Linear Parameter Varying Torque Control of a 13.2 MW Segmented Ultra-Light Morphing Rotor Wind Turbine

Dana P. Martin and Kathryn Johnson

Abstract

In the design of a Linear Parameters Varying (LPV) torque controller for the 13.2 MW Segmented-Ultra Morphing Rotor (SUMR), optimal aerodynamic efficiency is accomplished by maintaining the optimal Tip Speed Ratio (λ_*) and maximum Power Coefficient ($C_{p_{max}}$) using variable speed torque control. The novelty of the SUMR technology lies in the *morphing* ability of the rotor to reduce Out-of-Plane (OoP) blade root bending moments using hinged blades to augment rotor geometry.

An LPV torque controller is synthesized for the 13.2 MW SUMR using multiple operating points lying on a desired torque trajectory path to account for changes in plant dynamics resulting from the morphing rotor. The LPV architecture allows linear control techniques and analysis to be used in the optimal control of a nonlinear plant.

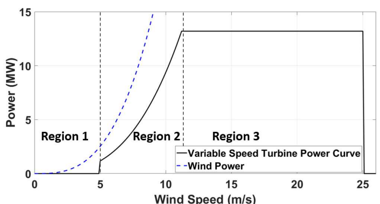

Figure 1. Operation Regions for a 13.2 MW variable speed wind turbine

Introduction

For traditional wind turbines, the rotor maintains constant projected radius (R_{rotor}) and the optimal torque trajectory can be tracked using the traditional torque control law given by (1).

$$\tau = K_{opt}\omega^2 \qquad (1)$$

With K_{opt} given by (2).

$$K_{opt} = \frac{1}{2}\pi R_{rotor}{}^5 \frac{C_{p_{max}}}{\lambda_*{}^3} \qquad (2)$$

The values of $C_{p_{max}}$ and λ_* are fixed during the aerodynamic design process, and can be found by empirically building a C_p surface using nonlinear aerodynamic simulators. The C_p surface for the SUMR is shown in Figure 2.

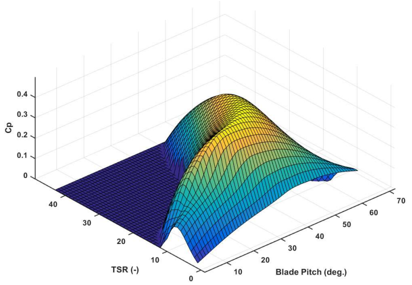

Figure 2. C_p Surface for the 13.2 MW SUMR.

Closed-Loop Equations with Integral Error Reference Tracking

$$\dot{x} = Ax + Bu$$
$$\dot{e} = -Cx + r$$
$$u = K_{state}x + K_{error}e$$
$$\begin{bmatrix}\dot{x}\\ \dot{e}\end{bmatrix} = \begin{bmatrix}A & 0\\ -C & 0\end{bmatrix}\begin{bmatrix}x\\ e\end{bmatrix} + \begin{bmatrix}B\\ 0\end{bmatrix}\begin{bmatrix}K_{state} & K_{error}\end{bmatrix} + \begin{bmatrix}0\\ B\end{bmatrix}r$$
$$y = \begin{bmatrix}C & 0\end{bmatrix}\begin{bmatrix}x\\ e\end{bmatrix}$$

The stability of the system depends on the eigenvalues of

$$A_{cl} = \begin{bmatrix}A & 0\\ -C & 0\end{bmatrix} + \begin{bmatrix}B\\ 0\end{bmatrix}\begin{bmatrix}K_{state} & K_{error}\end{bmatrix}$$

Close-Loop Block Diagram

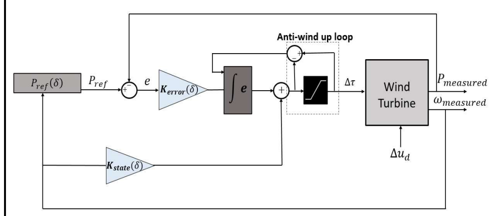

Figure 3. LPV *Block Diagram with integral error reference tracking*

Normal Turbulent Model (NTM) Simulation

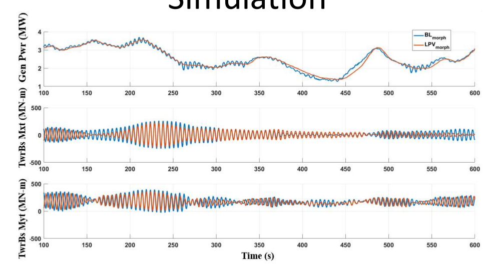

Figure 6. *NTM inflow time series data for mean wind speed of* $6\frac{m}{s}$

Time series data for turbine generator power (GenPwr), tower base side-to-side moment (TwrBsMxt), and tower base fore-aft moment (TwrBsMyt) for a baseline torque look up table torque controller (BL_{morph}) and the LPV torque controller (LPV_{morph}) is shown in Figure 6. The LPV torque controller is able to maintain smoother power production during turbulent inflow conditions with smaller TwrBsMxt and TwrBsMyt load oscillations.

Linearization Operating Points

Wind Speed (m/s)	Generator Speed (rpm)	Generator Torque (MN-m)	Blade Pitch (deg)	Cone Angle (deg)
5	553.69	16.824	0	2.5
6	584.78	30.753	0	5.36
7	616.06	45.027	0	8.22
8	694.1	58.183	0	11.08
9	768.39	70.071	0	12.5
10	849.83	85.752	0	12.5
11	926.88	102.23	0	12.5
12	1173	115	0	12.5

Parameter Varying State-Feedback Gain for Optimal Power Tracking

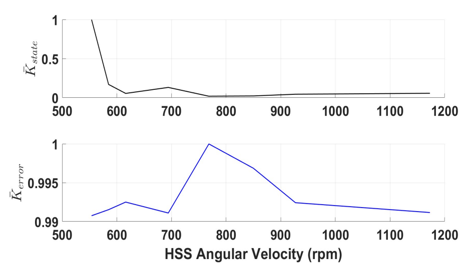

Figure 4. *Parameter varying state and error gains*

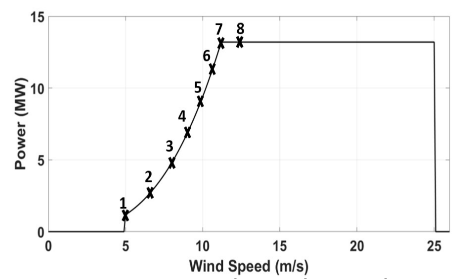

Figure 5. *Linearization points for optimal power production*

Discussion

Using a simplified wind turbine model with a single Degree of Freedom (DOF) linearized along an optimal power production trajectory, parameter varying state and integral error gains were synthesized to stabilize the closed-loop system using the Acker method to place the eigenvalues of A_{cl} in open left half plane for desired system performance. Performance of the LPV torque controller was compared to a baseline torque loop-up table control architecture for a turbulent inflow with a mean wind speed of 6 $^m/_s$ using generator power and tower base bending moments data channels. The LPV torque controller showed increased performance in terms of smoother power production and reduced tower base bending moment load oscillations.

Conclusion

Wind turbines are highly nonlinear plants due to the nonlinear aerodynamics of rotor blades making linear control analysis techniques valid for small perturbations around the desired operating point. Using a simplified degree of freedom turbine model and multiple operating points, a linear parameter varying system can be constructed to synthesize scheduled gain values to optimize plant performance. The controller performance during NTM inflow conditions shows advantages over the baseline torque look-up table controller for multiple data channels without additional states included in control architecture design.

Contributors

University of Colorado -Boulder
University of Illinois -Urbana Champaign
Sandia National Laboratories
National Renewable Energy Laboratory
University of Virginia

References

[1] D. P. Martin and K. E. Johnson, *LPV-Based Torque Control for an Extreme-Scale Morphing Wind Turbine Rotor*, American Controls Conference, ACC 2017
[2] S. Wang and P. Seiler, *LPV Active Power Control and Robust Analysis for Wind Turbines, 33rd Wind Energy Symposium, AIAA SciTech, (AIAA 2015-2010)*