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
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

thousand megawatthours per day


Coal 49.8% 49.6% 49.0% 48.5% 48.2% 44.4% 44.8% 42.3% 37.3% 40.1%
Natural gas 17.9% 18.8% 20.1% 21.6% 21.4% 23.3% 23.9% 24.7% 30.6% 27.2%
Petroleum 2.0% 2.1% 2.1% 2.2% 2.2% 2.2% 2.2% 2.2% 2.2% 2.2%
Nuclear 1.6% 1.7% 1.8% 1.9% 2.0% 2.1% 2.2% 2.3% 2.4% 2.5%
Hydropower 3.5% 3.6% 3.7% 3.8% 3.9% 4.0% 4.1% 4.2% 4.3% 4.4%
Renewables 3.4% 3.5% 3.6% 3.7% 3.8% 3.9% 4.0% 4.1% 4.2% 4.3%
Other sources 0.1% 0.1% 0.1% 0.1% 0.1% 0.1% 0.1% 0.1% 0.1% 0.1%

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

Source: www.owenscorning.com
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)

Total Installed Capacity (MW) (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

Western Interconnection

Eastern Interconnection

Texas Interconnection

Not While I'm Writing! Now I'm Mad!

HOW TO SURVIVE A POWER OUTAGE!

230,000 volts
345,000 volts
500,000 volts
765,000 volts
High-voltage direct current

www.sanfranciscosentinal.com

DOE, 2006
Utility-scale horizontal axis wind turbine (HAWT)

- **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

Image: NWTC, NREL
Equation for power captured by a wind turbine:

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

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

\[ P_{\text{wind}} = \frac{1}{2} \rho AC \rho w^3 \]
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: \( e_y = y - y_m \xrightarrow{t \to \infty} 0 \)

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

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

- **Define ideal trajectories** for plant:

\[
\begin{align*}
\dot{x}_* &= A x_* + B u_* + \Gamma u_D \\
y_* &= C x_* = y_m; x_*(0) = x_0
\end{align*}
\]

\[(*)\]

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:

\[
\begin{align*}
A S_{11}^* + B S_{21}^* &= S_{11}^* A_m \\
A S_{12}^* + B S_{22}^* &= S_{11}^* B_m + S_{12}^* F_m \\
C S_{11}^* &= C_m \\
C S_{12}^* &= 0 \\
A S_{13}^* + B S_{23}^* + \Gamma \Theta &= S_{13}^* F \\
C S_{13}^* &= 0
\end{align*}
\]

Solutions to matching conditions must exist for analysis purposes, BUT they don’t need to be known for adaptive controller design!
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. $e_y \equiv y - y_m = Ce_\ast \xrightarrow{t \to \infty} 0$

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

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

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

Nonlinear Wind Turbine Plant

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

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

Adaptive Controller

\[
y_c = y_p - \hat{y}_Q
\]

Residual Mode Filter

\[
\hat{y}_Q
\]
Addition of disturbance estimator & FLL

Nonlinear Wind Turbine Plant

\[ \dot{x} = Ax + Bu + \Gamma u_D \]
\[ y = Cx + Du \]

Retained Modes

\[ \dot{x}_Q = A_Q x_Q + B_Q u + \Gamma_Q u_D \]
\[ y_Q = C_Q x_Q \]

Residual Modes

Adaptive Controller

\[ \hat{u}_D \]

Disturbance Estimator

Residual Mode Filter

Frequency-locked Loop

\[ \tilde{e}_y = y_p - \hat{y}_Q \]

Bandpass Filter

\[ \text{US Patent Pending} \]
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
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/
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*

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

In-plane root bending moment for blade 1

- 0%
- 3%
- 5%
- 10%

Wind Speed (m/sec)

Damage Equivalent Loads

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 Wind Input

Generator set-point

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