Wind Turbine Modeling and Control

CE4011: October 25, 2018

Peter Seiler
- **James Blyth, 1887**: 1st electric wind turbine in Marykirk, Scotland. (Not Shown)
- **Turbine Shown, ~1890**: Enough power “to light ten 25-volt bulbs.” [Ref: Hardy, 2010]
• Charles Brush, 1888: 1st automatic electric wind turbine in Cleveland, OH. (17m diam, 12kW)
• **Clipper Liberty, 2012:** Modern utility scale turbine in Rosemount, MN. (96m diam, 2.5MW)

• \( \frac{C_{p,\text{Liberty}}}{C_{p,\text{Brush}}} = 6.5 \)
Outline

• Introduction to Feedback Control

• Wind Turbines: Modeling, Control, and Fault Detection

• Wind Farms: Modeling and Control

• Conclusions
Introduction to Feedback Control
What is control?

• The idea of feedback
• Open vs. closed loop systems
• Block diagrams – a useful abstraction
• Current status
The Idea of Feedback

• Feedforward
  • Also called open loop control
  • Make a plan and execute it

• Feedback
  • Also called closed loop control
  • Compare the actual result with the desired result and take actions based on difference
  • Goal: Reduce the effects of disturbances & dynamic variations
**Open vs. Closed Loop: Simple Static System**

- **Goal:** Choose $u$ so that $y = 1$

- **Open Loop:**
  - Preplan to choose $u=0.2$
  - Output is $y=1+d$
  - Goal is not achieved ($y \neq 1$) due to disturbance

- **Closed Loop:**
  - Measure error $e = 1-y$
  - Choose $u = k(1-y)$ so that $y=5k(1-y)+d \rightarrow y = (5k+d) / (5k+1)$
  - For very large $k$ we have $y \approx 1$ even if there is a disturbance
Feedback: Examples
Automotive Cruise Control

Objective: Use the engine throttle to track a desired speed specified by the driver.

User interface

Vehicle
Block Diagrams

- Capture the essence
- Hide the rest
- Abstraction
- Also some limitations

- Block diagrams: similarity between different types of control systems
Open Loop

• Open Loop: Compute an engine throttle angle based on the desired velocity.

• Issue: Incomplete knowledge of the car dynamics
  • Uncertain mass, e.g. different #’s of passengers
  • Varying environment conditions, e.g. hills and wind
  • Imprecise models for complex effects, e.g. engine dynamics and tire forces.
Closed Loop

- Closed Loop: Update the throttle command based on a measurement of the current vehicle speed.
- Feedback is the basic principle used to control the system despite our incomplete knowledge.
- The use of feedback involves tradeoffs
  - Stability, robustness, noise rejection
Cruise Control Block Diagram

Desired Velocity → Error → Controller → Throttle Cmd. → Actuator → Car → Sensor → Measured Velocity

Slope of Road / Uncertain Mass

Error feedback loop
The reference (desired velocity) is the desired condition for the system.
The algorithm computations are done on an embedded processor.
The plant (car) is the system being controlled.
The actuator (throttle motor) is a device used to control the plant.
The sensor (wheel speed sensor) is a device used to measure the behavior of the plant.
Uncertainties/Disturbances

Desired Velocity $\rightarrow$ Error $\rightarrow$ Controller $\rightarrow$ Throttle Cmd. $\rightarrow$ Actuator $\rightarrow$ Car $\rightarrow$ Sensor $\rightarrow$ Measured Velocity

- Slope of Road
- Uncertain Mass

- Throttle Actuator
- Sensor
Control Design

Objective: Maintain the desired velocity

Considerations:

- Transient response (rise time, overshoot)
- Changes in desired velocity
- Driver comfort (control effort)
- Disturbances, model uncertainty, sensor noise
Control Design

• Design Process
  1. Model the system: Differential equations
  2. Design the controller: PID control is a basic technique
  3. Analyze and simulate: Theory + MATLAB
  4. Implement the controller and experiment
  5. Iterate
Proportional-Integral-Derivative (PID) Control

\[ u(t) = k_p e(t) + k_i \int_0^t e(\tau) d\tau + k_d \frac{de(t)}{dt} \]
Wind Turbines: Modeling, Control, and Fault Detection
Outline

• Eolos Wind Consortium

• Wind Turbine Modeling, Control and Fault Detection

• On-going Research at UMN

• Conclusions and Future work
Eolos Consortium

- Established via US DOE Grant
  - http://www.eolos.umn.edu/
- Wind Energy Essentials Course
- Wind Field Station
  - UMore Park located 25 miles south of Twin Cities
  - 2.5 MW, 96m Liberty Turbine
  - Custom blade and tower sensors: accels / strain gauges
  - 130m Met tower
  - All data transmitted back to UMN

Clipper Liberty Turbine
Commissioned on 10/25/2012
Performance Objectives

1. Maximize captured power

\[ P = \frac{1}{2} \rho A v^3 C_p \]

*Power in Wind*  *Power Coefficient: Function of turbine design, wind conditions, and control*

2. Minimize structural loads

3. Reduce operational downtime
Turbine Components

Figure from the US DOE
Newton’s second law for rotational systems

\[ J \ddot{\omega} = \tau_a(\omega, v, \beta) - \tau_g \]

Control inputs are the generator torque (\(\tau_g\)) and blade pitch (\(\beta\)).

Rotational inertia of blades, rotor and drivetrain

Aerodynamic torque depends on rotor speed (\(\omega\)), wind speed (\(v\)), and blade pitch angles (\(\beta\)).
Power Coefficient, $C_p$

- $C_p := \frac{P_{captured}}{P_{wind}} = C_p(\beta, \lambda)$
  - $\beta =$ Collective blade pitch
  - $\lambda =$ Tip speed ratio $= \frac{\omega R}{v}$

- Aerodynamic torque

$$\tau_a = \frac{P_{captured}}{\omega} = \frac{\rho A v^3 C_p(\beta, \lambda)}{2\omega}$$

Figure from:
Turbine Modeling

- Rigid body model neglects
  - Flex modes: drivetrain, blade and tower
  - Detailed turbine aerodynamics
- Drivetrain flexibility and tower fore/aft modes are important in the control law design
- Higher fidelity models
  - State-space linearizations (periodic and time-invariant)
  - Fluid-structure interaction models (Stolarski, UMN)
  - Turbine interaction models (Sotiropoulos, Chamorro, et al)
Wind Turbine Control

• Control strategies depend on the wind conditions
  • Supervisory control and mode logic
  • Yaw control
  • Power capture at low wind speeds
  • Rated power + load reduction at high wind speeds

• Good Survey References
Simplified Turbine Operating Modes

- Initialize
- Wind Sense
- Ramp Up Speed
- Ramp Up Power
- RUN

Diagram shows the transition between different operating modes in a turbine system.
Typical Operating ("Run") Modes

Plot based on Clipper Liberty C100 2.5MW turbine assuming $C_{p,max} = 0.4$
(Theoretical bound for power capture given by Betz Limit: $C_{p,Betz} = 0.59$)
Region 2 Control

- **Objective**: Maximize captured power
- **Strategy**: Hold $\beta = \beta_{\text{opt}}$ (constant) and use $\tau_g$ to track $\lambda_{\text{opt}}$

Figure from: K. Johnson, L. Pao, M. Balas, and L. Fingersh, Control of Variable Speed Wind Turbines, IEEE Control Systems Mag., June 2006
Region 2: Possible Control Strategy

- Compute desired rotor speed using the optimal tip speed ratio (TSR) and measured wind speed.

\[ \omega_{des} = \frac{\lambda_{opt} v}{R} \]

- Issues:
  - Shadowing effects corrupt wind speed measurement
  - Uncertainty in power coefficient model
Region 2: Standard Controller

- Control law (Johnson, et al, 2006 Control System Mag.)

\[ \tau_g = K \omega^2 \quad \text{where} \quad K = \frac{1}{2} \rho AR^3 \frac{C_{p,\text{max}}}{\lambda_{\text{max}}^3} \]

- Comments
  - Convergence to optimal power capture (\( \lambda \) converges to \( \lambda_{\text{max}} \)) in steady wind. See next slide for proof.
  - Only requires rotor speed sensor
  - Control law still depends on uncertain power coefficient model. Adaptive laws have been developed.
Region 3 Control

- **Objective**: Maintain rated power and reduce loads
- **Strategy**: Hold $\tau_g = \tau_{\text{rated}}$ (constant) and use $\beta$ to track $\omega_{\text{rated}}$
- **Reference**:  
Region 3 Control

• Issues:
  • Excitation of flexible modes, e.g. tower fore/aft
  • Loads on blades due to wind gusts

• Advanced control methods
  • Reduce tower fore/aft with notch filters and/or accelerometer measurements in the nacelle
  • Use individual blade pitch control to reduce loads
  • Reduce drivetrain vibrations by adding a small generator torque ripple computed by filtering the rotor speed measurement.
Fault Detection and Diagnostics

- Reduce downtimes
- Reduce maintenance costs
- Prevent catastrophic failures

Damaged Gear Teeth (Image courtesy of Mesabi Range Wind Technology Program)
**Individual Pitch Control**

**Issue:** Structural loads increase at high wind speeds and these loads depend on the rotor position.

**Idea:** Use individual blade pitch control and advanced multi-variable control algorithms to reduce structural loads.

Wind Farms: Modeling and Control
Wind Farm Control

• Wind Farm Control
  • Maximize Power
  • Mitigate Loads
  • Enable operation similar to conventional power plants

• Understand aerodynamic interactions in a wind farm

Horns Rev 1 (Photographer: Christian Steiness)
Turbine Model: Actuator Disk + Park Model

Turbine Efficiency:
\[ C_P(a) = 4a(1-a)^2 \]

Velocity Deficit (Jensen, 83):
\[ k(x) = 2 \left( \frac{D}{D+2k_r x} \right)^2 \]

\[ P = \frac{1}{2} \rho A v^3 C_P(a) \]

\[ v = v_\infty (1-k(x)a) \]
Derivation of Park Model

Assumptions
1. Steady Inflow
2. Uniform velocity in wake cross-section
3. Linear wake expansion
4. Betz $U_0 = \frac{U_\infty}{3}$

Conservation of Mass

$$-\pi r_0^2 U_0 - \pi (r^2 - r_0^2) U_0 + \pi r^2 U_1 = 0$$

$$U_1 = \left(1 - \frac{2}{3} \left(\frac{r_0}{r_0 + kx}\right)^2\right) U_\infty$$

Wake Expansion Coefficient
Coordinated Control: Two Turbines

Johnson & Thomas, ACC, 2009
• **Objective:** Determine (quasi-steady) control inputs to maximize power produced by an array of turbines

Ref: Bitar and Seiler, ACC, 2013
Power Maximization: Near Field

- Problem: Determine joint induction factor \( a = (a_1, a_2, \ldots, a_N) \) to maximize total power \( J(a, v_\infty) = \sum_{i=1}^{N} P_i(a_i, v_i) \).
- Optimal induction factors obtained via Dynamic Programming

**Bellman Equation:** Solve backwards iteration for value function (power produced by turbines \( i,...,N \) with inlet velocity \( v \))

\[
J_i^o(v) = \max_{a \in \mathcal{A}_i} \left\{ P_i(a, v) + J_{i+1}^o(v(1 - a \kappa_{i,i+1})) \right\}
\]

**Boundary Condition:**

\[
J_N^o(v) = \max_{a \in \mathcal{A}_N} P_N(a, v)
\]
Aerospace Engineering and Mechanics

Power Maximization: Near Field

- Problem: Determine joint induction factor $a = (a_1, a_2, \cdots, a_N)$ to maximize total power $J(a, v_\infty) = \sum_{i=1}^{N} P_i(a_i, v_i)$.

- Dynamic Programming Results

**Optimal Induction Factors:** Obtained via backwards iteration

$$a_i^o = \frac{1}{3} \left( \frac{2 - 3\phi \kappa^2 - \sqrt{1 - 12\phi \kappa^2 + 9\phi \kappa + 3\phi \kappa^3}}{1 - \phi \kappa^3} \right)$$

$$\phi_i = (1 - a_i^o \kappa_{i,i+1})^3 \phi_{i+1} + a_i^o (1 - a_i^o)^2 \quad (BC: \phi_{N+1} = 0)$$

For $\kappa_r = 0$

$$a_i^o = \frac{1}{2(N - i) + 3}$$

For uniformly spaced infinite arrays

$$\frac{C_P^o - C_P}{C_P} = 8.33\%$$
Key Questions
1. What is the impact of the control law on the trailing wake?
2. What is appropriate level of model fidelity required for coordinated wind turbine control?
3. Can we take advantage of wake interactions to better integrate wind into the energy system?
SAFL Large Eddy Simulation

• **Approach:** Use high fidelity simulations
  - Flow: 3-D incompressible Navier-Stokes equations
  - Turbine: Fixed speed or tip speed ratio

• **Opportunity:** Integrate Clipper dynamics/control law
  - Joint work with Yang, Annoni, and Sotiropoulos
Wind Tunnel and Field Tests

• **Approach:** Wind tunnel tests using a 3 turbine array
  - Experiments with turbine spacing by fixing 1\textsuperscript{st} and 3\textsuperscript{rd} turbine
  - De-rating first turbine

• **Opportunity:** Understand wake interactions and potential gains from coordinated turbine control
  - Joint work with Howard, Annoni, and Guala

*Wind Farm in Wind Tunnel*  
*Photo Credits: Kevin Howard*
Conclusions
Conclusions

• Control systems increase power capture and reduce structural loads on utility-scale wind turbines.

• Performance and reliability trade-offs are becoming more difficult with trends to larger / off-shore turbines.

• Potential to coordinate all turbines in a wind farm in order to increase power and reduce overall loads
  • Requires a better understanding of trailing wakes and how these are affected by the control algorithms.
Acknowledgments

• Xcel RDF
  • Virtual Wind Simulator with Advanced Control & Aeroelastic Model for Improving the Operation of Wind Farms
  • Simulation, Measurement, Modeling, and Control of Wind Plant Power

• Institute for Renewable Energy and the Environment
  • Grant No. RL-0010-12: “Design Tools for Multivariable Control of Large Wind Turbines.”
  • Grant No. RS-0039-09: “Improved Energy Production for Large Wind Turbines.”

• US Department of Energy
  • Grant No. DE-EE0002980

• US National Science Foundation
  • Grant No. NSF-CNS-0931931