Two Control Problems in Wind Energy

Mario A. Rotea
Mechanical Engineering
rotea@utdallas.edu
Structural Control of Floating Wind Turbines

Collaboration with Matthew Lackner
The Big Picture

• 20% electricity from wind energy by 2030
  – 37 GW (2010) → 305 GW (2030)

• Critical elements for 2030 scenario*
  – Reduce capital costs (10%)
  – Reduce O&M costs (35%)
  – Improve performance (wind farm)
  – Improve transmission infrastructure
  – Need land and offshore installations
  – Communication & outreach, policy

• Advanced control systems can improve wind turbine reliability and reduce O&M costs

Offshore Wind Technology Today

- Initial development and demonstration stage; 22 projects, 1135 MW installed
- Fixed bottom shallow water 0-30m depth
- 2 – 5 MW upwind rotor configurations
- 70+ meter tower height on monopoles and gravity bases
- Mature submarine power cable technology
- Existing oil and gas experience is essential
- Reliability problems and turbine shortages have discouraged early boom in development.
- Cost are not well established in the US.

Problem we want to solve


~ 3 yrs ago
Floating wind turbine technology

- Higher wind speeds and energy capture over deep waters (> 60 m)
  - 60% of U.S. wind resource past 60 m depth
  - Floating systems the only option

- Other incentives of floating systems
  - Site independence, mass production
  - Assembly greatly simplified
  - Lower impact on human activities (and environment)

- Challenges
  - No experience
  - Reduced accessibility
  - Increased motion and mechanical loads due to coupled wind and wave loading

Hywind, 2009
- Size: 2.3 MW
- Weight: 138 tons
- Height: 65 m
- Rotor diameter: 82.4 m
- Water depths: 120-700 m
Structural control of floating wind turbines

- **Objective**
  - Add new control degrees of freedom to reduce motion and mechanical loads
  - Improve reliability, reduce O&M costs

- **Approach**
  - Develop passive & active systems for managing dynamic loads and motions
  - Incorporate/develop new advances in actuator technology and control theory
Floating turbine with tuned mass damper

• NREL 5-MW turbine model
  – 3 bladed, upwind, 126 m rotor diameter, 90 m hub height
  – Barge platform
  – FAST-SC: NREL code FAST plus structural control degrees of freedom

• Tuned mass damper (TMD)
  – Mass-spring-damper system in nacelle, fore-aft translation
  – Parameters tuned using FAST-SC to minimize tower fore-aft displacement
  – Reaction on nacelle to external force $f$ serves as control input
Structural control system

- Sensor signals
  - Tower top acceleration in fore-aft direction (TTA)
  - Platform pitch acceleration (PPA)

- Control signal
  - Force f on nacelle by TMD

- Design process
  - Design model from synthetic data generated with FAST-SC using Matlab’s SysID toolbox
    - Design model captures essential dynamics: 1st fore-aft tower bending, platform pitch, TMD
  - Want the tradeoff between load/vibration reduction and the cost of active control
Controller design process

Ideal Process
- Define evaluation criteria to measure loads & vibration reduction and cost of active control
- Determine the set of Pareto optimal controllers for the selected evaluation criteria
- Exact but time consuming

Practical Process
- Select a controller design method known to work well for damping augmentation and disturbance rejection
- Use the chosen method to generate a family of controllers with increasing control authority
- Calculate the evaluation criteria for this controller family
- Approximate but very efficient

Loading & Vibration vs Control Cost
H∞ loop-shaping yields nearly Pareto optimal solutions in structural control problems.

H∞ loop-shaping is amenable to generating a family of controllers with increasing control authority.

Controller family obtained by calculating the Loop Shaping Controller for each fixed GAIN.

Estimate tradeoffs by calculating evaluation criteria using detailed FAST-SC simulations for each controller.
Evaluation criteria

• Structural
  – Tower base fore-aft damage equivalent load (DEL)

• Active control cost
  – Active control power
  – TMD stroke

• Computed using FAST-SC simulations under realistic wind/wave loading

• Other criteria not shown
  – Tower base side-to-side DEL, Blade root flapwise DEL, power error, peak loads, and pitch actuator usage
  – All criteria improve with active control
Tower fore-aft DEL reduction

Passive TMD → 10% reduction

3% Active Power → 30% reduction

Baseline
Remarks

• Active or passive structural control
  – Reduce mechanical loads in wind turbines
  – Do not require transfer of power or data to the blade reference frame
  – Power for active control obtained from excess power when wind speed is high (region 3)
  – Conventional active systems may have large stroke requirements

• Impact
  – More reliable wind turbine $\rightarrow$ reduced O&M
  – Lighter wind turbine?

• To probe further
Control of Battery Storage Systems for Wind Energy Applications

Collaboration with Ali Borhan and Daniel Viassolo
Intermittency Issue

Example: 24-Hr Output From NREL Monitoring at Buffalo Ridge Sub, Lake Benton, MN
Wind Farm with Battery Storage

• The combined power of the wind farm and the BSS goes to the grid
• BSS is charged/discharged to deliver an operator reference power with appropriate battery usage
• BSS is controlled by commanding the battery current
Control Objectives

• Power error objective
  – To minimize the error between the output power of the system and an operator reference power over an Optimization horizon $H$
  – Minimization is subject to battery constraints (SOC, current, ...)

• Battery life objective
  – To minimize the loss of battery life in order to reduce the O&M and replacement costs
Models for Control Objectives

Power error objective

\[ P_{\text{error}} = \frac{1}{H} \int_{t}^{t+H} \left| P_{\text{out}}(\tau) - P_{\text{ref}}(\tau) \right| d\tau \]

with

\[ P_{\text{out}}(\tau) = P_{\text{wind}}(\tau) + P_{bs}(\tau) \]
\[ P_{bs}(\tau) = n_{\text{batt}}V_{\text{batt}}(\tau)I_{\text{batt}}(\tau) \]

Battery dynamics and constraints*

\[ \frac{dSOC}{d\tau} = \frac{I_{\text{batt}}(\tau)}{C_{\text{batt}}} \]
\[ I_{\text{batt,min}} \leq I_{\text{batt}}(\tau) \leq I_{\text{batt,max}} \]
\[ SOC_{\text{min}} \leq SOC(\tau) \leq SOC_{\text{max}} \]

* Note that the battery parameters can be function of battery operating conditions
Models for Control Objectives (continued)

Battery life objective

- Weighted Amp-hr throughput model for the battery life consumption over $H$

- Weight factors to model the irregular operating conditions

- *Life objective*: terminal weighted Amp-hr throughput over $H$

\[
\frac{dW_{Ah_{batt}}}{d\tau} = \begin{cases} 
\prod_i f_i(\tau) \cdot I_{batt}(\tau) & \text{if } I_{batt}(\tau) \geq 0 \\
0 & \text{if } I_{batt}(\tau) < 0 
\end{cases}
\]

Life Objective: $W_{Ah_{batt}}(t + H)$

\[
f_{SOC}(t) = 1 + (c_{SOC,0} + c_{SOC,min} \cdot (1 - SOC_{min}(t))^{\mu t}) 
\times \sqrt{\frac{I_{ref}}{I}} \Delta t_{SOC}(t)
\]
Control Problem

Given

- \( P_{\text{ref}} \): reference power demand from operator over an optimization horizon \( H \)
- \( P_{\text{wind}} \): an estimate of the wind power over \( H \)
- Current state of BS (e.g., SOC,...)

Find the command current \( I_{\text{batt}} \) over the optimization horizon \( H \) to jointly minimize the power and battery life objectives:

\[
J = w_{\text{error}} \cdot P_{\text{error}} + w_{\text{life}} \cdot w_{Ah\text{batt}} (t + H)
\]
Solution to Control Problem

- Problem is decomposed into three stages
- Stage 1 (performance)
  - Find family of current profiles that minimize power error subject to terminal SOC constraints
- Stage 2 (battery life analysis)
  - Calculate the terminal weighted Amp-hr throughput for each current profile
- Stage 3 (find best compromise)

\[
J_n^* = w_{\text{error}} \cdot P_{\text{error},n}^* + w_{\text{life}} \cdot wAh_{\text{batt},n}^*
\]

\[
n = 1 \cdots L
\]

\[
I_{\text{batt, opt}}^*(\tau) = \arg \min_{\{I_{\text{batt},1}^*, \ldots, I_{\text{batt},L}^*\}} \{J_1^*, \ldots, J_L^*\}
\]
Simulation Conditions

- Actual wind farm data from a 150 MW wind farm in Texas
- One-hour power dispatching scenario over a 24 hour simulation time
- Control sampling time = 1 minute; Prediction horizon $H = 10$ minutes
- 10 pre-defined terminal SOC’s
- Constraints: $\text{SOC}_{\text{max}} = 1.0$, $\text{SOC}_{\text{min}} = 0.3$, $I_{\text{batt, max}} = I_{\text{batt, min}} = 400$ A
- Nominal battery storage specifications: 18 (MW) maximum power with 18 MW-hr capacity (12% of the wind farm maximum power)
- Dynamic Programming to solve the optimization problem in stage 1
Simulation results

![Graph showing simulation results with various w_error/w_life values and minimum power error标注。]
Solution for Minimum Power Error

\[ P_{\text{out}} = P_{\text{wind}} + P_{\text{bss}} \]

\[ \text{SOC} \]

\[ |I_{\text{batt}}| \leq \text{400 Amp} \]

\[ w_{Ah,\text{batt}} \text{ (Amp-hour)} \]

Error (MW)

\[ P_{\text{out}} - P_{\text{ref}} \text{ with averaged power error = 0.5977 (MW)} \]

1472.6 (Amp-hr)
Solution for \( w_{\text{error}} \)/\( w_{\text{life}} = 80 \)

\[
P_{\text{out}} = P_{\text{wind}} + P_{\text{bss}}
\]

- \( 0.3 \leq \text{SOC} \leq 1 \)
- \(-400 \text{ (Amp)} \leq I_{\text{batt}} \leq 400 \text{ (Amp)} \)

\[
\text{Error (MW)} = P_{\text{out}} - P_{\text{ref}} \quad \text{with averaged power error} = 0.8126 \text{ (MW)}
\]

\[
\text{wAh}_{\text{batt}} = 1093.3 \text{ (Amp-hr)}
\]
Remarks

• Developed a real-time optimization-based strategy to reduce both the power error and the loss of the battery life

• The strategy is modular
  – More elaborate models can be used for the battery life without more complex optimization solvers

• To probe further
  – Borhan, Rotea, Viassolo, “Optimization-based power management of a wind farm with battery storage,” submitted to Wind Energy
Message

• Control technology will
  – Improve the reliability of wind turbines
  – Improve the efficiency of wind farms
  – Enable the integration of wind energy and storage systems