

Advanced Control Design and Field Testing for Wind Turbines at the National Renewable Energy Laboratory

Preprint

M.M. Hand, K.E. Johnson, L.J. Fingersh, and
A. D. Wright

*To be presented at the World Renewable Energy
Congress VIII
Denver, Colorado
August 29 – September 3, 2004*



NREL

National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
by Midwest Research Institute • Battelle

Contract No. DE-AC36-99-GO10337

NOTICE

The submitted manuscript has been offered by an employee of the Midwest Research Institute (MRI), a contractor of the US Government under Contract No. DE-AC36-99GO10337. Accordingly, the US Government and MRI retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at <http://www.osti.gov/bridge>

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: <mailto:reports@adonis.osti.gov>

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: <http://www.ntis.gov/ordering.htm>



ADVANCED CONTROL DESIGN AND FIELD TESTING FOR WIND TURBINES AT THE NATIONAL RENEWABLE ENERGY LABORATORY*

M. Maureen Hand
maureen_hand@nrel.gov

Lee J. Fingersh
lee_fingersh@nrel.gov

Kathryn E. Johnson
kathryn_johnson@nrel.gov

Alan D. Wright
alan_wright@nrel.gov

National Renewable Energy Laboratory
1617 Cole Blvd. MS 3811
Golden, CO 80401-3393 USA
Ph: 303.384.6900, Fax: 303.384.6901

ABSTRACT

Utility-scale wind turbines require active control systems to operate at variable rotational speeds. As turbines become larger and more flexible, advanced control algorithms become necessary to meet multiple objectives such as speed regulation, blade load mitigation, and mode stabilization. At the same time, they must maximize energy capture. The National Renewable Energy Laboratory has developed control design and testing capabilities to meet these growing challenges. Several algorithms that seek to maximize power production in below rated wind speeds have been evaluated through simulation and field testing. The importance of precise, prior knowledge of the tip speed ratio at which maximum power coefficient is attained has been documented, and an adaptive control algorithm has been developed. Linear, state-space models that incorporate sufficient detail of wind turbine dynamics have been designed to mitigate blade loads, reduce tower motion, minimize blade pitch actuator demand, and maintain speed regulation. Because coherent turbulence can be generated in atmospheric boundary layers where large wind turbine will operate, the vortex/wind turbine interaction has been quantified and a blade load mitigation control scheme implemented in simulation. All these activities improve the viability of multimegawatt wind turbine deployment and increase turbine reliability.

NOMENCLATURE

k	torque control gain	P_{wind}	power available in the wind
A	rotor swept area	Q_A	aerodynamic torque, N·m
C_P	rotor power coefficient	Q_E	generator torque, N·m
$C_{P_{MAX}}$	maximum rotor power coefficient	R	turbine radius, m
G	Optimally Tracking Rotor gain	W	wind speed, m/s
J_T	rotor inertia, kg·m ²	λ_*	tip speed ratio at maximum power coefficient
M	adaptive control gain	ρ	air density, kg/m ³
P	mechanical power delivered to rotor	Ω	rotor angular speed, rad/s
		$\dot{\Omega}$	first derivative of Ω with respect to time, d/dt

* This work was performed at the National Renewable Energy Laboratory in support of the U.S. Department of Energy under Contract No. DE-AC36-99GO10337.

INTRODUCTION

Wind turbine manufacturers have recently turned to variable-speed turbines to capture power over a wide range of wind speeds. These turbines require active control systems that meet different objectives depending upon the wind speed. A wind turbine can be described by the following simple relationship:

$$J_T \dot{\Omega} = Q_A - Q_E \quad (1)$$

Basically, rotor rotation is a balance between the aerodynamic torque applied by the wind and the electrical torque applied by the generator. The power coefficient is a measure of the mechanical power delivered by the rotor to the turbine's low-speed shaft. It is frequently defined as the ratio of the mechanical power to the power available in the wind:

$$C_P = \frac{Q_A \Omega}{\frac{1}{2} \rho A W^3} = \frac{P}{P_{wind}} \quad (2)$$

The mechanical power produced by a rotor is purely a function of the geometry and the incident velocity. The design parameters that affect aerodynamic performance include blade pitch (angle of attack), taper (solidity), and twist distribution. For a given blade, its geometric shape is usually fixed, i.e., the aerodynamic shape, taper, and twist distribution do not change. The C_P for any fixed rotor geometry is a well-prescribed function of the blade tip speed ratio (ratio of blade tip speed to wind speed) with a single maximum value. The torque produced by the rotor can be controlled in two ways: by changing the geometry by varying the blade pitch angle, or by changing the rotor's rotational speed so the rotor operates at the optimal blade tip speed ratio.

EXPERIMENTAL TURBINE FOR CONTROLS TESTING

At the National Renewable Energy Laboratory's (NREL) National Wind Technology Center, a 43-m diameter, 600-kW, two-blade wind turbine has been retrofitted specifically to test innovative control algorithms [1]. The Controls Advanced Research Turbine (CART) is pictured in Figure 1. A PC-based control implementation system provides flexibility to accommodate numerous and varied control algorithms. The servo-electric motors that actuate blade pitch angles operate with high angular acceleration to attain blade pitch angles that are commanded collectively or independently. Precise control of generator torque permits variable speed operation. Finally, the wind turbine is highly instrumented to evaluate and compare control designs.

VARIABLE SPEED CONTROL INNOVATIONS

When the wind turbine operates at variable rotational speeds, the standard control algorithm requires generator torque to be commanded along the following trajectory:

$$Q_E = k \Omega^2 \text{ where } k = \frac{1}{2} \rho A R^3 \frac{C_{P_{MAX}}}{\lambda_*^3} \quad (3)$$

The value of k is often derived from performance code simulations [2]. It can be determined experimentally via a lengthy process if the wind turbine can be operated at constant rotational speeds over a range of wind speeds. Ideally, commanding the rotor speed along this trajectory would yield maximum power coefficient values for all wind speeds.

Experimental validation of this control algorithm on the CART has demonstrated that the ideal situation is generally not achievable in real-world situations. The variability in the wind speed causes the turbine to operate at tip speed ratios other than the optimal value because the large magnitude rotor inertia ($388,500 \text{ kg}\cdot\text{m}^2$) causes the turbine to track the wind variation slowly. The turbine spends much of its time attempting to regain the optimum tip speed ratio rather than operating at the optimum point. Because the power available in the wind is proportional to the cube of the wind speed, it becomes more important for a large wind turbine to catch wind gusts rather than wind lulls. Simulations show that reducing the magnitude of k by 5%-20% improves power capture [3] for a wind turbine with large rotor inertia.

The generator torque control trajectory was modified to actively accelerate and decelerate the rotor in response to wind speed fluctuations. Optimally Tracking Rotor control relies on the generator torque to assist in rotor acceleration and deceleration, which causes the turbine to operate more closely to the optimum tip speed ratio [4]. The standard generator torque control law is amended as follows:

$$Q_E = k\Omega^2 - G(Q_A - k\Omega^2) \quad (4)$$

where Q_A can be determined by rearranging Eq. (1). Selection of the gain, G , must trade off acceleration and deceleration rate.

An approach that eliminates the need for prior knowledge of the turbine's performance and accommodates slowly changing aerodynamic properties caused by blade erosion is Model Reference Adaptive Control. A simple, highly intuitive gain adaptation algorithm improves capture in below-rated wind speeds compared to the standard controller [5]. This algorithm is similar to the standard controller.

$$Q_E = \rho M \Omega^2 \quad (5)$$

The adaptive gain, M , incorporates all the terms in torque control gain, k , except for the air density, which is time varying and uncontrollable. The adaptive controller begins by changing M by some value ΔM . At the end of the adaptation period, which could be tens of minutes to hours, the controller evaluates the turbine's performance. The average power coefficient for the adaptation period is compared to the average power coefficient for the previous adaptation period. If the magnitude is increasing, the next ΔM will be of the same sign. Eventually M should converge to a value that results in maximum power capture. Figure 2 illustrates the improved energy capture for the adaptive controller compared to a standard controller. The adaptive controller produces more power, particularly at below-rated wind speeds, which translates into a 5.5% increase in annual energy production. Although this control algorithm does not require performance criteria such as $C_{P_{MAX}}$ and λ_* , a wind speed measurement is necessary.

STATE-SPACE-BASED CONTROL DESIGN TOOLS

As wind turbines become larger and more flexible, advanced control becomes essential to achieve stable operation in turbulent, above-rated wind speeds. Blade pitch angle control is used to shed excess torque by regulating rotor speed to produce rated power. In addition to rotor speed regulation, load mitigation and vibration attenuation become important objectives. Current industry standard control algorithms use classical proportional-integral-derivative schemes in single-input-single-output loops to meet simple objectives. State-space based control designs have the potential to incorporate

multiple inputs to achieve multiple objectives and to provide insight into the dynamic interactions influenced by feedback [6].

The highly nonlinear wind turbine dynamics must be linearized about an operating point to allow for state-space representations. Tools have been developed that provide linear wind turbine models with as many as 18 degrees of freedom[6].

The ability to use state-space based control design to regulate rotor speed in above-rated wind speeds and to enhance damping in low-damped flexible modes of the wind turbine was investigated by Wright [6]. Incrementally increasing the modeled states from 1 to 7 identified modes that tend to become unstable in closed-loop control, such as the drive-train torsion mode. This mode was stabilized by creating an additional control loop that commanded slight variations in generator torque to accommodate drive-train torsion flexibility. In addition to stabilizing the mode, the demand on the blade pitch actuators was reduced. Tower top and blade deflection were reduced when damping was added to these modes through pole placement in the state-space controller as shown in Figure 3. Finally, disturbance accommodating control (DAC) methods were used to reject wind disturbances that are modeled as steps (uniform over the rotor disk) or sinusoids (spatial variation resulting from vertical shear).

Wind turbines on towers nearly 100 m high operate in atmospheric boundary layers with different turbulence generation mechanisms than those that occur closer to the ground. This coherent turbulence contains vorticity that is not predicted with current wind turbine simulation models and that adversely affects wind turbine blade fatigue life. A simple, Rankine, vortex model was used as input to a wind turbine simulation to quantify the vortex/rotor interaction [7]. The vortex characteristics (size, orientation, circulation strength) that contribute to high cyclic blade loads, which reduce blade fatigue life, were identified (Figure 4).

A disturbance model that incorporates the gross vertical shear property of the vortex impinging on the wind turbine rotor was used in a DAC design to demonstrate the potential for advanced control to address this problem. Blade pitch control was used to mitigate the blade loads induced by the vortex by 9% as compared to a standard proportional-integral controller. However, an idealized model that incorporated highly detailed vortex inputs indicates that up to 30% load mitigation is possible if the disturbance model incorporates sufficient vortex detail.

CONCLUSIONS

Advanced control algorithms are necessary for the future deployment of multimegawatt, flexible wind turbines. NREL has invested in field test facilities that are flexible enough to accommodate a variety of control algorithms. Current research has advanced the understanding of variable speed operation via an adaptive algorithm. State-space based algorithms have been designed to stabilize lightly damped modes thereby reducing blade loads and tower deflection. DAC methods have been applied to reduce blade loads that result from passage of a coherent vortex through the rotor plane. Further development in each of these areas will enhance the reliability and performance of utility-scale wind turbines.

REFERENCES

- [1] Fingersh, L.J., Johnson, K. (2002). *Controls Advanced Research Turbine (CART) Commissioning and Baseline Data Collection*. 27 pp. NREL Report No. TP-500-32879, Golden, CO: NREL.
- [2] Buhl, M.L. (Last modified November 21, 2000). "WT_Perf User's Guide." http://wind.nrel.gov/designcodes/wtperf/wt_perf.pdf. Accessed October 21, 2003.
- [3] Johnson, K.E., Fingersh, L.J. (2004). "Methods for Increasing Region 2 Power Capture on a Variable Speed HAWT." *Collection of the 2004 ASME Wind Energy Symposium Technical Papers Presented at the 42nd AIAA Aerospace Sciences Meeting and Exhibit, 5-8 Jan., Reno, Nevada*. New York: American Society of Mechanical Engineers (ASME); pp. 103-113.
- [4] Fingersh, L., Carlin, P. (1998). "Results from the NREL Variable-Speed Test Bed." *Collection of the 1998 ASME Wind Energy Symposium Technical Papers Presented at the 36th AIAA Aerospace Sciences Meeting and Exhibit, 12-15 Jan., Reno, Nevada*. New York: ASME; pp. 233-237.
- [5] Johnson, K.E. (2004). *Adaptive Torque Control of Variable Speed Wind Turbines*. Ph.D. thesis. Boulder, CO: University of Colorado.
- [6] Wright, A. (2003). *Modern Control Design for Flexible Wind Turbines*. Ph.D. thesis. Boulder, CO: University of Colorado, 2003. Also published as NREL Report No. TP-500-35816, Golden, CO: NREL.
- [7] Hand, M.M. (2003). *Mitigation of Wind Turbine/Vortex Interaction Using Disturbance Accommodating Control*. Ph.D. thesis. Boulder, CO: University of Colorado. Also published as NREL Report No. TP-500-35172, Golden, CO: NREL.



Figure 1. CART wind turbine near Boulder, Colorado

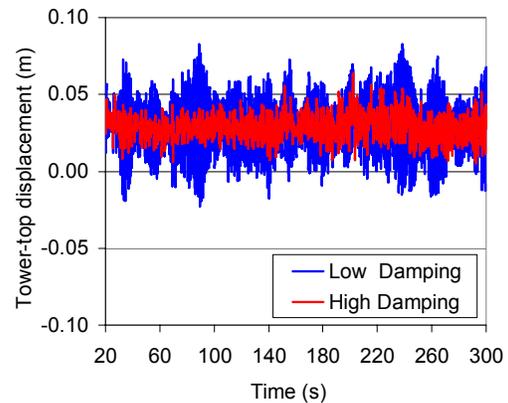


Figure 3. Effect of adding damping through pole placement

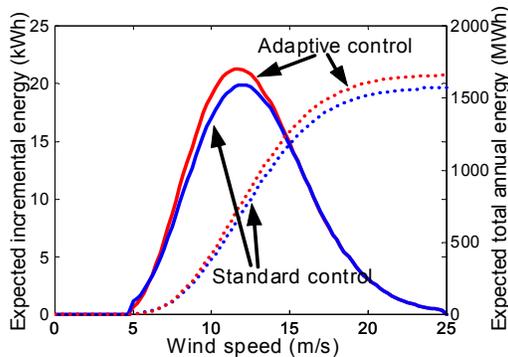


Figure 2. Energy capture comparison for standard and adaptive controller (incremental energy: solid; annual energy: dashed)

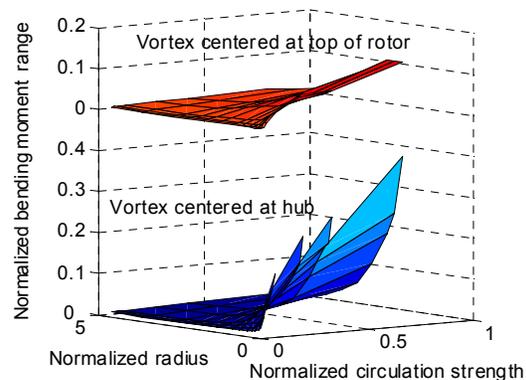


Figure 4. Blade bending moment response to impinging vortices

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Executive Services and Communications Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE (DD-MM-YYYY) May 2004		2. REPORT TYPE Conference paper		3. DATES COVERED (From - To) August 29 – September 3, 2004	
4. TITLE AND SUBTITLE Advanced Control Design and Testing for Wind Turbines at the National Renewable Energy Laboratory: Preprint				5a. CONTRACT NUMBER DE-AC36-99-GO10337	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) M.M. Hand, L.J. Fingersh, K.E. Johnson, and A.D. Wright				5d. PROJECT NUMBER NREL/CP-500-36118	
				5e. TASK NUMBER WER4.3105	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393				8. PERFORMING ORGANIZATION REPORT NUMBER NREL/CP-500-36118	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S) NREL	
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER	
12. DISTRIBUTION AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT (Maximum 200 Words) Utility-scale wind turbines require active control systems to operate at variable rotational speeds. As turbines become larger and more flexible, advanced control algorithms become necessary to meet multiple objectives such as speed regulation, blade load mitigation, and mode stabilization. At the same time, they must maximize energy capture. The National Renewable Energy Laboratory has developed control design and testing capabilities to meet these growing challenges.					
15. SUBJECT TERMS wind turbine; control systems; control algorithms; wind energy					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code)