Adaptive Control of Variable-Speed Variable-Pitch Wind Turbines Using RBF Neural Network

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October 2012, London, ON

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OVERVIEW

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2. Wind Turbine Modeling
3. Torque Control Using RBF Neural Network
4. Pitch Control Using RBF Neural Network
5. Results of Simulations Using FAST Software
6. Future Work: $L_1$-Optimal Control of Wind Turbines

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Wind Turbine Control System

Outer Loop (slow time response)
- Aerodynamics
- Mechanical Subsystems (Drive Train and Structure)

Inner Loop (fast time response)
- Power Generator Unit
- Pitch Servo

[Ref: Boukhezzar, B., H. Siguerdidjane, “Nonlinear Control with Wind Estimation of a DFIG Variable Speed Wind Turbine for Power Capture Optimization]
Control Strategy and Objectives

- Variable-Speed, Variable-Pitch Control

![Ideal power curve](Ref: Wind Turbine Control Systems, Page 51)

- **Control Objectives:**
  1) Energy Capture
  2) Power Quality
  3) Mechanical Loads

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Non-linear Equations of Wind Turbine

- **Drive-train shaft dynamics:**
  \[(J_R + J_G)\ddot{\Omega} + C_L\Omega + T_{el_e}(\Omega, V_w) - T_a(\Omega, V_w, \dot{d}) = 0\]

- **Elastic tower fore-aft motion:**
  \[M_T\ddot{d} + C_T\dot{d} + K_T d - F_a(\Omega, V_w, \dot{d}, \dot{d},) = 0\]

- **Where:**
  - \(\Omega\): Rotor Speed
  - \(d\): Tower top Displacement
  - \(\lambda\): Tip-Speed Ratio
  - \(C_T\): Power Coefficient
  - \(V_w\): Wind Speed
  - \(T_a\): Aerodynamic Torque:
  - \(T_{el_e}\): Generator Torque
  - \(F_a\): Thrust Force
  - \(M_t, C_t, K_t\): Equivalent Mass, Damping Ratio, and Stiffness of Tower

Ref: C.L. Bottaso, Politecnico di Milano, Italy, Wind Turbine Modeling and Control
Non-linear Equations of Wind Turbine

- \( \lambda \): Tip-Speed Ratio
  \[
  \lambda = \frac{\Omega R}{V_w - \dot{d}}
  \]

- \( T_a \): Aerodynamic Torque
  \[
  T_a = \frac{1}{2} \rho \pi R^3 \frac{C_p(\lambda, \beta_e)}{\lambda} (V_w)^2
  \]

- \( F_a \): Thrust Force
  \[
  F_a = \frac{1}{2} \rho \pi R^2 C_f (V_w - \dot{d})^2
  \]

- \( C_p \): Power Coefficient
  \[
  C_p(\lambda, \beta) = c_1 \left( \frac{c_2}{\lambda_i} - c_3 \beta - c_4 \right) e^{\frac{-c_5}{\lambda_i}} + c_6 \lambda
  \]
  \[
  \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta - \beta^3 + 1}
  \]
  \[
  c_1 = 0.5176, c_2 = 116, c_3 = 0.4, c_4 = 5, c_6 = 0.0068
  \]

- **Control Inputs**: Generator Torque (Tel) & Pitch Angle (\( \beta_e \))
FAST Wind Turbine Simulation Software

- FAST: (Fatigue, Aerodynamics, Structures and Turbulence) is an Aero-elastic Simulator.
  Developed by NREL (National Renewable Energy Laboratory), Golden, CO
- A Variable-Speed Variable-Pitch Wind Turbine:
  NREL-Offshore-Baseline-5MW (Parameters developed by NREL)

<table>
<thead>
<tr>
<th>Rating</th>
<th>5 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Orientation, Configuration</td>
<td>Upwind, 3 Blades</td>
</tr>
<tr>
<td>Control</td>
<td>Variable Speed, Variable Pitch</td>
</tr>
<tr>
<td>Rotor, Hub Diameter</td>
<td>126 m, 3 m</td>
</tr>
<tr>
<td>Hub Height</td>
<td>90 m</td>
</tr>
<tr>
<td>Cut-In, Rated, Cut-Out Wind Speed</td>
<td>3 m/s, 11m/s, 25 m/s</td>
</tr>
<tr>
<td>Cut-In, Rated Rotor Speed</td>
<td>6.9 rpm, 12.1 rpm</td>
</tr>
<tr>
<td>Rotor Mass</td>
<td>110,000 kg</td>
</tr>
<tr>
<td>Optimal Tip-Speed-Ratio</td>
<td>7.55</td>
</tr>
<tr>
<td>Rated Generator Torque</td>
<td>43,100 Nm</td>
</tr>
<tr>
<td>Maximum Generator Torque</td>
<td>47,400 Nm</td>
</tr>
<tr>
<td>Rated Generator Speed</td>
<td>1174 RPM</td>
</tr>
</tbody>
</table>
Radial-Basis Function (RBF) Neural Networks

- RBF Neural Networks Approximate the Nonlinear Dynamics of Control System
- Robust to Uncertainties and Disturbances in the System
- Fast Time Response

\[ \phi(||x - x^{(i)}||) = \exp\left(-\frac{||x - x^{(i)}||}{2\sigma_i^2}\right) \]

A two-point radial-basis function [Ref: Stanislaw H Zak, Systems and Control, pg 495]
Torque Control

- At wind speeds lower than rated wind speed
- Maximum power capture
- Constant Pitch Angle
- Equation is in the affine form

\[ \dot{\Omega} = f(\Omega, V_w) + gu \]

\[ f(\Omega, V_w) = \frac{1}{2} \rho \pi R^3 \frac{C_p(\lambda)}{\lambda} (V_w)^2 - C_t \Omega \]

\[ g = \frac{-1}{(J_R + J_G)} \]

\[ u = T_{el_e} (\text{control input}) \]

- RBF NN Approximator

\[ \frac{f(\Omega, V_w)}{g} = Q(\Omega, V_w)w + d(\Omega, V_w) \]
Control Design and Updating Rule Using Lyapunov Theory

- Tracking error:
  \[ e = \Omega - \Omega_{opt}(V_w) \]

- Controller:
  \[ \hat{u} = T_{ele} = -Q(\Omega, V_w)\hat{w} + k \left( \Omega - \Omega_{opt}(V_w) \right) \]

- Lyapunov function:
  \[ V = \frac{1}{(-2g)} e^2 + \frac{1}{2\beta_1} \hat{w}^T\hat{w} \quad , \quad g < 0 \text{ (constant)} \quad , \quad \beta_1 > 0 \]

- Robust weight update using e-modification method:
  \[ \dot{\hat{w}} = -\beta_1 \left( Q^T(\Omega, V_w) \left( \Omega - \Omega_{opt} \right) + \nu \left| \Omega - \Omega_{opt} \right| \hat{w} \right) \quad , \quad \nu > 0 \]
Pitch Control

- At wind speeds Higher than rated wind speed
- Limiting the power capture at nominal capacity of wind turbine
- Constant generator torque
- Equation is in the non-affine form

\[ \dot{\Omega} = f(V_w, \Omega, \beta_e) \]

\[ \dot{\Omega} = \frac{1}{2} \rho \pi R^3 C_p(\lambda, \beta_e) \frac{(V_w)^2}{(J_R+J_G)} - \frac{1}{(J_R+J_G)} (T_{nom} + C_L \Omega) \]
Control Design and Updating Rule Using Lyapunov Theory

- **Transformation (Inverse Dynamics Method)**
  \[ v = \dot{x}, \quad v = f(x, u^*) \quad \nu - f(x, \alpha(x, v)) = 0 \]
  \[ e = x - x_{des} \quad \nu = \dot{x}_{des} - ke \]

- **Approximating ideal controller using NN:**
  \[ u^* = \varphi(x, \nu)w^* + \varepsilon(x) \quad u = \varphi(x, \nu)\hat{w} \]

- **Mean value theorem:**
  \[ f(x, u) = f(x, u^*) + (u - u^*)f_u \]
  \[ f_u = \left[ \frac{\partial f(x,u)}{\partial u} \right]_{u=u_\lambda}, \quad u_\lambda = \lambda u + (1 - \lambda)u^* \]

- **Lyapunov function:**
  \[ V = \frac{1}{2} \frac{e^2}{-f_u} + \frac{1}{2\beta} \hat{w}^T \hat{w}, \quad f_u < 0 \]

- **Robust weight updating rule:**
  \[ \dot{\hat{w}} = -\beta (e\varphi^T(x, \nu) + v|e|\hat{w}) \]

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Wind Speed Profile

![Wind Speed Profile Graph](image)
Results (Electrical Output Power)
Results (Control inputs)
Results of Simulation Using FAST Software for Region I (Maximum Power area)

- **Wind Inputs:** TurbSim-generated 24 x 24 grids of IEC Class A Kaimal-spectrum turbulence
- Six turbulence realizations per mean wind speed are simulated.

![Graph showing Electrical Power Output vs. Average Wind Speed]

- **Neural Network Controller**
- **PI Controller**

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Results of Simulation Using FAST Software for Region III (Rated Power Area):

- Comparing The Performance of Controllers:
  1) Gain-Scheduled PI-Control (Developed by NREL)
  2) Proposed Adaptive Neural Network Control
Results (Electrical Output Power)
Results (Control input1: Generator Torque)
Results (Control input2: Pitch Actuation)
Introduction to $L_1$-Optimal Control

- The final purpose of $L_1$-optimal control is to find a controller ($K$) to stabilize the closed-loop system and minimize the $L_\infty$-norm between disturbance input ($w$) and performance output ($z$).

\[ \|z\|_\infty < \gamma \|w\|_\infty \]

Why $L_1$-Optimal Control?

- **1)** Persistent exogenous disturbances and noises. These inputs obviously have infinite energy ($L_2$-norm). However, they have bounded magnitudes ($L_\infty$-norm).
  - EX: varying wind conditions that face the wind turbine.

- **2)** Direct time-domain performance specifications
  - EX: overshoot, bounded magnitude, bounded slope, or actuator saturation

LMI (Linear Matrix Inequality) Approach to $L_1$-Optimal Control

- LMI method results in a convex minimization problem subject to LMI constraints.
Thank You For Your Attention

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