Controlling Wind Turbines
to Reduce the Cost of Wind Energy
and to Increase Utility Grid Reliability

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Fellow of RASEI, 2009-

Founding Scientific Director of CREW, 2007-2011

Lucy Pao
Rensselaer Polytechnic Institute ECSE Seminar

March 2014
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# United States Wind Map

## Colorado

### Wind Power Classification

<table>
<thead>
<tr>
<th>Wind Power Class</th>
<th>Resource Potential</th>
<th>Wind Power Density at 50 m W/m²</th>
<th>Wind Speed at 50 m m/s</th>
<th>Wind Speed at 50 m mph</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Fair</td>
<td>300 - 400</td>
<td>6.4 - 7.0</td>
<td>14.3 - 15.7</td>
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<tr>
<td>4</td>
<td>Good</td>
<td>400 - 500</td>
<td>7.0 - 7.5</td>
<td>15.7 - 16.8</td>
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<tr>
<td>5</td>
<td>Excellent</td>
<td>500 - 600</td>
<td>7.5 - 8.0</td>
<td>16.8 - 17.9</td>
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<tr>
<td>6</td>
<td>Outstanding</td>
<td>600 - 800</td>
<td>8.0 - 8.5</td>
<td>17.9 - 19.7</td>
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<tr>
<td>7</td>
<td>Superb</td>
<td>800 - 1600</td>
<td>8.8 - 11.1</td>
<td>19.7 - 24.8</td>
</tr>
</tbody>
</table>

*a Wind speeds are based on a Weibull k value of 2.0*
Colorado Wind Map

National Wind Technology Center

Boulder

Denver

Colorado Annual Average Wind Speed at 80 m

Wind Speed m/s

- >10.5
- 10.0
- 9.5
- 9.0
- 8.5
- 8.0
- 7.5
- 7.0
- 6.5
- 6.0
- 5.5
- 5.0
- 4.5
- 4.0
- < 4.0

50 0 50 100 150 200 Kilometers

50 0 50 100 100 Miles

AWS Truepower™
Where science delivers performance.

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Background

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National Wind Technology Center
National Wind Technology Center

- 4 multi-megawatt turbines
  - Alstom 3 MW Eco100
  - Gamesa 2 MW G97
  - GE 1.5 MW
  - Siemens 2.3 MW

- 2 controls advanced research turbines (CARTs)
  - 2-bladed (CART2) 600 kW
  - 3-bladed (CART3) 675 kW

- 10 smaller turbines (< 500 kW)
NREL Wind and Controls Simulation Codes
[ wind.nrel.gov/designcodes ]

Wind Modeling

- **TurbSim**
  - Generation of wind fields

- **FAST** – Fatigue, Aerodynamics, Structures, & Turbulence
  - Simulation of wind turbine response
  - Dynamically linked with Simulink

- **SOWFA** – Simulator for Offshore Wind Farm Applications
  - Computational Fluid Dynamics based code
  - High-fidelity, computationally intensive
Wind Energy

- Fast growing electrical energy source
- Current global installed capacity is over 320,000 MW; average annual growth more than 23% over last decade

[Installed Capacity [GW]

[data from wwindea.org and windpoweringamerica.gov]
Worldwide Wind Power Capacity

Data from Global Wind Energy Council

Total Year End 2013 Capacity: 318 GW
Installed in 2013: 35.5 GW

Growth of Wind Energy
Wind Penetration

Approximate Wind Penetration, end of 2012
Approximate Wind Penetration, end of 2011
Approximate Wind Penetration, end of 2010
Approximate Wind Penetration, end of 2008
Approximate Wind Penetration, end of 2006

[Source: 2012 Wind Technologies Market Report, Lawrence Berkeley National Lab]
2003 Year End Wind Power Capacity (MW)
[http://www.windpoweringamerica.gov/wind_installed_capacity.asp ]

Total: 6,350 MW
(As of 12/31/2003)

Data from the Global Energy Concepts (DNV-GEC) database.

U.S. Department of Energy
National Renewable Energy Laboratory

2008 Year End Wind Power Capacity (MW)
[http://www.windpoweringamerica.gov/wind_installed_capacity.asp ]
2013 Year End Wind Power Capacity (MW)
[http://www.windpoweringamerica.gov/wind_installed_capacity.asp]
2012 Year End Wind Penetrations by State

2012 Wind Penetration Estimates from:
R. Wiser and M. Bolinger, 2012 Wind Technologies Market Report, LBNL
Increasing Wind Turbine Sizes

[diagrams and schematic from NREL, en.wikipedia.org/wiki/Airbus_A380, and www.123rf.com/photo_13150740_soccer-field.html]
Increasing Wind Turbine Sizes

Airbus A380

Rotor Diameter (m)
Rating (kW)

Hub Height (m)

1980-1990
1990-1995
1995-2000
2000-2005
2005-2010
2010-
2010-
Future
Future

17m 75kW
30m 300kW
50m 750kW
70m 1,500kW
80m 1,800kW
100m 3,000kW
125m 5,000kW
150m 10,000kW
250m 20,000kW

P \propto A \nu^3

[diagrams and schematic from NREL, en.wikipedia.org/wiki/Airbus_A380, and www.123rf.com/photo_13150740_soccer-field.html]
Wind Turbine Components

[figure courtesy of US Dept. of Energy]
Outline

- **Wind Energy Background**
  - Growth of wind energy
  - Wind turbine operating regions

- **Wind Turbine Control**
  - Combined feedforward/feedback control

- **Utility Grid Operation**

- **Summary and Emerging Areas**
Operating Regions

- **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 turbines vary speed to maximize aerodynamic efficiency

- **Region 3: High wind speeds (above 11.7 m/s)**
  - Variable-pitch turbines vary the pitch of blades to limit power to avoid exceeding safe electrical and mechanical load limits

If sited properly, a wind turbine will spend a lot of time in Region 2.5.
Wind Turbine Control Loops

Wind turbine axis

instantaneous wind field

Desired Rotor Speed $\omega_d$

Pitch Controller

Torque Controller

Speed Sensor

Rotor Speed

$\omega$

Wind

Pitch Control, seconds

Torque Control, milliseconds

Power

Region 1

Region 2

Region 3

Wind Speed

Z

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Combined Feedforward and Feedback Control of Wind Turbines

Torque Control, milliseconds

Pitch Control, seconds

Instantaneous wind field
Pitch Control Using Preview Wind Measurements

Wind (ahead of turbine)

Commands

TURBINE

Outputs

Desired Setpoints

FEEDBACK CONTROL
Pitch Control Using Preview Wind Measurements

Wind (ahead of turbine)

EVOLUTION MODEL
LIDAR SYSTEM

WIND EVOLUTION

CONTROL SYSTEM

Commands

Outputs

Desired Setpoints

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Pitch Control Using Preview Wind Measurements

Wind (ahead of turbine)

LIDAR SYSTEM

DELAY

CONTROL SYSTEM

Commands

TURBINE

Outputs

Σ

Desired Setpoints

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Advanced Wind Turbine Control

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Pitch Control Using Preview Wind Measurements

Wind (ahead of turbine)

CONTROL SYSTEM

Commands

DELAY

TURBINE

Outputs

Desired Setpoints

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Advanced Wind Turbine Control
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Pitch Control Using Preview Wind Measurements

E. Simley, 2010-

- NREL 5MW turbine model
- WindPACT 1.5 MW model

Wind (ahead of turbine)

LIDAR SYSTEM

WIND EVOLUTION

Command outputs

TURBINE

Outputs

Desired Setpoints

Pao – Wind Energy 16 Advanced Wind Turbine Control RPI – March 2014
Pitch Control Using Preview Wind Measurements

F. Dunne, 2009-

• NREL 5MW turbine model

Wind (ahead of turbine)

LIDAR SYSTEM

Outputs

Commands

FEEDFORWARD CONTROL

TURBINE (FAST)

FEEDBACK CONTROL

Desired Setpoints
Pitch Control Using Preview Wind Measurements

- Wind (ahead of turbine)
- LIDAR SYSTEM
- MIMO CONTROL SYSTEM
- commands
- Outputs
- Desired Setpoints

J. Laks, 2008-2013
E. Simley, 2010-

• 675 KW CART3 model
Region 2.5 Control with Preview Wind Measurements

J. Aho, 2011-

- NREL 5MW turbine model
- 675 KW CART3 model

Wind (ahead of turbine)

MIMO CONTROL SYSTEM

LIDAR SYSTEM

DELAY

TURBINE (FAST)

Outputs

Desired Setpoints

Commands
Pitch Control Using Preview Wind Measurements
Pitch Control Using Preview Wind Measurements

CONTROL SYSTEM

LIDAR (Light Detection And Ranging)

Generator Rotation

Blade Flap Bending Moment

Drive-train Torsion

Tower Fore-Aft

Blade Pitch
**Preview Measurement Accuracy**

- **Mean wind speed** is 18 m/s
- **2 seconds of preview** (36 m)
- **Continuous-wave LIDAR**
- **LIDAR angle** at 22.6 deg

---

**Ideal Rotating Measurements**

- **Std = 0.09 m/s**

**Rotating LIDAR Measurements**

- **Std = 0.9 m/s**
Selected Results: Combined Feedforward/Feedback Control

[J. Laks, L. Pao, A. Wright, et al., 2008-]

Blade Flap Loads

- CP
- IP
- LTI OFBK
- LTI OFBK LIDAR
- MPC SFBK LIDAR

Percentage of Occurrences

Load Cycle Amplitude [kN-m]

CART3 (675 KW)
above-rated wind speeds

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Selected Results: Combined Feedforward/Feedback Control

[J. Laks, L. Pao, A. Wright, et al., 2008-]

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Selected Results: Combined Feedforward/Feedback Control

[J. Laks, L. Pao, A. Wright, et al., 2008-]

Blade Flap Loads

Percentage of Occurrences vs. Load Cycle Amplitude [kN-m]

- CP
- IP
- LTI OFBK
- LTI OFBK LIDAR
- MPC SFBK LIDAR

OUTLIERS

CART3
(675 KW)
above-rated wind speeds

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Outline

- Wind Energy Background
- Wind Turbine Control
- Utility Grid Operation
  - Challenges of increasing penetrations of renewable energy
  - Possible solutions
    - Active power control of wind turbines
- Summary and Emerging Areas
Most traditional power plants have synchronous generators.

When synchronous generators that are operating at nearly the same frequency are interconnected, they will “swing” together at nearly the same frequency.

Large deviations in frequency can destabilize the network of connected generators.

[Based upon a slide from Mark Ahlstrom of WindLogics]
Frequency Fluctuations

governed by swing equation

\[ \frac{df_{grid}}{dt} = \frac{P_G - P_L}{M} \]

\[ f_{grid} = 60 \text{ Hz} \quad f_{grid} < 60 \text{ Hz} \quad f_{grid} > 60 \text{ Hz} \]

[Slide courtesy of Jacob Aho]
Response to Frequency Event

\[ \frac{df_{\text{grid}}}{dt} = \frac{P_G - P_L}{M} \]

loss of generation event

\[ M \propto \text{inertia} \]

[ Figure based upon one from P. Pourbeik, EPRI ]

Enabled via generators with governors
Distributed automatic response
Arrests frequency & brings to ‘steady state’
Response to Frequency Event

\[ \frac{df_{\text{grid}}}{dt} = \frac{P_G - P_L}{M} \]

\( M \propto \text{inertia} \)

[ Figure based upon one from P. Pourbeik, EPRI ]

- **Primary Frequency Response**
- **Secondary/Tertiary (AGC) Frequency Regulation**

Automatic or manual power commands
Drive frequency back to desired level
Primary Frequency Control (PFC) (Droop Control)

- Conventional generators provide PFC via governors
- Governor response characterized by a ‘droop curve’
  - Droop with deadband (proportional control with a deadband)

\[
df_{grid} = \frac{P_G - P_L}{M}
\]

3% Droop:

3% change in \( f_{grid} \)

\[ \Rightarrow 100\% \text{ change in commanded power} \]
Traditionally, generation is controlled to match varying load

- Operational reserves needed
- Imbalance causes frequency variations on utility grid
Balancing Electrical Generation and Load

- Traditionally, generation is controlled to match varying load
  - Operational reserves needed
  - Imbalance causes frequency variations on utility grid

Large frequency fluctuations can cause load shedding, or even blackouts
Maintaining Balance with Changing Load

Hour of the Day

[Based upon a slide from Mark Ahlstrom of WindLogics]
Changes due to Wind (and Solar)

- Wind turbines are typically decoupled from the grid through their power electronics
  - In US, wind generally does not participate in PFC and AGC
  - Creates increased burden on remaining generating units
Changes due to Wind Energy

- Remaining system load that must be met with other generating sources
- Often more wind power available at night

[Based upon a slide from Mark Ahlstrom of WindLogics]

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Grid Challenges of Wind Energy RPI – March 2014
Changes due to Wind Energy

Remaining system load that must be met with other generating sources

Hour of the Day

System Load

[Based upon a slide from Mark Ahlstrom of WindLogics]

Gas
Hydro
Coal
Nuclear

Possible Solutions: Load Regulation

- Improved wind forecasts
- Demand-side management
  - Thermal storage
  - Time-of-use pricing and “optimal” pricing strategies
- Storage (at GWh scale)
  - Expensive
  - Effect of millions of electric vehicles, whose batteries can be either a load or a supply

[figure from a presentation by A. Kowli, original from SVK (Swedish national grid)]
Possible Solution: APC of Wind and Solar

- **Active Power Control of Wind and Solar Power Plants**
  - De-rate wind and solar power plants so that there is headroom to both increase and decrease power to respond to utility grid balancing needs
  - Develop methods that enable wind turbines to effectively provide primary (PFC) and secondary (AGC) control

[Aho, Buckspan, Fleming, Jeong, Johnson, Pao, Ela, Milligan, Kirby, Gevorgian, Ma, Chowdury, Juankorena, Esandi, Lopez, Marroyo, de Almeida, Hansen, Sorensen, Iov, Blaabjerg, Gesino, Chandorkar, Divan, Adapa, Piagi, Lasseter, Kroposki, Pink, DeBlasio, Thomas, Simoes, Sen, Hoke, Maksimovic, … ]

[figure from a presentation by A. Kowli, original from SVK (Swedish national grid)]
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![Example Power Curves for 2.5 MW Wind Turbine](chart)

- **Region 1**: Wind turbines not run, because power available in wind is low compared to losses in turbine system.
- **Region 2**: Variable-speed turbines vary speed to maximize aerodynamic efficiency.
- **Region 3**: Variable-pitch turbines vary the pitch of blades to limit power to avoid exceeding safe electrical and mechanical load limits.
Contributions

[2012- ]

Instantaneous wind field

Pitch Controller

Torque Controller

Speed Sensor

Rotor Speed

Wind

Turbine axis

Power

Region 3

Region 2

De-rated Turbine Power

Wind Speed

Desired

Rotor Speed

ω

ω_d

ω_e

Both Torque Control and Pitch Control used throughout Regions 2 and 3
Wind turbines traditionally decoupled from grid

Wind turbine droop curve implemented via controller software

- Can be time-varying and dynamically changed on-line
  - Vary droop based on “rate of change of frequency” (ROCOF or $\frac{df_{\text{grid}}}{dt}$)
Dynamic Droop Curve Example

\[ \frac{df_{\text{grid}}}{dt} = 0 \text{ mHz/sec} \]

Dynamic droop curve interpolates between 2 static droop curves based upon ROCOF.
Dynamic Droop Curve Example

\[ \frac{df_{\text{grid}}}{dt} = -5 \text{ mHz/sec} \]

Dynamic droop curve interpolates between 2 static droop curves based upon ROCOF.

- More aggressive static droop curve
- Less aggressive static droop curve

Graph showing % change in commanded power versus frequency [Hz] with dynamic droop curve and static droop curves labeled.
Dynamic Droop Curve Example

\[ \frac{df_{\text{grid}}}{dt} = -7 \text{ mHz/sec} \]

Dynamic droop curve interpolates between 2 static droop curves based upon ROCOF.

- More aggressive static droop curve
- Less aggressive static droop curve

Dynamic droop curve, \( f_{\text{grid}} \), \( \frac{df_{\text{grid}}}{dt} \)
Dynamic Droop Curve Example

\[
\frac{df_{grid}}{dt} = -8 \text{ mHz/sec}
\]

Dynamic droop curve interpolates between 2 static droop curves based upon ROCOF.
Dynamic Droop Curve Example

\[ \frac{df_{\text{grid}}}{dt} = -9 \text{ mHz/sec} \]

The dynamic droop curve interpolates between two static droop curves based upon ROCOF (Rate of Change of Frequency). The curve is more aggressive compared to the static droop curve.

The diagram shows the percentage change in commanded power against frequency. Three different droop curves are represented:
- DDC1: 3%, 10 mHz deadband
- SDC1: 5%, 50 mHz deadband
- SDC2: 2.5%

The dynamic droop curve is indicated by the blue dotted line and is more aggressive than the static droop curve represented by the red dashed line.
Dynamic Droop Curve Example

\[ \frac{df_{\text{grid}}}{dt} = -10 \text{ mHz/sec} \]

The dynamic droop curve interpolates between two static droop curves based upon ROCOF. The graph shows the relationship between frequency and the change in commanded power, with three different static droop curves: DDC1, SDC1, and SDC2. The more aggressive static droop curve is represented by a steeper slope, indicating a quicker response to frequency changes. The less aggressive static droop curve is represented by a gentler slope. Dynamic droop curves are used to ensure a smoother transition between static droop curves, providing a more stable and responsive power control system.
Wind PFC Using Dynamic Droop Curves
[A. Buckspan, J. Aho, P. Fleming, & L. Pao, 2012-]

Grid Simulation Results (with IEEE RTS-96)

- **No Wind**
- **Wind Baseline**
- **Wind APC**

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>990</td>
<td>60</td>
</tr>
<tr>
<td>995</td>
<td>60</td>
</tr>
<tr>
<td>1000</td>
<td>60</td>
</tr>
<tr>
<td>1005</td>
<td>59.85</td>
</tr>
<tr>
<td>1010</td>
<td>59.9</td>
</tr>
<tr>
<td>1015</td>
<td>60</td>
</tr>
<tr>
<td>1020</td>
<td>60</td>
</tr>
<tr>
<td>1025</td>
<td>60</td>
</tr>
</tbody>
</table>

- WECC begins shedding loads at 59.5 Hz
- ERCOT at 59.3 Hz
- 5% of generating capacity goes offline at $t = 1000s$
- 15% wind penetration
Higher wind penetration levels, higher levels of wind PFC participation, and more de-rating all improve grid response.

Structural loads generally decrease due to de-rating.
Recent and on-going work

- Stability analysis
  [Buckspan et al., ACC13]

- Developed AGC method

- Combined PFC and AGC methods
  [Aho et al., AIAA ASM13]

- Field testing on CART3 at NREL
  - Limited experimental results in the published literature
Initial Field Test Results

[Winter / Spring 2013]

-0.1
-0.05
0
-0.1
-0.15
Power [kW]

Freq Deviation [Hz]

Ideal
Field Test Input

Rated Power
Commanded Power
Generated Power

Active Power Control
Outline

- Wind Energy Background
- Wind Turbine Control
- Utility Grid Operation
  - Challenges of increasing penetrations of renewable energy
  - Possible solutions
    - Active power control of wind turbines

- Summary and Emerging Areas
Increasingly large, flexible turbines lend themselves to control solutions.

Many advanced control methods apply:
- Advanced generator torque control
- Advanced pitch control
- Combined feedforward/feedback pitch control

Higher penetrations of wind motivate APC with wind turbines:
- Wind turbines enable faster response to frequency events on the grid
- Proper market incentives should be established

[Photo courtesy of L. J. Fingersh, NREL]
Many Emerging Areas

- Coordinated control of arrays of wind turbines
- Active de-icing control of wind turbine blades in cold climates
- Modeling and control of floating offshore wind turbines

[Horns Rev 1 owned by Vattenfall. Photographer Christian Steiness.]
Active Power Control of Wind Farms


- Wind farm receives primary frequency control and secondary/tertiary frequency regulation commands
- Individual wind turbine power commands
Wind Turbine Control Area Acknowledgments

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Jason Marden  Ned Patton

as well as industry (who wish to remain anonymous)
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Eric Simley

Floris Teeuwisse

Shervin Shajiee

Jason Laks

Fiona Dunne

Andrew Buckspan

Jacob Aho

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Thank You