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

U.S. Electricity Generation by Fuel, All Sectors

Note: Labels show percentage share of total generation provided by coal and natural gas.

Source: Short-Term Energy Outlook, November 2012
EIA (US Energy Information Association)
Renewable electricity generation capacity

Note: Hydropower is omitted

Electricity Generation Capacity (GW)

Forecast →

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

Huge off-shore wind resource: US estimate is 54 GW
- 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
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
Wind Power Penetration - End of 2010

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

Capacity Installed in 2011

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

Source: GWEC
U.S. transmission grid as of 2006

www.sanfranciscosentinal.com

- 230,000 volts
- 345,000 volts
- 500,000 volts
- 765,000 volts
- High-voltage direct current
Utility-scale horizontal axis wind turbine (HAWT)

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:

\[ P = \frac{1}{2} \rho AC_p (\lambda, \beta) \omega^3 \]

- \( \rho \equiv \text{air density} \)
- \( A \equiv \text{rotor swept area} \)
- \( C_p \equiv \text{power coefficient} \)
- \( \beta \equiv \text{blade pitch angle} \)
- \( \lambda \equiv \text{tip-speed ratio} \equiv \frac{\text{speed of blade tip}}{\text{wind speed}} \)
- \( \omega \equiv \text{wind velocity} \)
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

\[ P_{\text{wind}} = \frac{1}{2} \rho AC_p w^3 \]
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:**
  \[
  \begin{align*}
  \dot{x} &= Ax + Bu + \Gamma u_D \\
  y &= Cx; \quad x(0) = x_0
  \end{align*}
  \]
  where plant parameters \((A, B, C, \Gamma)\) are **unknown**

- **Disturbance Generator:**
  \[
  \begin{align*}
  u_D &= \Theta z_D \\
  z_D &= L\phi_D; \quad z_D(0) = z_0
  \end{align*}
  \]
  where disturbance basis functions \(\Phi_D\) are **known** but amplitude \(L\) is **unknown**

  - Ex: Step disturbance: \(u_D = a_0 \cdot 1; \quad z_D = L\phi_D\) where \(a_0, L\) are unknown and \(\phi_D = 1\)

- **Reference Model:**
  \[
  \begin{align*}
  \dot{x}_m &= A_m x_m + B_m u_m \\
  y_m &= C_m x_m; \quad x_m(0) = x_0^m \\
  \dot{u}_m &= F_m u_m; \quad u_m(0) = u_0^m
  \end{align*}
  \]
  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:** \( y \equiv y - y_m \xrightarrow{t \to \infty} 0 \)

- **Control Law:**
  \[
  u = G_m x_m + G_u u_m + G_e e_y + G_D \phi_D
  \]

- **Controller Gains:**
  \[
  \dot{G} \equiv \begin{cases}
  \dot{G}_u = -e_y u_m^T h_u \\
  \dot{G}_m = -e_y x_m^T h_m \\
  \dot{G}_e = -e_y e_y^T h_e \\
  \dot{G}_D = -e_y \phi_D^T h_D
  \end{cases}
  \]
Model Matching Conditions

- Define **ideal trajectories** for plant:

  \[
  \begin{align*}
  \dot{x}_* &= Ax_* + Bu_* + \Gamma u_D \\
  y_* &= Cx_* = y_m; x_* (0) = 0
  \end{align*}
  \]

  where

  \[
  \begin{align*}
  x_* &= S_{11} x_m + S_{12} u_m + S_{13} z_D \\
  u_* &= S_{21} x_m + S_{22} u_m + S_{23} z_D
  \end{align*}
  \]

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

  \[
  \begin{align*}
  AS_{11}^* + BS_{21}^* &= S_{11} A_m; \quad AS_{12}^* + BS_{22}^* = S_{11} B_m + S_{12} F_m \\
  CS_{11}^* &= C_m; \quad CS_{12}^* = 0; \quad AS_{13}^* + BS_{23}^* + \Gamma \Theta &= S_{13}^* F; \quad CS_{13}^* = 0
  \end{align*}
  \]

  **Matching conditions are necessary and sufficient for existence of ideal trajectories**

  **Matching conditions exist if CB is nonsingular**

  **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 $u_m$ are bounded (i.e., all eigenvalues of $F_m$ are in the closed left-half plane and any eigenvalues on the $j\omega$-axis are simple);
2. The reference model $(A_m, B_m, C_m)$ is stable;
3. $\phi_D$ is bounded (i.e., all eigenvalues of $F$ are in the closed left-half plane and any eigenvalues on the $j\omega$-axis are simple);
4. $(A, B, C)$ is **Almost Strict Positive Real (ASPR)** (i.e., $CB > 0$ and the open-loop transfer function is minimum phase)

Then the adaptive gains $G_m, G_u, G_e, G_D$ are bounded, and **asymptotic tracking occurs**, i.e. $e_y = y - y_m = Ce_\ast \xrightarrow{t \to \infty} 0$

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)
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

<table>
<thead>
<tr>
<th>Controlled Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reduced Order Model</strong></td>
</tr>
<tr>
<td>All Open-Loop <strong>Unstable</strong> Modes that are ASPR</td>
</tr>
<tr>
<td><strong>All Residual Modes</strong></td>
</tr>
<tr>
<td>Q modes: Open-loop stable but <strong>not ASPR</strong></td>
</tr>
</tbody>
</table>

Assume original system \((A_p, B_p, C_p)\) can be partitioned as:

\[
\begin{align*}
\dot{\mathbf{x}} &= \begin{bmatrix} A & 0 \\ 0 & A_Q \end{bmatrix} \mathbf{x} + \begin{bmatrix} B \\ B_Q \end{bmatrix} u_p + \begin{bmatrix} \Gamma \\ \varepsilon \Gamma_Q \end{bmatrix} u_D \\
\dot{\mathbf{x}}_Q &= \begin{bmatrix} 0 & A_Q \\ A & 0 \end{bmatrix} \mathbf{x}_Q \\
y_p &= \begin{bmatrix} C \\ C_Q \end{bmatrix} \begin{bmatrix} \mathbf{x} \\ \mathbf{x}_Q \end{bmatrix} ; \quad \varepsilon \geq 0
\end{align*}
\]

Use RMF to remove these modes from controller feedback.
Adaptive controller using RMF

Nonlinear Wind Turbine Plant

\[ \begin{align*}
\dot{x} &= Ax + Bu \\
y &=Cx + Du
\end{align*} \]

Retained Modes

\[ \begin{align*}
\dot{x}_Q &= A_Q x_Q + B_Q u \\
y_Q &= C_Q x_Q
\end{align*} \]

Residual Modes

Adaptive Controller

Residual Mode Filter

\[ y_c = y_p - \hat{y}_Q \]
Addition of disturbance estimator & FLL

Nonlinear Wind Turbine Plant

Retained Modes
\[
\begin{align*}
\dot{x} &= Ax + Bu + \Gamma u_D \\
y &= Cx + Du
\end{align*}
\]

Residual Modes
\[
\begin{align*}
\dot{x}_Q &= A_Q x_Q + B_Q u + \Gamma_Q u_D \\
y_Q &= C_Q x_Q
\end{align*}
\]

Adaptive Controller
\[\hat{u}_D\]

Disturbance Estimator
\[\hat{y}_Q\]

Residual Mode Filter

Frequency-locked Loop

Bandpass Filter

US Patent Pending
Controls Advanced Research Turbine (CART)

CART2, NWTC, Golden, Colorado

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

- 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

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

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

Excursions from set-point cause higher blade loads

* 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

Image: www.vertigo.net.au
Leading causes of blade failures:

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

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

In-plane root bending moment for blade 1

Wind Speed (m/sec)

Damage Equivalent Loads

Percent reduction in generator set-point from rated value
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

No contingency control

Adaptive contingency control
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

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

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

Input: Above rated turbulent wind