Disturbance Accommodating Adaptive Control with Application to Wind Turbines

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December 5, 2012

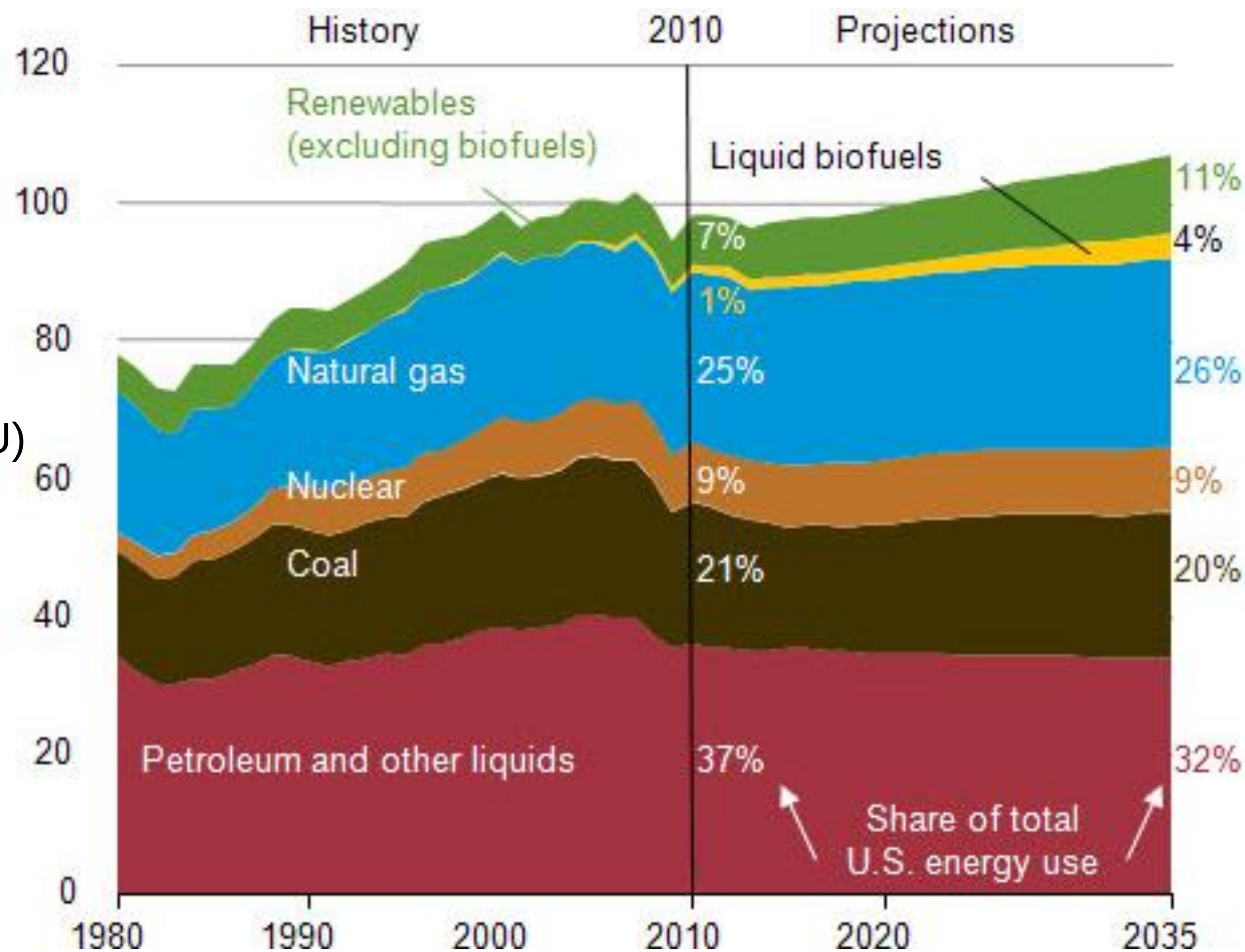
Outline

- Why wind energy
- Advances and challenges
- Wind turbine control
- Disturbance accommodating adaptive control
- Residual mode filters for flexible structure control
- Application to wind turbine control
- Adaptive contingency control using system health information for wind turbines

Why wind energy?

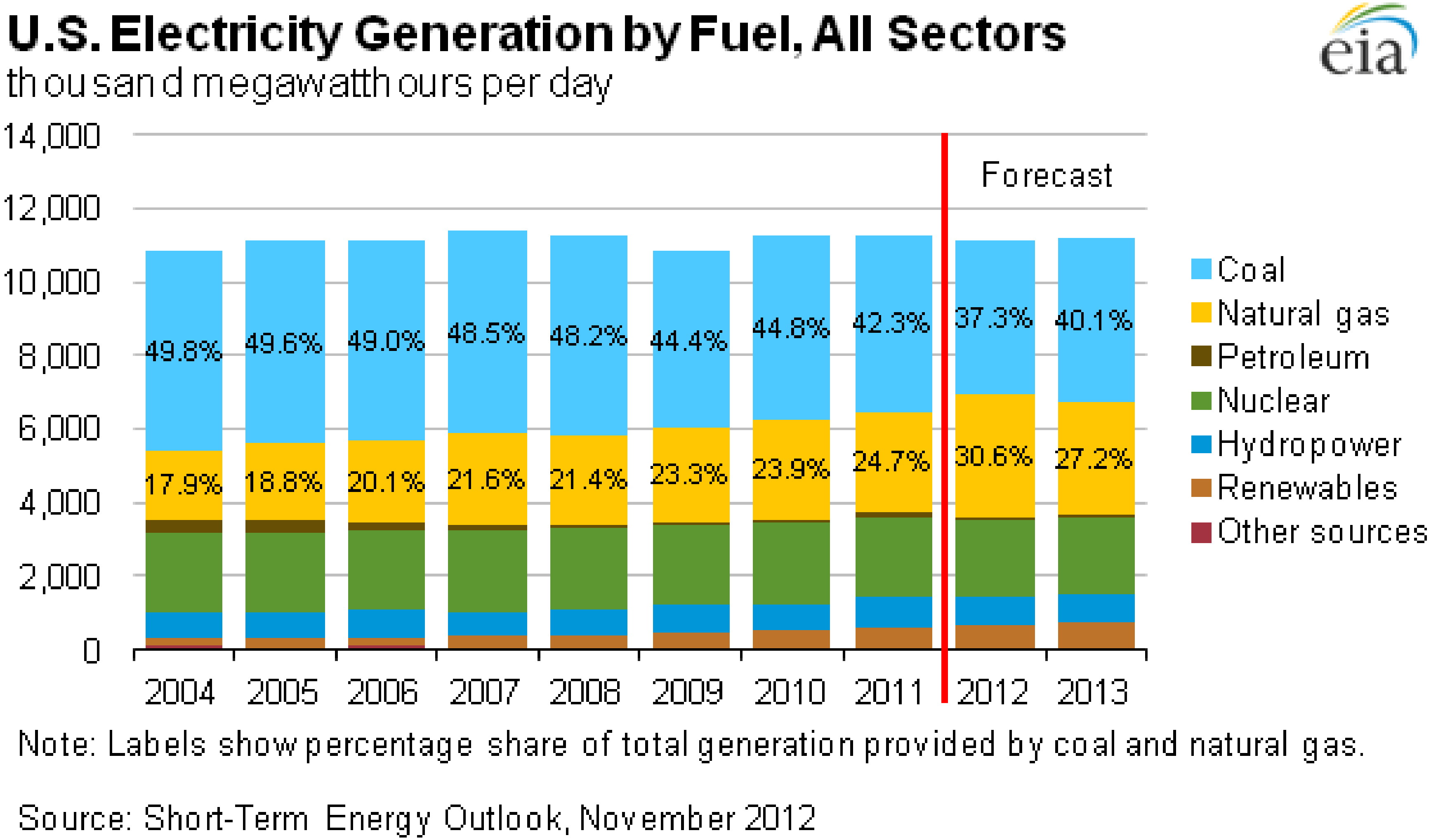
Primary energy use by fuel in U.S.

Fuel Use
(x 10^{15} BTU)



EIA (US Energy Information Association)

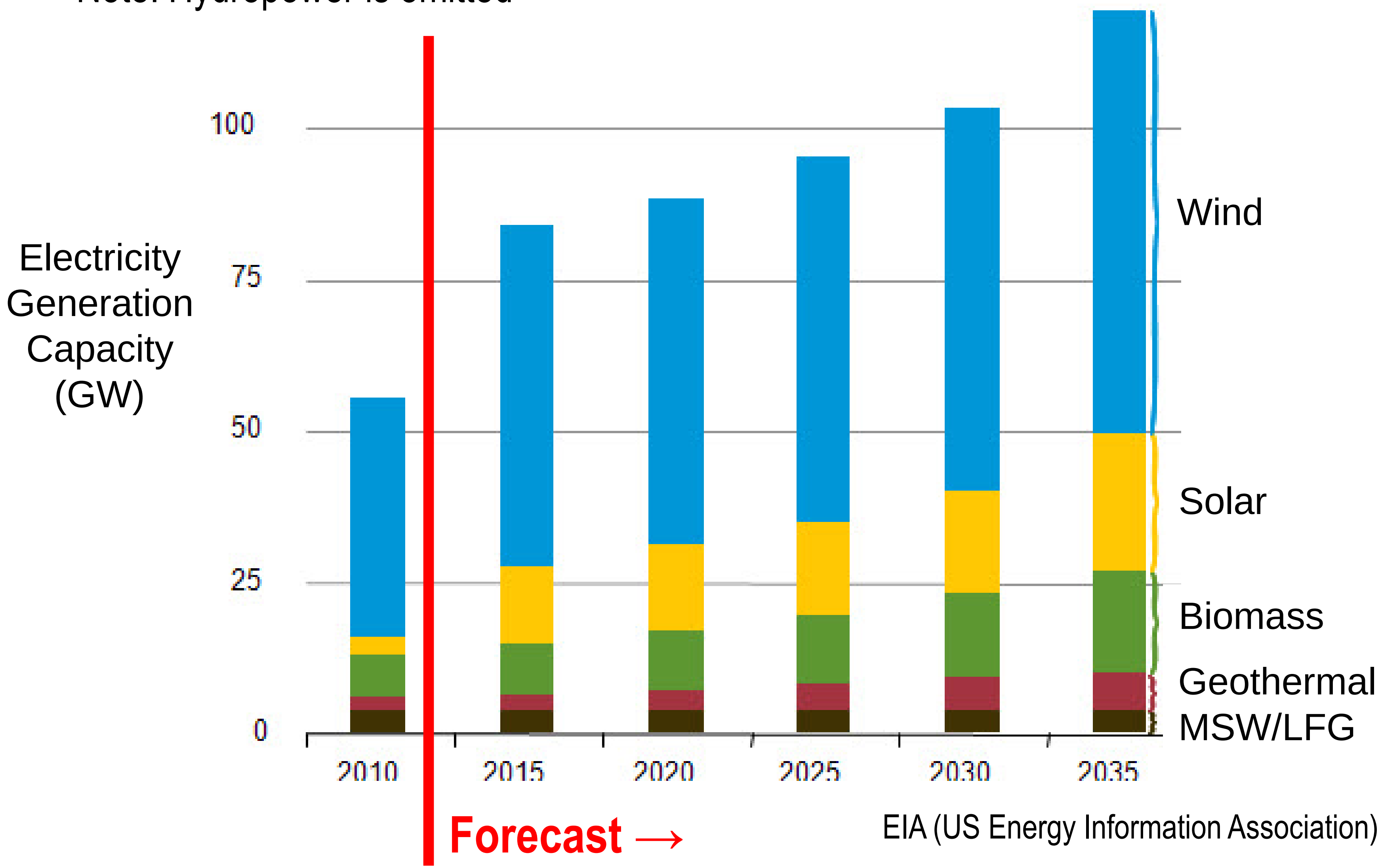
US electricity generation by fuel



EIA (US Energy Information Association)

Renewable electricity generation capacity

Note: Hydropower is omitted



EIA (US Energy Information Association)

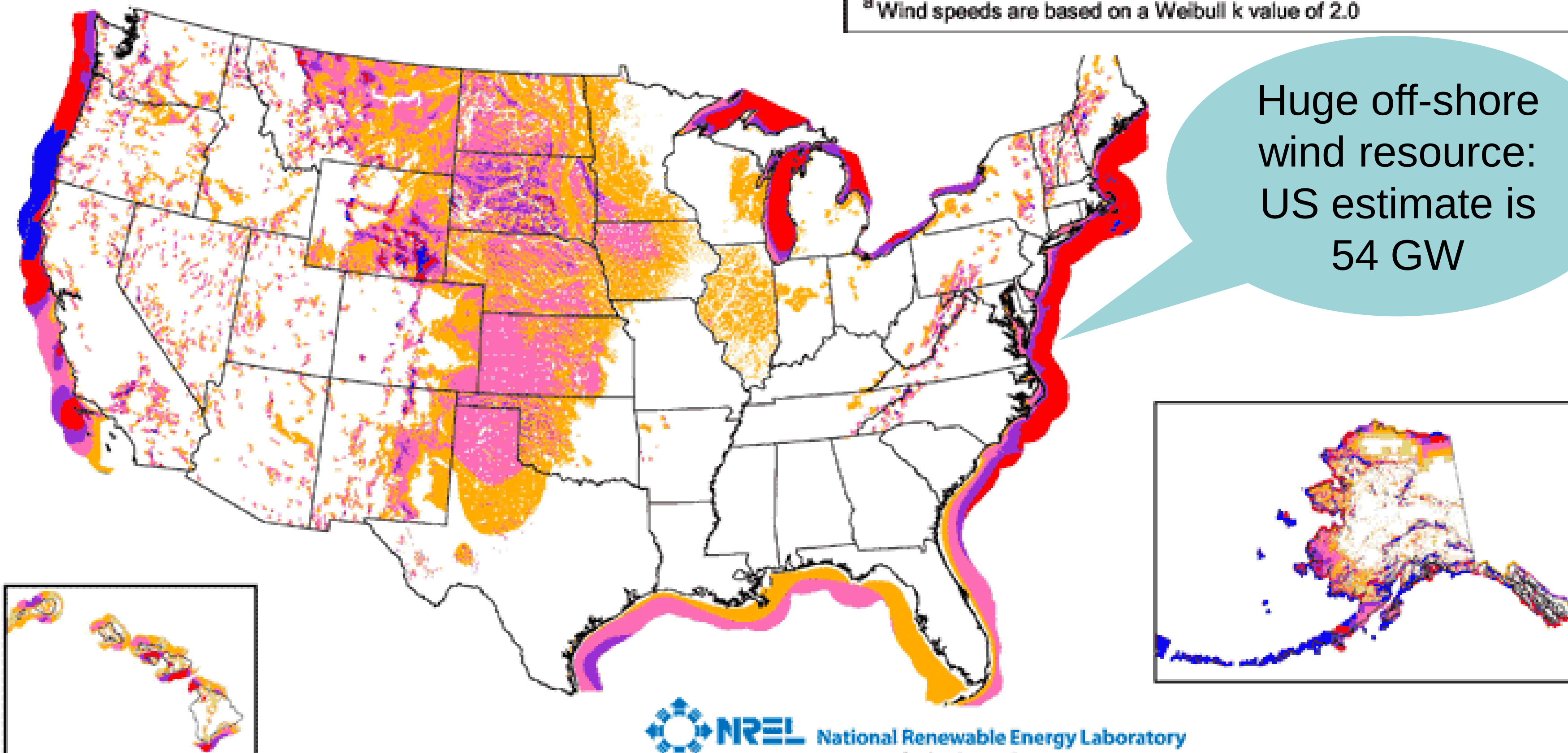
Wind power resources in U.S.

- Class 4 or higher wind suitable for utility-scale turbines
- Class 3 areas could have higher wind power at 80 meters

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m^2	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

[a] Wind speeds are based on a Weibull k value of 2.0

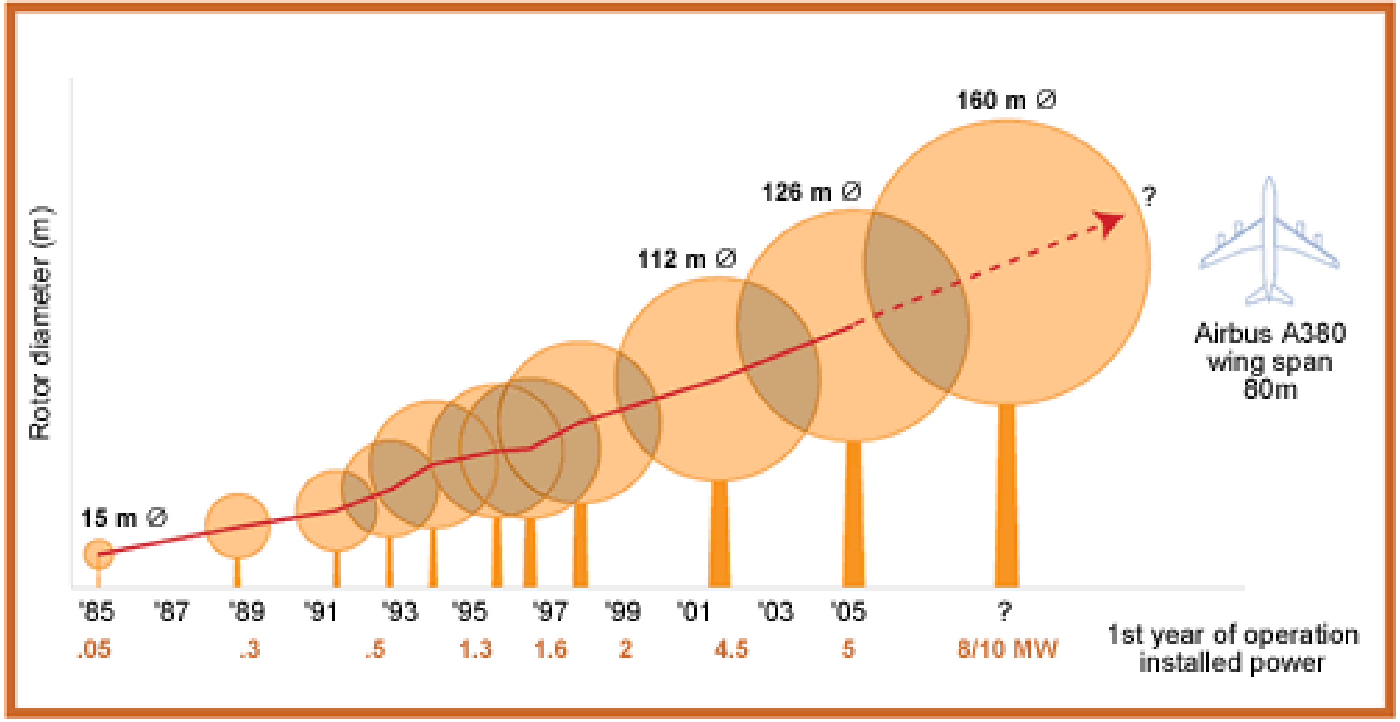


Huge off-shore wind resource: US estimate is 54 GW

NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Evolution of wind turbines

Turn of the Century Wind Mill



Source: www.owenscorning.com

- Wind speed can increase by 20% with 10 m increase in height
- Largest turbine in production is 126 meter diameter (5 MW)
- Wind power is proportional to rotor area times wind speed cubed

Wind industry observations

Decreasing Cost of Energy

(~$0.40/kW-hr in 1979

~$0.07/kW-hr in 2010)

- R&D Advances
- Increased Turbine Size
- Manufacturing Improvements
- Large Wind Farms

Wind Industry Challenges

- Building large turbines (>5 MW)
- Developing off-shore turbines
- CFD models of turbine interactions
- Operating & maintenance costs
- Turbine reliability
- Grid integration
- Community noise
- Wind farm siting
- Unstable public policy

Why wind energy?

US Energy Needs

- Aging nuclear plants
- Reduce fuel emissions
- Protect fossil fuel sources for future generations
- Mitigate reliance on foreign energy sources
- Stability of electricity prices
- Comply with mandates
- Increase reliability of electric generation and distribution

Wind Energy Capabilities

- Becoming cost competitive with fossil fuels
- Clean, renewable energy
- Significant wind energy resources
- Encourages rural economic development
- Dual use land – ranching or oil/gas recovery and wind farms

Public support of wind energy is strong in most places

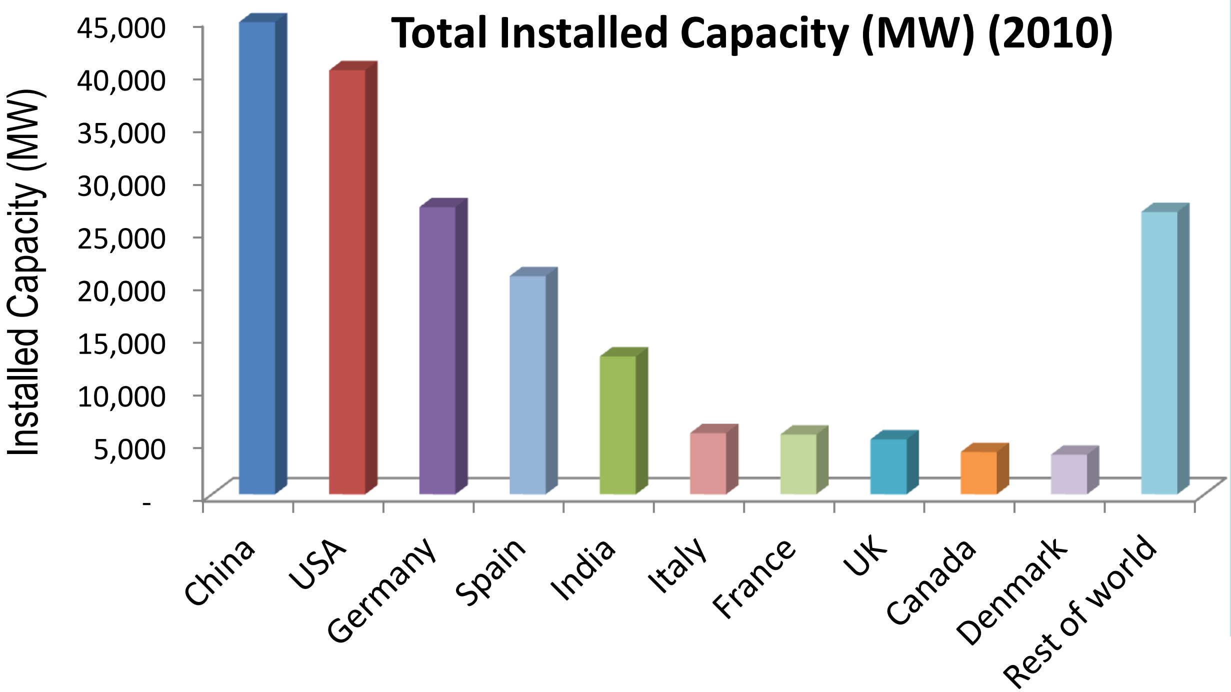
Wind power capacity

- **Name plate capacity:** maximum power output of a turbine
- **Installed capacity:** sum of nameplate power rating of all turbines installed during a specific time period or geographic area
- **Capacity factor:** indicator of how much power a particular turbine will make in a specific location
- Typical wind power capacity factors are 20-40%

U.S. Statistics for End of 2010 (AWEA)

- 40,180 megawatts (MW) total installed capacity in US
- Average nameplate capacity was 1.67 MW for new turbines
- Over 5,115 MW installed capacity in 2010

World installed capacity (Dec 2010)



Capacity Installed in 2011

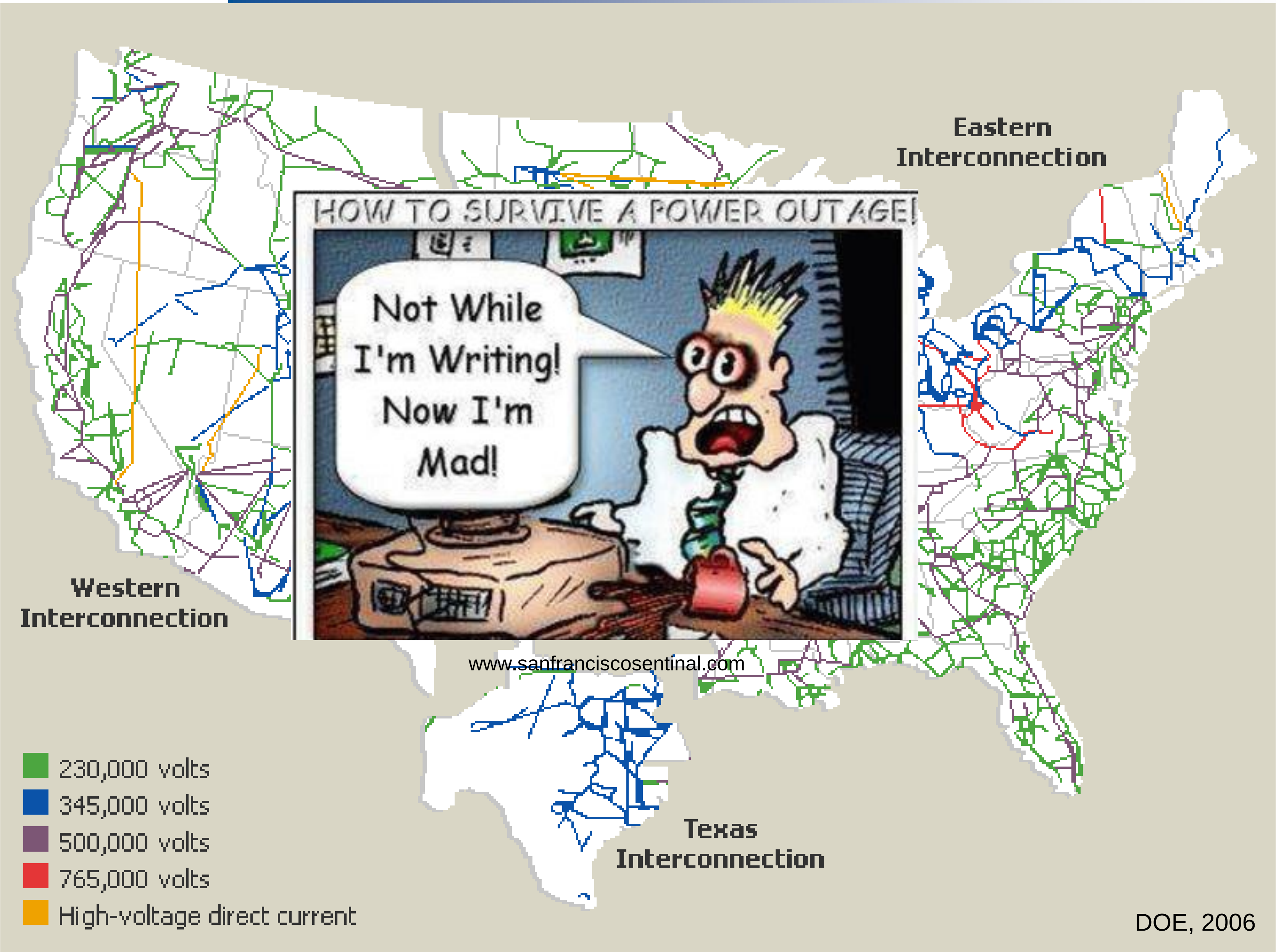
Country	MW
PR China	17,631
USA	6,810
India	3,019
Germany	2,086
UK	1,293
Canada	1,267
Spain	1,050
Italy	950
France**	830
Sweden	763
Rest of the world	4,865
Total TOP 10	35,699
World Total	**40,564**

Source: GWEC

Wind Power Penetration - End of 2010

- Denmark 21%
- Portugal 18%
- Spain 16%
- Ireland 14%
- Germany 9%
- U.S. 2.5%

U.S. transmission grid as of 2006



Utility-scale horizontal axis wind turbine (HAWT)

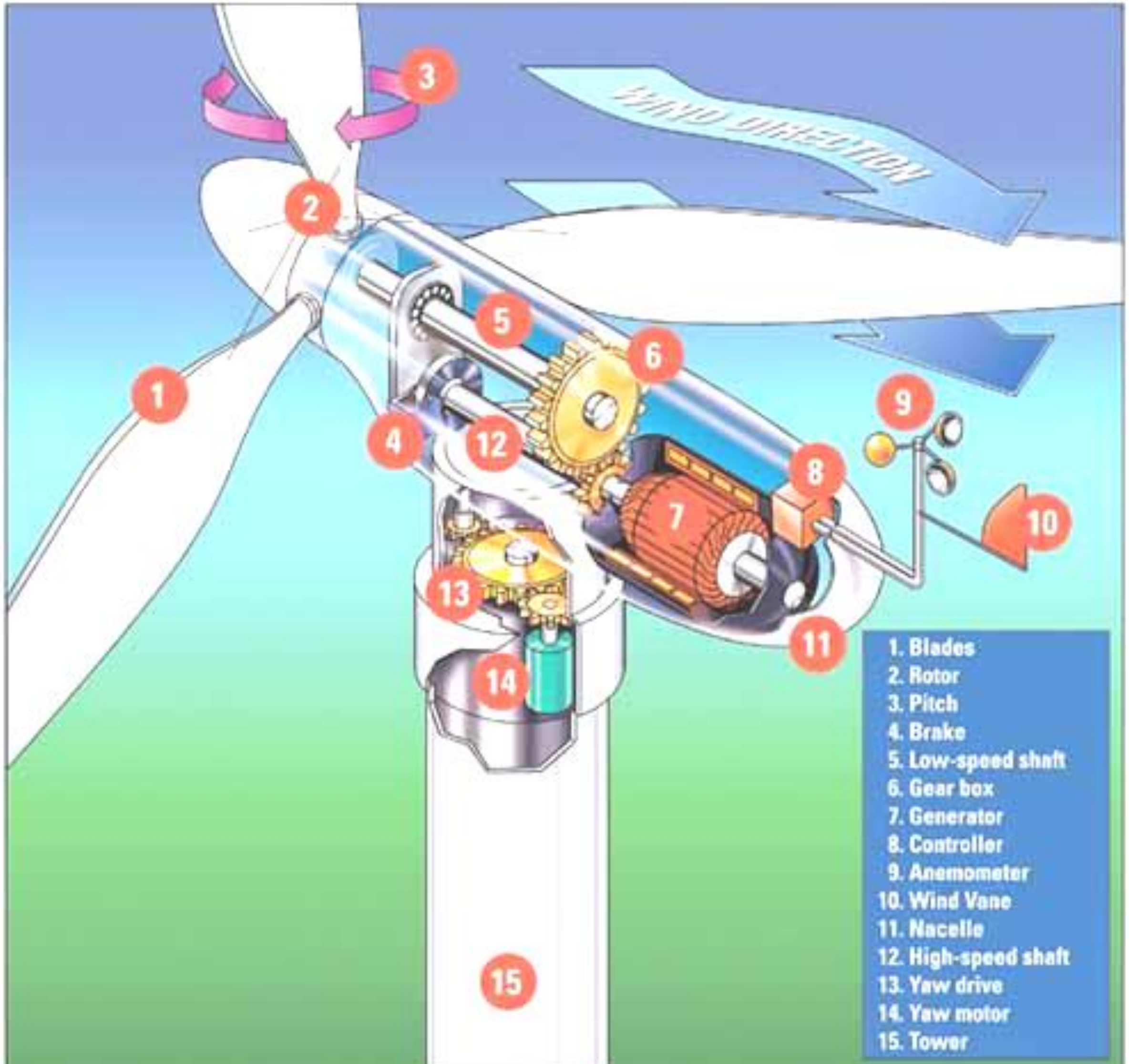
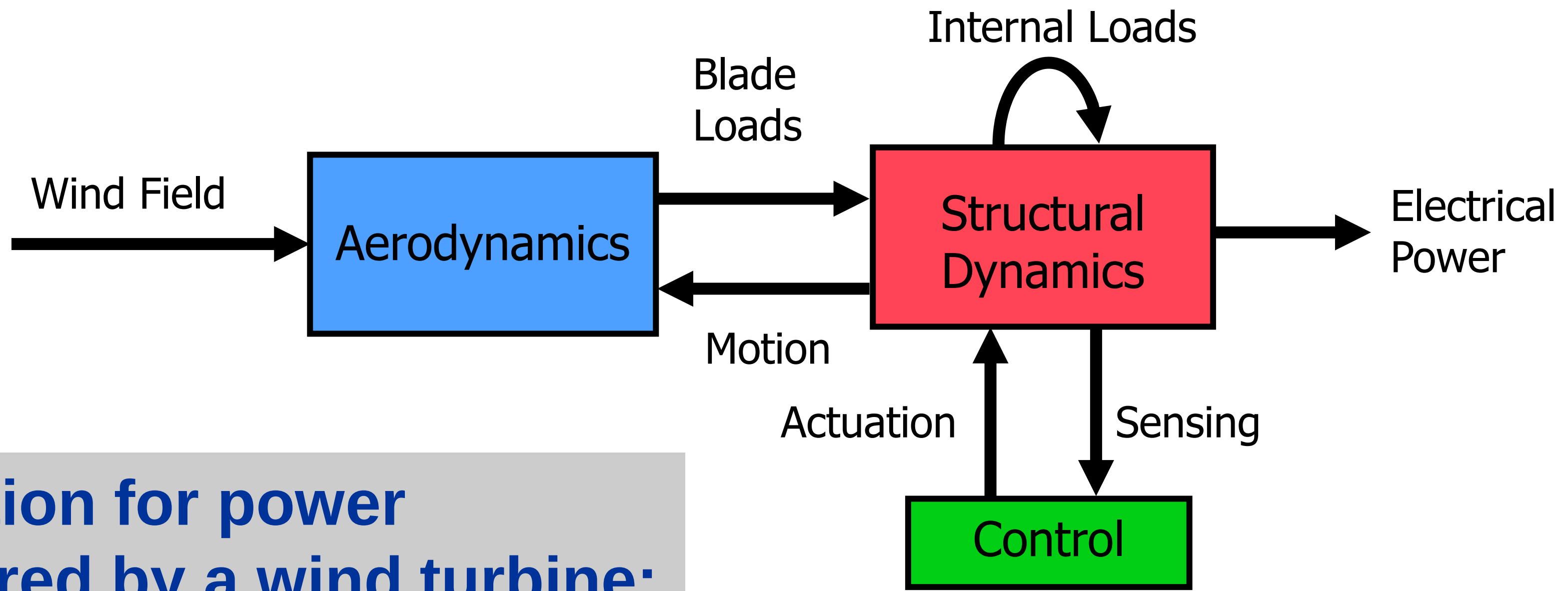


Image: NWTC, NREL

Utility-Scale HAWT's

- Rotor Diameter:
  - 40-95 m Onshore
  - 90-114 m Offshore
- Tower: 25-180 meters
- Capacity:
  - 0.1-3 MW Onshore
  - 3-6 MW Offshore
- Start up wind speed:
  4-5 mps
- Max wind speed:
  22-26 mps
- Low speed shaft:
  30-60 RPM
- High speed shaft:
  1000-1800 RPM



Equation for power captured by a wind turbine:

$$P = \tfrac{1}{2}\rho A C_p(\lambda, \beta)\omega^3$$

$\rho \equiv$ air density

$A \equiv$ rotor swept area

$C_p \equiv$ power coefficient

$\beta \equiv$ blade pitch angle

$\lambda \equiv$ tip-speed ratio $\equiv \dfrac{\text{speed of blade tip}}{\text{wind speed}}$

$\omega \equiv$ wind velocity

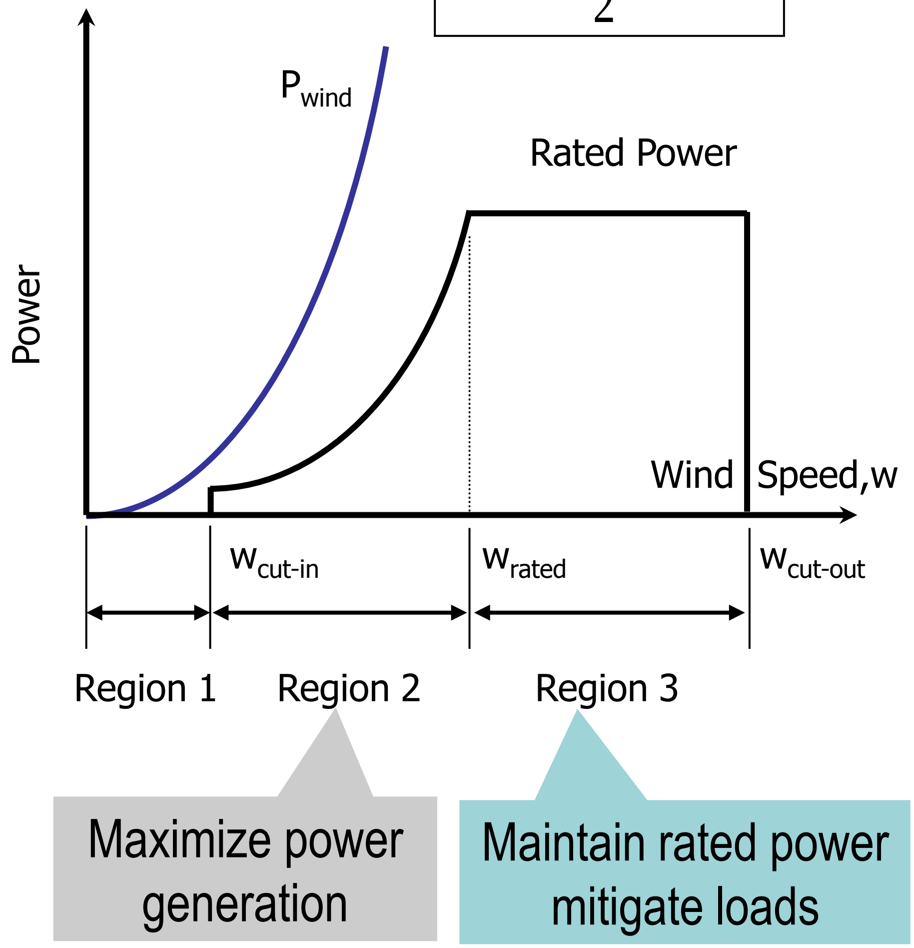
Operating regions & control strategies

Control Objectives:
- Reduce cost of wind energy
- Enhance power capture
- Mitigate turbine loads
- Maintain safe turbine operation

Region 2:
- Control generator torque to yield optimum power
- Hold blade pitch constant

Region 3:
- Control blade pitch to maintain constant rotor speed
- Generator torque held constant

$$P_{wind} = \frac{1}{2}\rho A C_P w^3$$



Wind turbine control and adaptive control

Why is control important?

- Future trends in wind turbines
  - Large multi-megawatt turbines
  - Increased likelihood of excitation of structural modes by highly turbulent flow
- Control can increase efficiency, uptime, and lifespan of turbines

What is adaptive control?

- Plant output is used to modify control law thereby responding to unmodeled plant dynamics, uncertain operating environment and time varying parameters

Benefits of adaptive control

- Provides good performance for poorly modeled plants with uncertain and quickly changing operating environments
- Controller is quick to design
- Controller is robust to slowly changing turbine parameters

Dynamical system definitions

- **Linear Time-invariant Plant:**

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \Gamma \mathbf{u}_D \\ \mathbf{y} = \mathbf{C}\mathbf{x}; \quad \mathbf{x}(0) = \mathbf{x}_0 \end{cases}$$

  - where plant parameters (A, B, C, Γ) are **unknown**

- **Disturbance Generator**:

$$\begin{cases} \mathbf{u}_D = \Theta \mathbf{z}_D \\ \mathbf{z}_D = \mathbf{L}\phi_D; \mathbf{z}_D(0) = \mathbf{z}_0 \end{cases}$$

  - where disturbance basis functions Φ_D are **known** but amplitude L is **unknown**

❖ Ex: Step disturbance: $\mathbf{u}_D = a_0 \cdot 1;\ \mathbf{z}_D = \mathbf{L}\phi_D$ where $a_0, \mathbf{L}$ are unknown and $\phi_D = 1$

- **Reference Model:**

$$\begin{cases} \dot{\mathbf{x}}_m = \mathbf{A}_m \mathbf{x}_m + \mathbf{B}_m \mathbf{u}_m \\ \mathbf{y}_m = \mathbf{C}_m \mathbf{x}_m;\ \mathbf{x}_m(0) = \mathbf{x}_0^m \\ \dot{\mathbf{u}}_m = \mathbf{F}_m \mathbf{u}_m;\ \mathbf{u}_m(0) = \mathbf{u}_0^m \end{cases}$$

  - where model is **stable** and model parameters are **known**

Disturbance accommodating adaptive control

- **Control Objective:** Cause plant output to asymptotically track reference model output while rejecting persistent disturbances
  - **Output error:** $\mathbf{e}_y \equiv \mathbf{y} - \mathbf{y}_m \xrightarrow[t \to \infty]{} 0$

- **Control Law:**

$$\mathbf{u} = \mathbf{G}_m \mathbf{x}_m + \mathbf{G}_u \mathbf{u}_m + \mathbf{G}_e \mathbf{e}_y + \mathbf{G}_D \phi_D$$

- **Controller Gains:**

$$\dot{\mathbf{G}} \equiv \begin{cases} \dot{\mathbf{G}}_u = -\mathbf{e}_y \mathbf{u}_m^T h_u \\ \dot{\mathbf{G}}_m = -\mathbf{e}_y \mathbf{x}_m^T h_m \\ \dot{\mathbf{G}}_e = -\mathbf{e}_y \mathbf{e}_y^T h_e \\ \dot{\mathbf{G}}_D = -\mathbf{e}_y \phi_D^T h_D \end{cases}$$

Model Matching Conditions

- Define **ideal trajectories** for plant:

$$(*)\quad \begin{cases} \dot{\mathbf{x}}_* = \mathbf{A}\mathbf{x}_* + \mathbf{B}\mathbf{u}_* + \Gamma \mathbf{u}_D \\ \mathbf{y}_* = \mathbf{C}\mathbf{x}_* = \mathbf{y}_m ; \mathbf{x}_*(0) = \end{cases}$$

where

$$\begin{cases} \mathbf{x}_* = \mathbf{S}_{11}^* \mathbf{x}_m + \mathbf{S}_{12}^* \mathbf{u}_m + \\ \mathbf{u}_* = \mathbf{S}_{21}^* \mathbf{x}_m + \mathbf{S}_{22}^* \mathbf{u}_m + \end{cases}$$

Matching conditions are necessary and sufficient for existence of ideal trajectories

Matching conditions exist if CB is nonsingular

- **Model Matching Conditions** are obtained by substituting ideal trajectories into $(*)$ above:

$$\mathbf{A}\mathbf{S}_{11}^* + \mathbf{B}\mathbf{S}_{21}^* = \mathbf{S}_{11}^*\mathbf{A}_m ; \mathbf{A}\mathbf{S}_{12}^* + \mathbf{B}\mathbf{S}_{22}^* = \mathbf{S}_{11}^*\mathbf{B}_m + \mathbf{S}_{12}^*\mathbf{F}_m$$

$$\mathbf{C}\mathbf{S}_{11}^* = \mathbf{C}_m ; \mathbf{C}\mathbf{S}_{12}^* = 0; \mathbf{A}\mathbf{S}_{13}^* + \mathbf{B}\mathbf{S}_{23}^* + \Gamma\Theta = \mathbf{S}_{13}^*\mathbf{F}; \mathbf{C}\mathbf{S}_{13}^* = 0$$

Solutions to matching conditions must exist for analysis purposes, BUT they don't need to be known for adaptive controller design!

Closed-loop stability result

Theorem: Suppose the following are true:

1. All $\mathbf{u}_m$ are bounded (i.e., all eigenvalues of $\mathbf{F}_m$ are in the closed left-half plane and any eigenvalues on the $j\omega$-axis are simple);
2. The reference model $(\mathbf{A}_m, \mathbf{B}_m, \mathbf{C}_m)$ is stable;
3. ϕ_D is bounded (i.e., all eigenvalues of **F** are in the closed left-half plane and any eigenvalues on the jω-axis are simple);
4. $(\mathbf{A}, \mathbf{B}, \mathbf{C})$ is **Almost Strict Positive Real (ASPR)** (i.e., $\mathbf{CB} > 0$ and the open-loop transfer function is minimum phase)

Then the adaptive gains $\mathbf{G}_m, \mathbf{G}_u, \mathbf{G}_e, \mathbf{G}_D$ are **bounded**,

and **asymptotic tracking occurs**, i.e. $\mathbf{e}_y \equiv \mathbf{y} - \mathbf{y}_m = \mathbf{Ce}_* \xrightarrow[t\to\infty]{} 0$

Note: A system (A, B, C) is ASPR when $CB > 0$ and its closed-loop transfer function $P(s) = C(sI - A)^{-1}B$ is minimum phase.

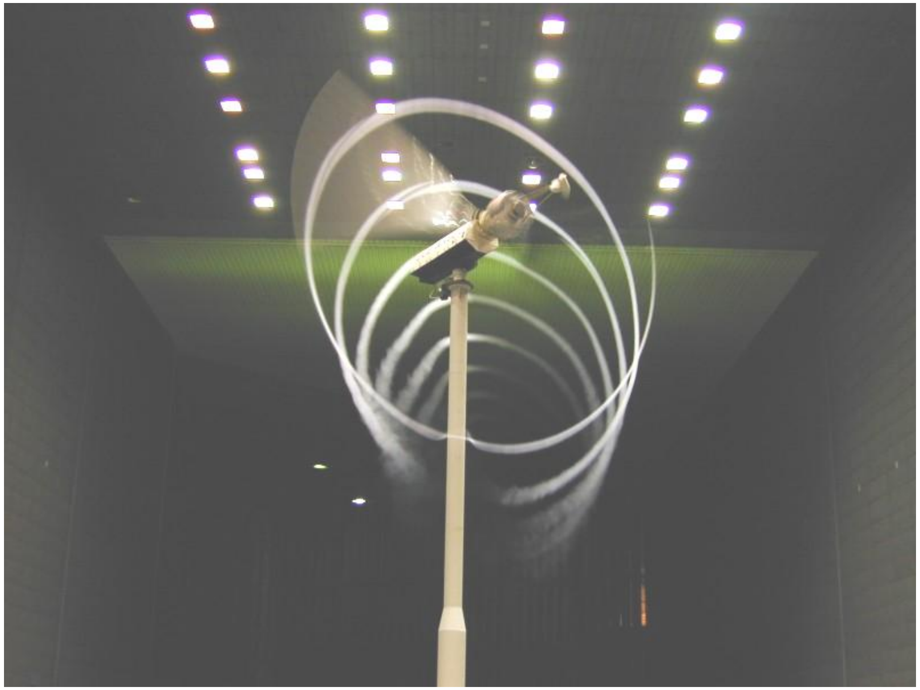
For Closed-Loop Stability Analysis, see: Frost, Balas, Wright, IJRNC (2009)

Flexible structure control challenges

Controller Structure Interaction:

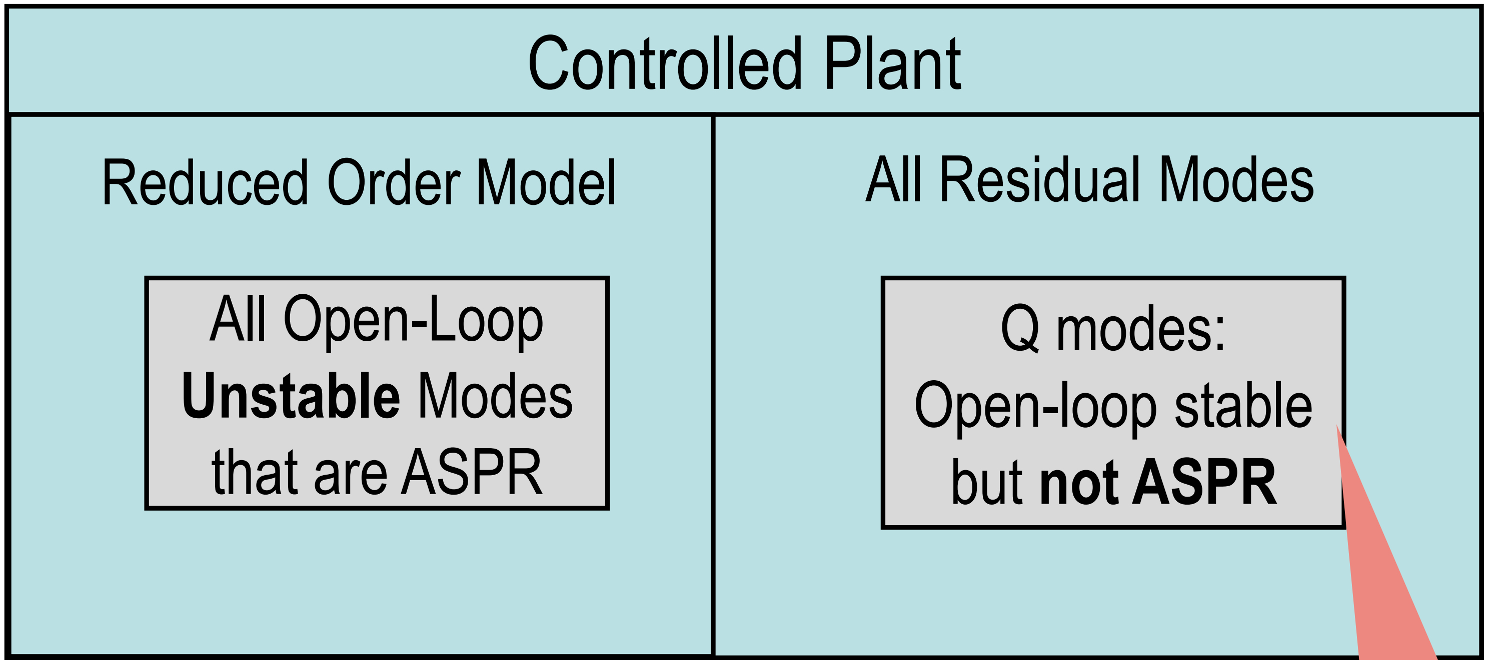
- Flexible structures are intrinsically modal systems
- Structural modes can be excited by feedback control
- Low pass & notch filters can reduce problems, but limitations exist
- Residual Mode Filter (RMF) has internal model of structural mode, including phase and frequency, that can be used to remove troublesome mode from feedback signal

Plant & operating environment uncertainties



- Flexible aerospace structures, including wind turbines, are difficult to model and they operate in poorly known environments
- Adaptive control **helps**, but requires minimum phase plants (ASPR)
- Residual Mode Filters (RMF) can restore ASPR to closed-loop system

Partition plant into ASPR & non-ASPR

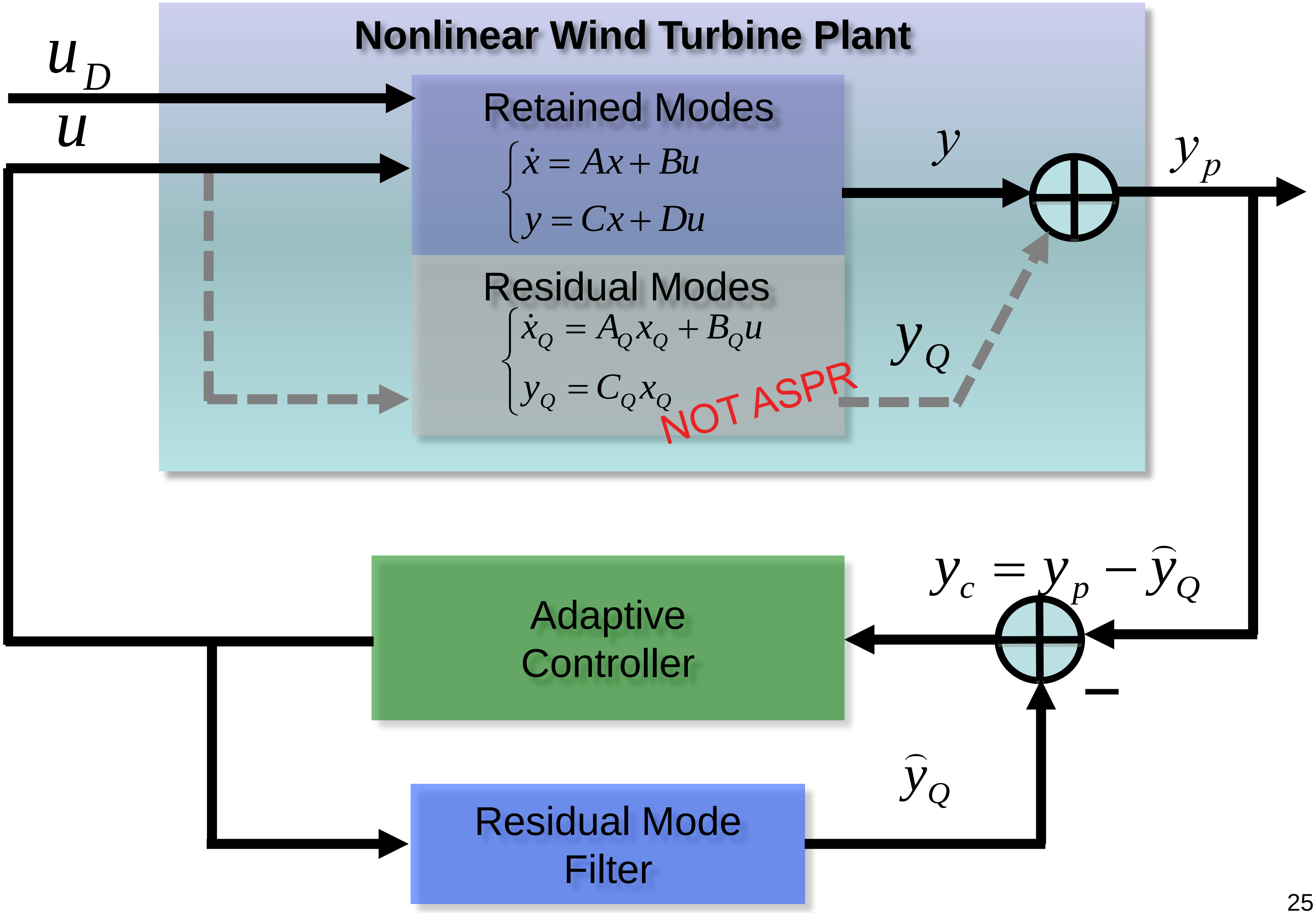


Assume original system $\left(\mathbf{A}_p, \mathbf{B}_p, \mathbf{C}_p\right)$ can be partitioned as:

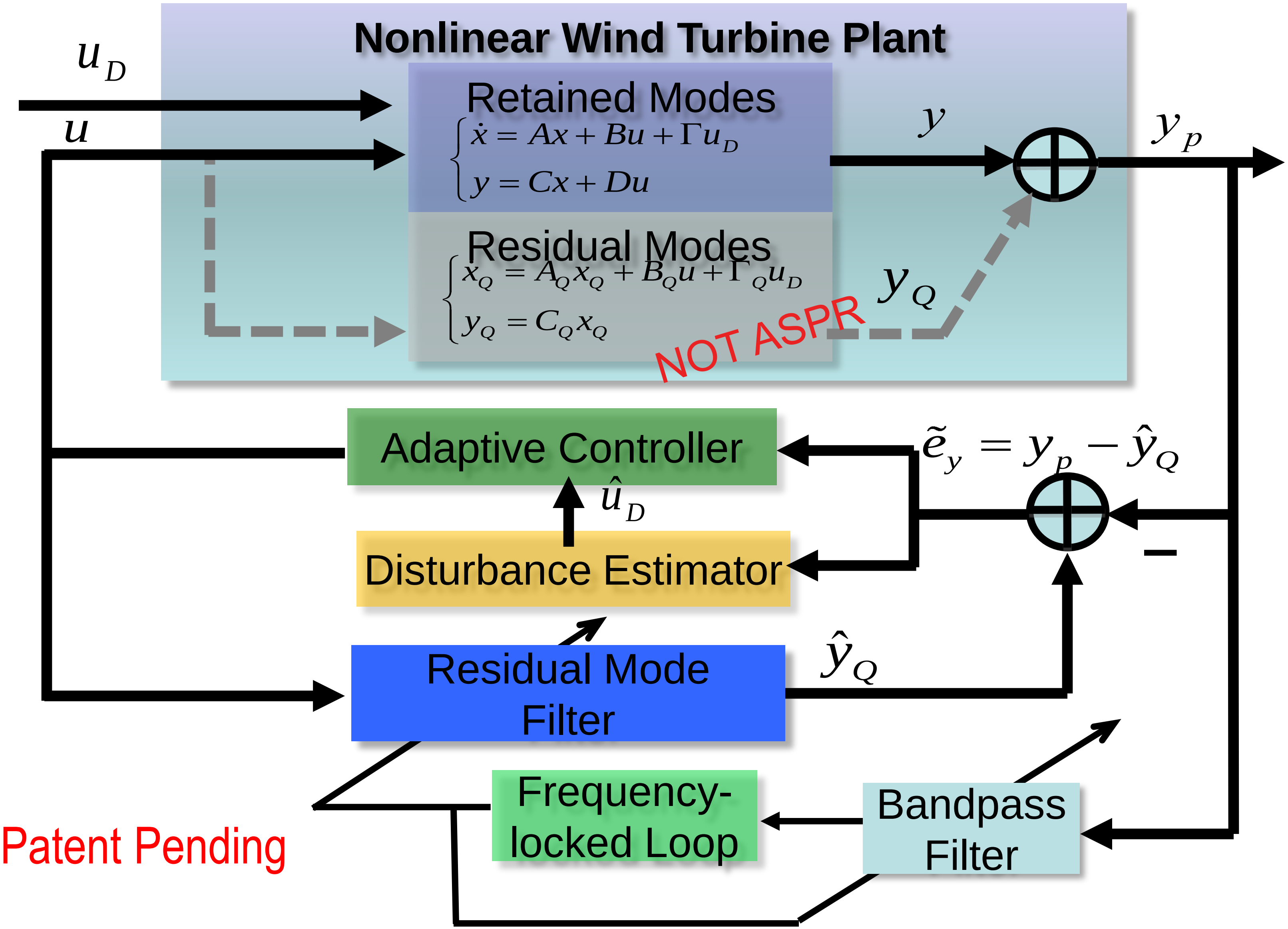
$$\begin{cases} \begin{bmatrix} \dot{x} \\ \dot{x}_Q \end{bmatrix} = \begin{bmatrix} A & 0 \\ 0 & A_Q \end{bmatrix} \begin{bmatrix} x \\ x_Q \end{bmatrix} + \begin{bmatrix} B \\ B_Q \end{bmatrix} u_p + \begin{bmatrix} \Gamma \\ \varepsilon \Gamma_Q \end{bmatrix} u_D \\ y_p = \begin{bmatrix} C & C_Q \end{bmatrix} \begin{bmatrix} x \\ x_Q \end{bmatrix}; \ \varepsilon \geq 0 \end{cases}$$

Use RMF to remove these modes from controller feedback

Adaptive controller using RMF



Addition of disturbance estimator & FLL



US Patent Pending

Controls Advanced Research Turbine (CART)

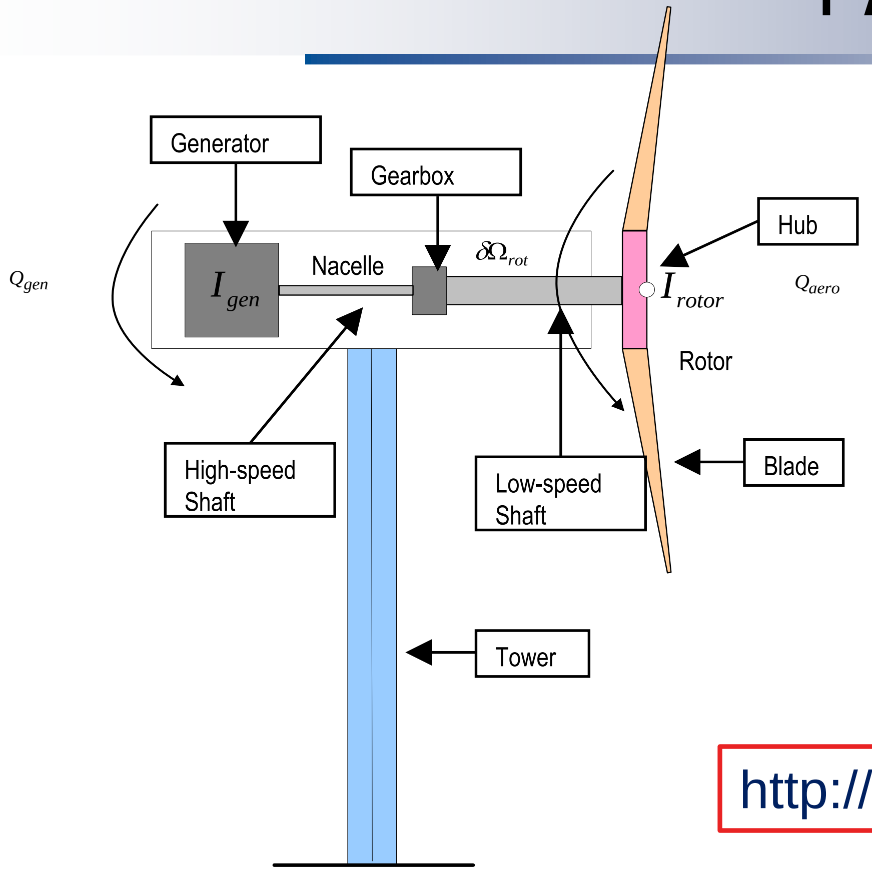
CART2, NWTC, Golden, Colorado

image credit: NREL

CART2 Specifications

- Variable-speed, two-bladed, teetered, upwind, active-yaw
- Rotor Diameter: 43.3 m
- Hub Height: 36.6 m
- Rated electrical power: 600 kW at 42 RPM in region 3
- Region 3 Rated generator speed: **1800 RPM**
- Power electronics command constant generator torque
- Blade pitch rate limit: **±18 deg/sec**
- **Baseline PI Pitch Controller**

FAST simulator for CART



Fatigue
Aerodynamics
Structures
Turbulence

http://wind.nrel.gov/designcodes/

- Configurable high fidelity simulation of CART with controller in the loop
- Aeroelastic simulator of extreme and fatigue loads
- Aerodynamic forces computed by AeroDyn code (Windward Engineering)
- Turbine modeled by rigid and flexible bodies

Adaptive pitch control in Region 3

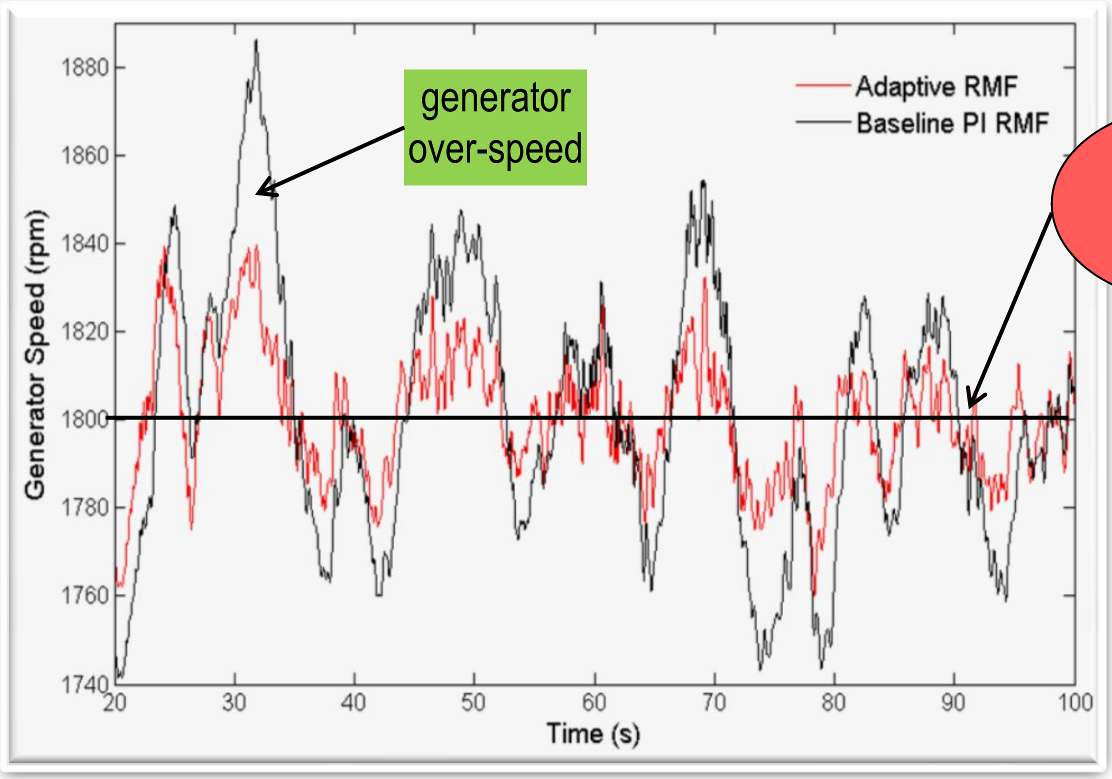
- **Objective**: Regulate generator speed and reject disturbances
- **Input:** Rotor speed
- **Output:** Collective blade pitch, constant generator torque
- **Disturbance:** Turbulent wind inflow

- Uniform disturbance of wind gust across rotor can be modeled by a step function of unknown amplitude, so $\phi_D = 1$
- RMF designed for drive-train rotational flexibility mode

Adaptive pitch control for FAST simulator*

Excursions from set-point cause higher blade loads

Generator speed for turbulent wind input
---- Baseline PI
---- Adaptive RMF



*NREL's FAST simulator of CART2 (high fidelity simulation of flexible 2-bladed wind turbine) see: http://wind.nrel.gov/designcodes/

Adaptive contingency control

- System health monitoring for safe operation of all turbines in wind farm
  - Ensure damaged turbines are off-line before failure
- Adaptive controls to reduce loads on turbines with faults
  - Function of current damage level & operating conditions
- Cost of Energy (CoE) optimization
  - Incorporate wind forecasts, grid requirements and maintenance schedules with prognostic health management information
  - Reduce loading cycles and extreme events on damaged turbines and extend remaining useful life
  - Smooth power production under variable wind conditions

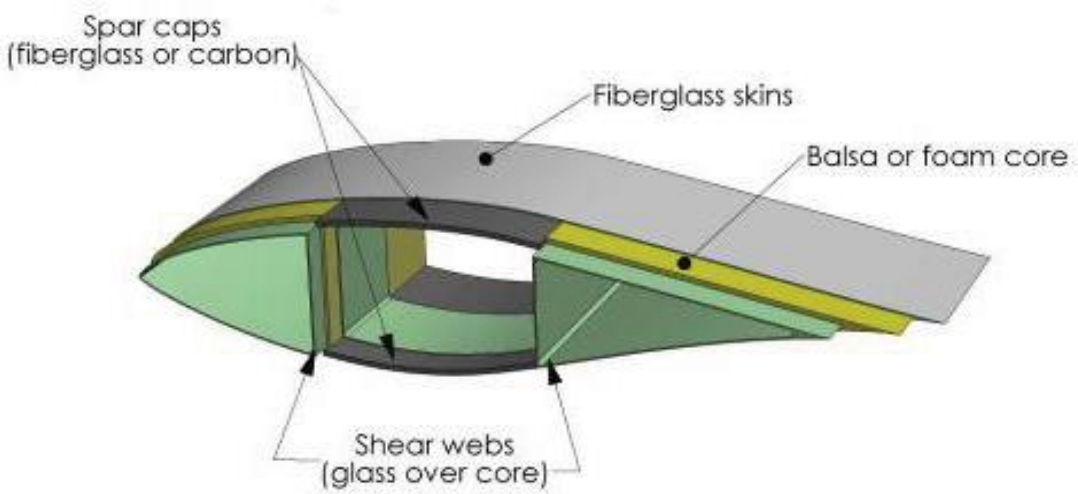
Some OEMs are moving towards guaranteed uptime

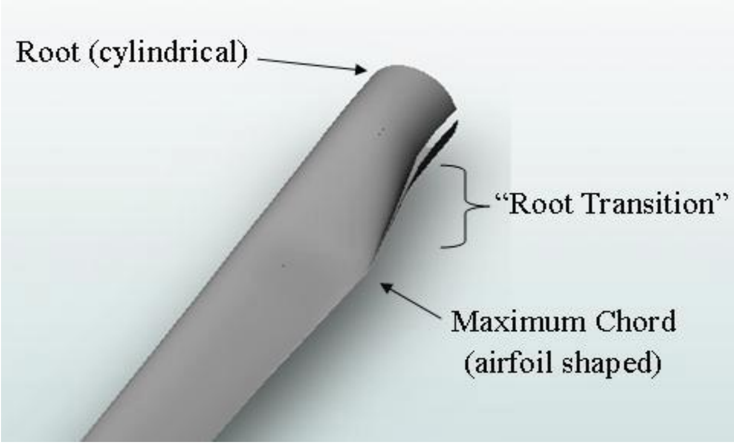
Operators and developers often need 20-25 years of life for profitability

Condition monitoring in wind turbines

- SCADA system: Supervisory Control and Data Acquisition for wind farm
  - Medium- and long-term changes in environmental & operating conditions
  - Minimal fault diagnosis
  - Lots of data, not always useful
- Short-term condition monitoring
  - Equipment set up for one month for vibration, acoustic, strain, nacelle acceleration testing
- Acceptance of CM by operators/developers
  - Dependent on cost of CM system
  - Might affect warranty

Leading causes of blade failures[1]





1) Manufacturing defects - wrinkles in laminate, missing or incomplete bond lines, dry fibers
2) Progressive damage initiating from leading-edge erosion, skin cracks, transport, handling, or lightning strikes
3) Excessive loads from turbine system dynamics or dynamic interaction with control system
4) Out-of-plane forces and distortion of blade sections ("bulging/breathing" effect) mostly in root transition region, due to blade loading
5) Excessive loads due to unusually severe atmospheric conditions

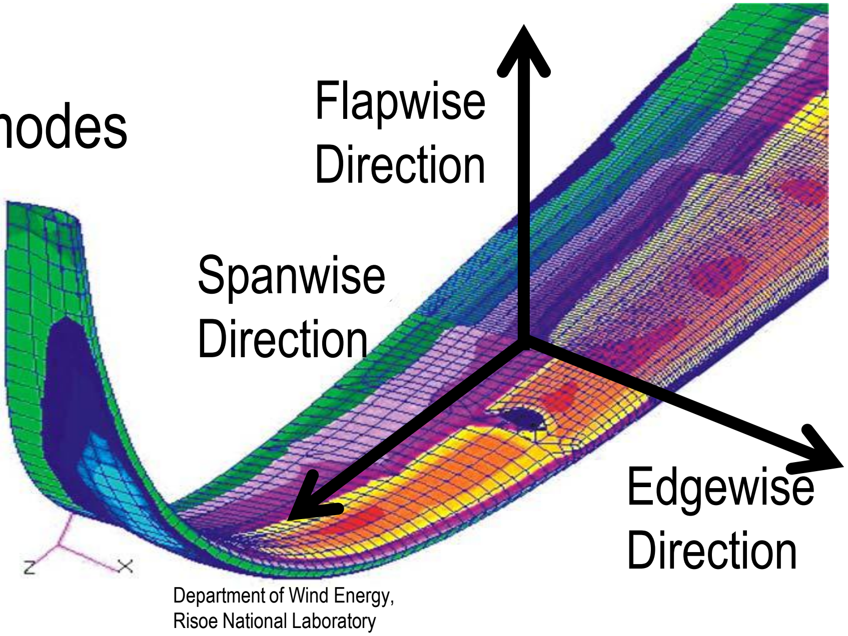
[1]DNV Renewables, Seattle, WA, "Lessons Learned from Recent Blade Failures: Primary Causes and Risk-Reducing Technologies", D.A. Griffin & M.C. Malkin, 49th AIAA Aerospace Sciences Meeting, Jan 2011

FAST turbine blades

FAST blade configuration files:

- 21 distributed stations along span
- Flapwise & edgewise stiffness
- Flapwise & edgewise bending modes

Assumption:
Blade damage can be represented by reduction in flapwise and edgewise stiffnesses



Damaged blade configuration files:

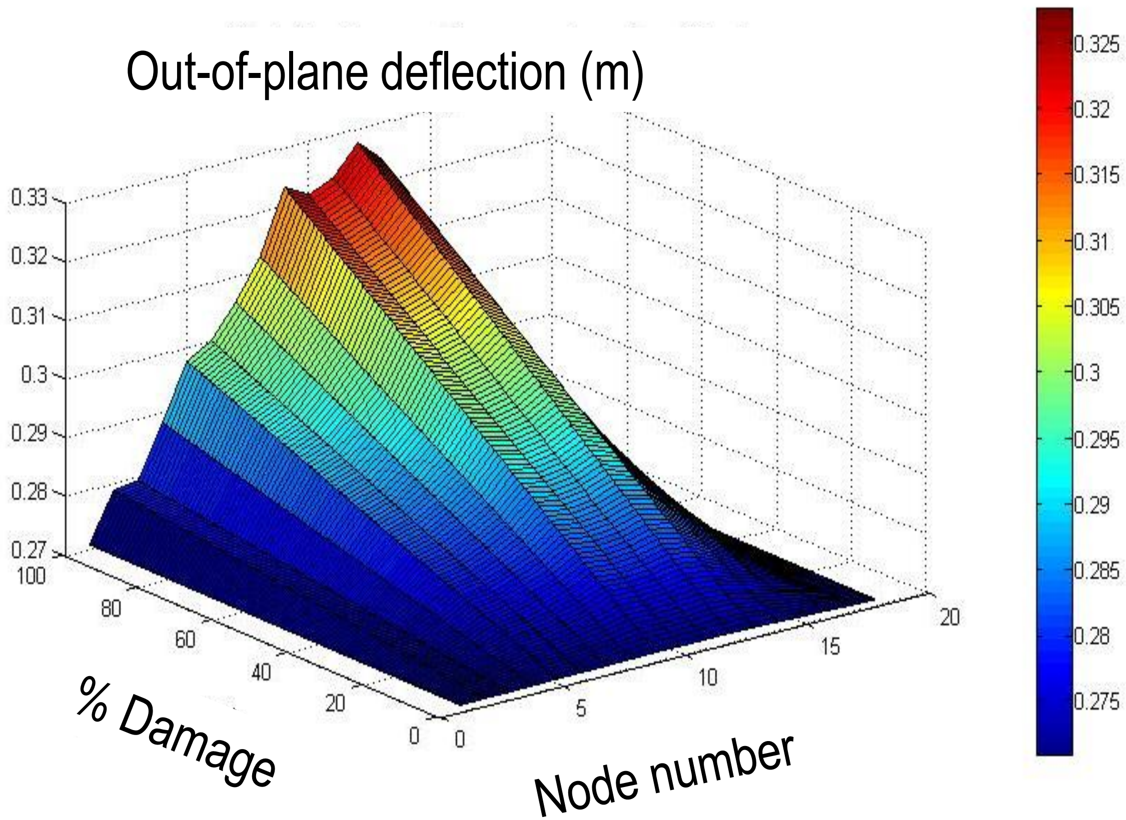
- Flapwise and edgewise stiffness are varied at 1-2 blade stations
- Blade bending mode shapes are recomputed
- Structural damping and other parameters were left unchanged

Blade node sensitivity to stiffness changes

Full factorial study performed to determine blade node sensitivity:

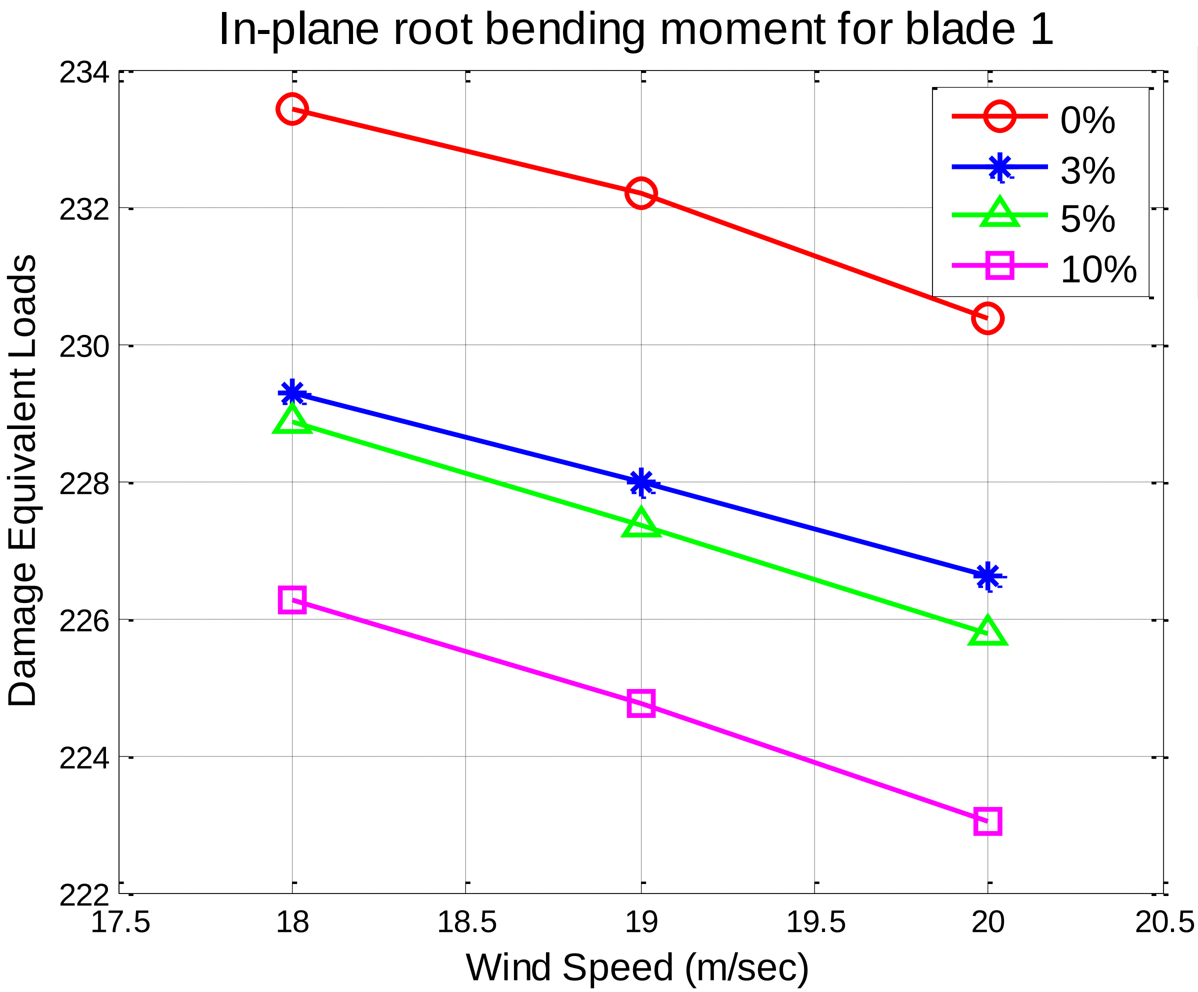
- Parameters: blade damage, wind speed, blade pitch
- Levels: 8 for damage, 7 for wind, 10 for blade pitch

Loads on blades are primarily due to aerodynamic forces



Effect of derating generator on blade loads

Hypothesis: Reducing power output through generator set-point reduction will reduce loads on turbine blades



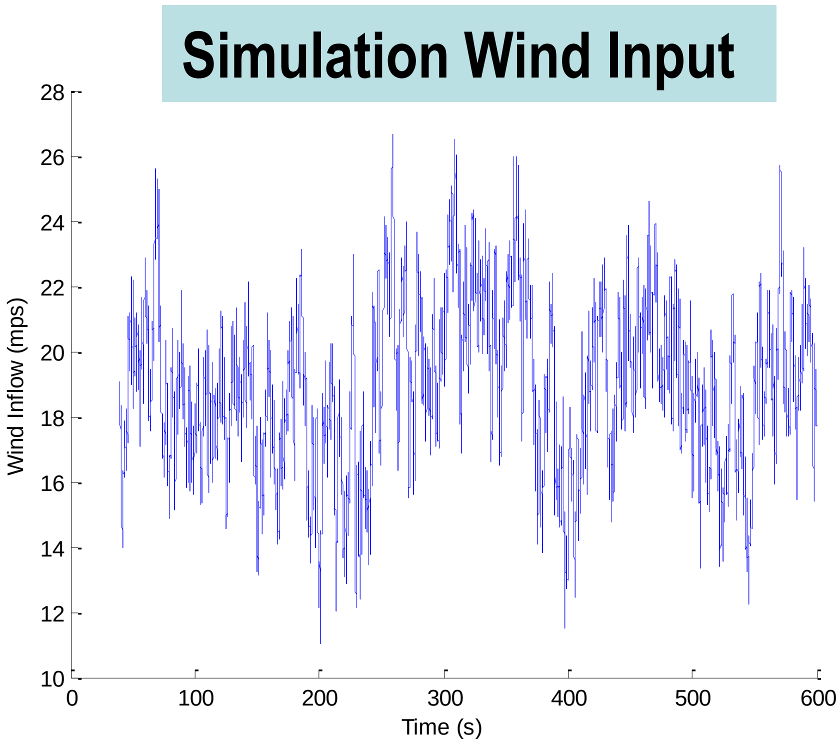
Percent reduction in generator set-point from rated value

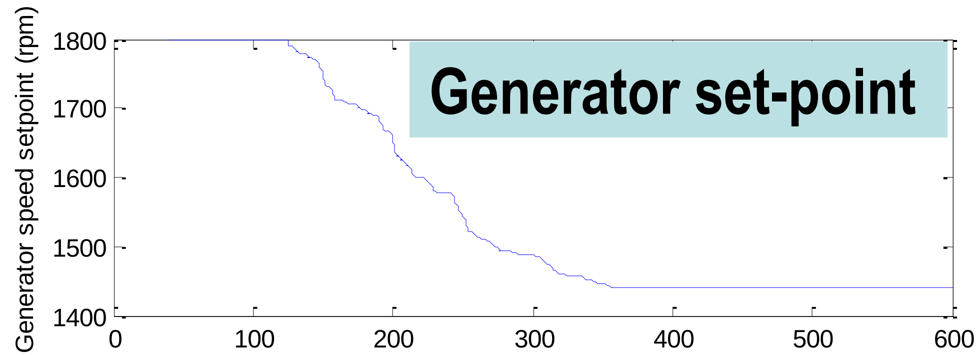
Adaptive contingency control in Region 3

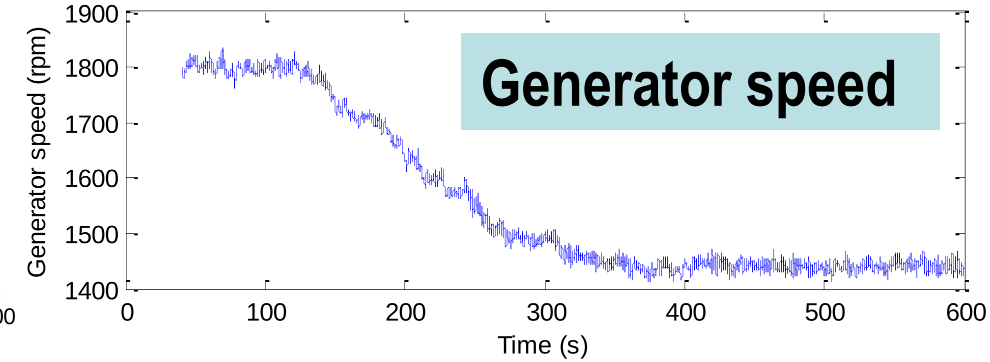
- **Objective**: Regulate generator speed, reject disturbances, and derate generator in turbulent conditions
- **Input:** Rotor speed
- **Output:** Collective blade pitch, constant generator torque
- **Disturbance:** Step function

- Uniform disturbance of wind gust across rotor can be modeled by a step function of unknown amplitude, so $\phi_D = 1$
- RMF designed for drive-train rotational flexibility mode
- Turbulent loading observer – uses delta rotor speed changes
- Generator de-rating by incremental steps

De-rating generator for reduced blade loads



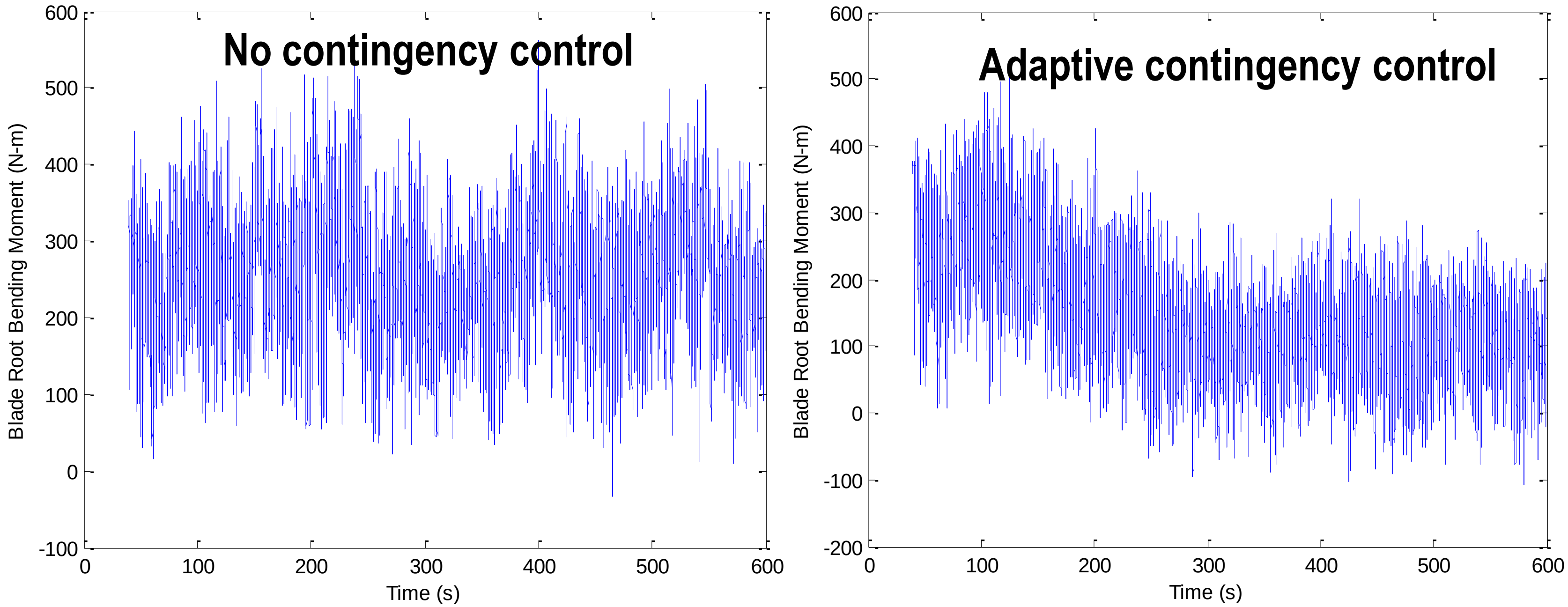




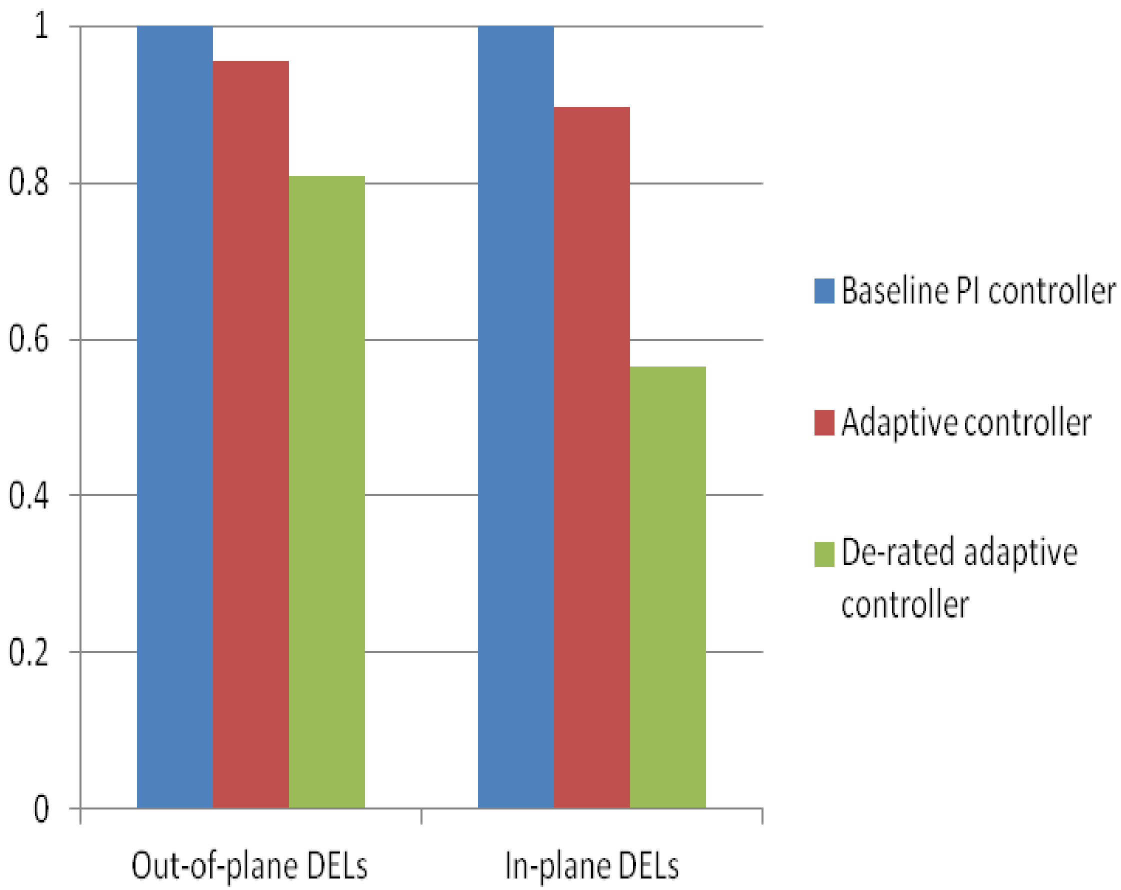
Simulation results

- Simulation demonstrating contingency controller lowering generator set-point for turbine with blade damage when winds are turbulent & above rated speed
- Resulting decrease in blade root bending could extend service life

Out-of-plane blade root bending moment



Damage equivalent loads



Blade damage at node 5 – with 20% reduction in stiffness

Future research: Cost of energy improvements

Proposed Solution

- Develop a multi-disciplinary game-changing approach to significantly improve the cost of energy for wind.
- By employing autonomous decision-making for adaptive contingency control of wind turbines in large wind farms using prognostic health management information, wind forecasting, and logistics information, a significant reduction in the cost of wind energy is possible.

Preliminary Study Results

- Simulation demonstrating contingency controller lowering power output for damaged turbines when winds could be destructive[1]
- Resulting decrease in wind turbine loads could extend service life
- Developed framework & path forward for autonomous decision-making, wind turbine controls, prognostic health management, and wind forecasting

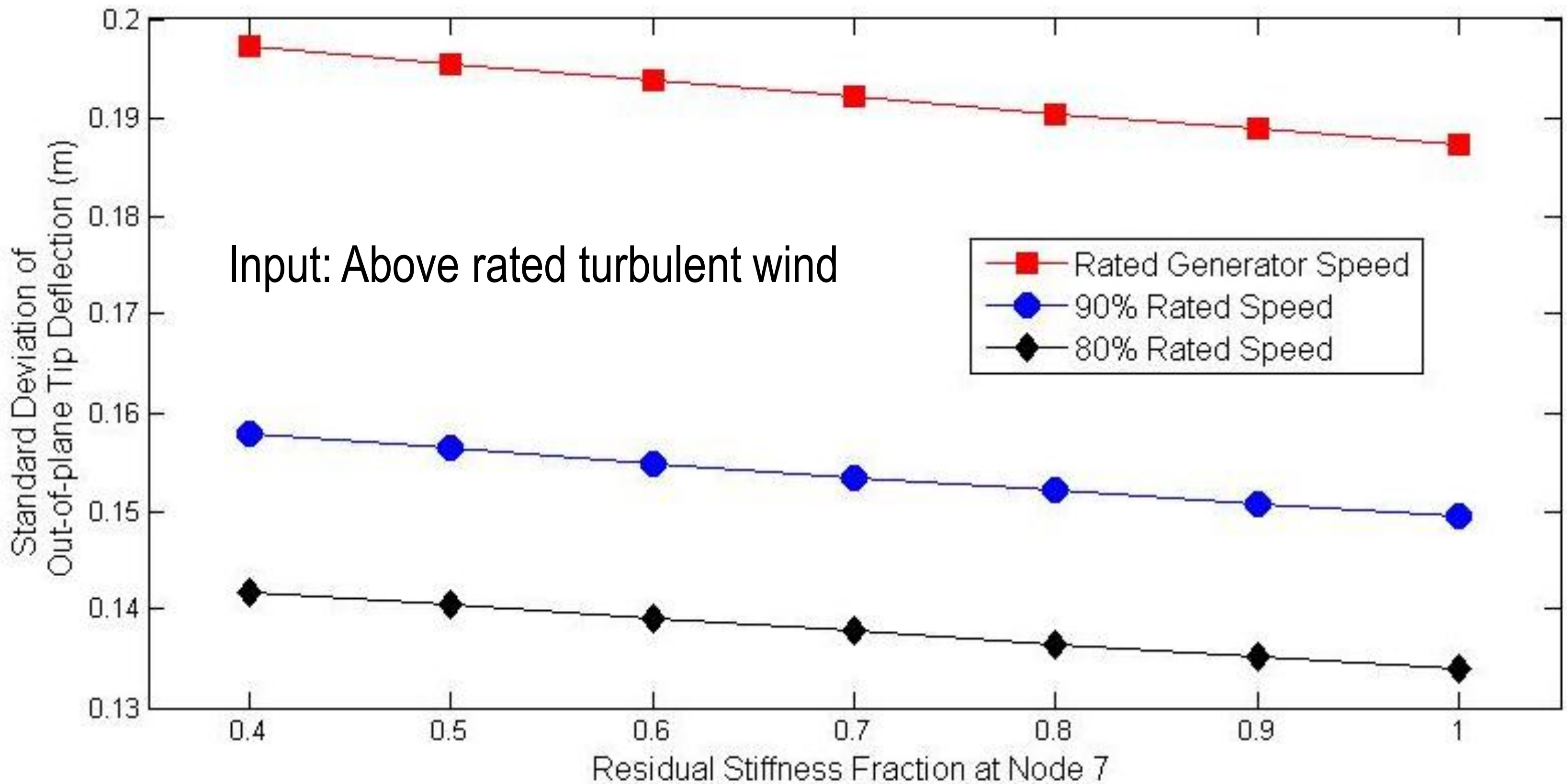
Study of turbine response to Blade Damage

Preliminary study of effects of blade stiffness reduction

- Damage located on one blade at station 7, 30% from blade root
- Study run in open-loop with no generator speed tracking
- Generator torque held fixed at rated torque
- Simulation run with steady wind speeds from 12-24 mps
- Collective pitch varied from 0.1-0.45 radians
- Blade tip displacement was measured

Change in tip deflection with generator derating

Std. dev. of out-of-plane tip deflection for different damage levels at node 7



Hypothesis: Reducing power output through generator set-point reduction will reduce loads on turbine blades

Backup slides