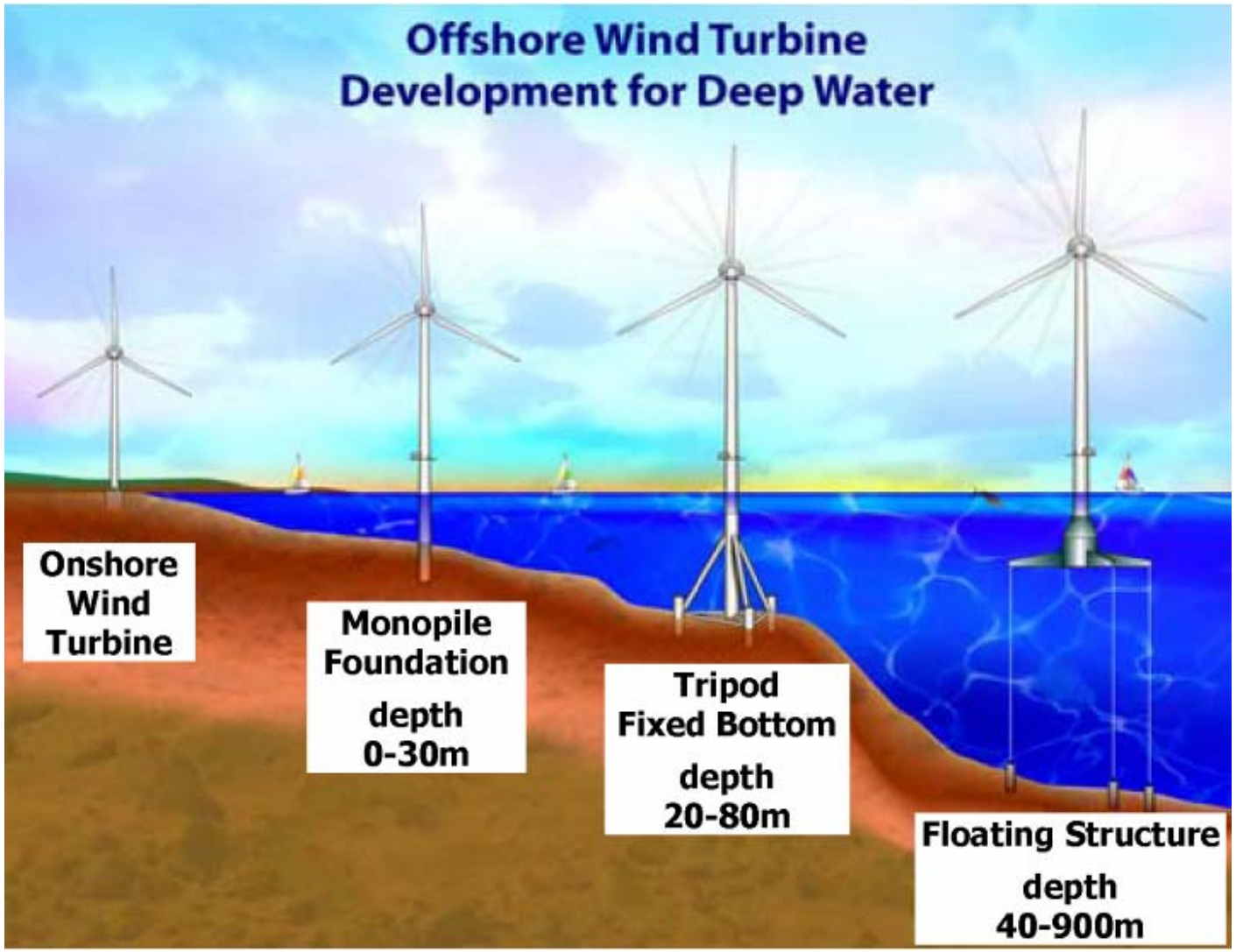
- Advantages to offshore wind
  - Wind resource typically higher and more consistent
  - Turbine size is not limited by transportation constraints
  - Visual and noise effects can be avoided more easily
  - More area available, especially near population centers



Offshore Wind Turbine Configurations

Partners in the Colorado Renewable Energy Collaboratory's Center for Research and Education in Wind

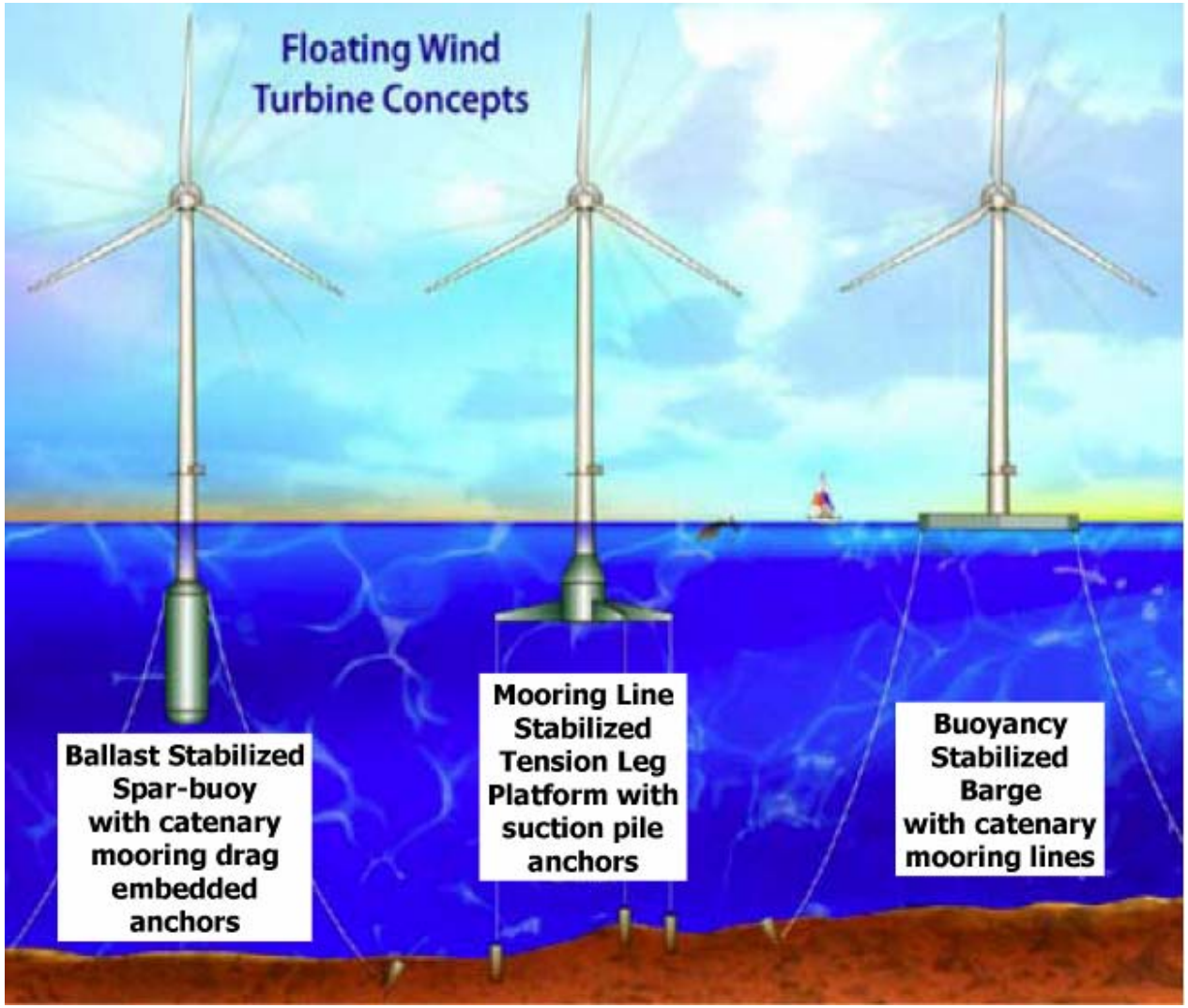
U.S. has relatively more deep water near the shoreline than Europe, so more floating turbines are likely in the U.S.



[Image courtesy of NREL]

Floating Platforms

- Floating platform configurations have been borrowed from offshore oil rig technologies



[Image courtesy of NREL]

Offshore Wind Challenges

- Waves can excite structural modes for both floating and fixed offshore turbines
- Deep water anchors are expensive
  - U.S. has more deep water near population centers than Europe
- What is the best way to control a floating inverted pendulum with a large spinning mass at its top?
  - What actuators are necessary?
  - How will control affect the energy capture?

Graphic courtesy of NREL

Conclusions

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- Large, flexible turbines lend themselves to control solutions, and turbines are getting larger and more flexible
- Existing turbine controllers tend not to take advantage of the wealth of available control theory
  - Industry has been slow to adopt advanced control strategies for both individual turbines and wind farms
- Offshore wind turbine control is a big prospective area for research