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

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

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

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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:

$$J_T\dot{\Omega} = Q_A - Q_E \tag{1}$$

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:

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

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:

$$Q_E = k\Omega^2 \text{ where } k = \frac{1}{2}\rho A R^3 \frac{C_{PMAX}}{\lambda_*^3} \tag{3}$$

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 kg•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:

$$Q_E = k\Omega^2 - G(Q_A - k\Omega^2) \tag{4}$$

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.

$$Q_E = \rho M\Omega^2 \tag{5}$$

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_{PMAX} 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

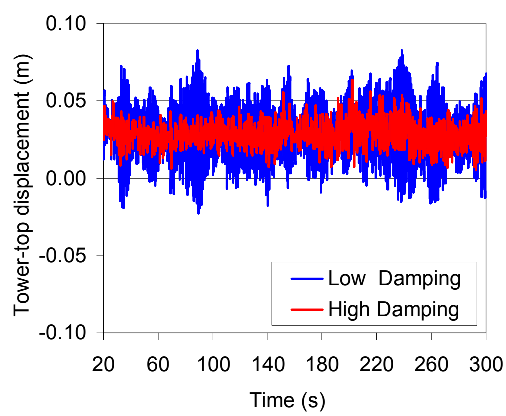

Figure 3. Effect of adding damping through pole placement

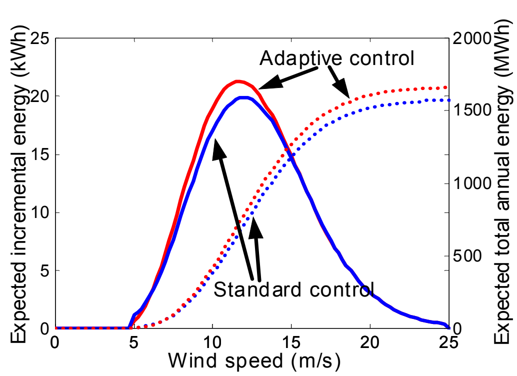

Figure 2. Energy capture comparison for standard and adaptive controller (incremental energy: solid; annual energy: dashed)

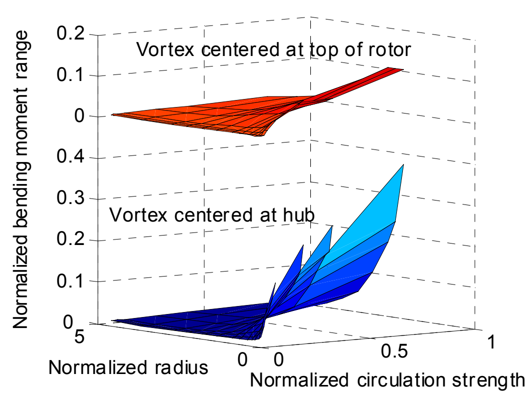

Figure 4. Blade bending moment response to impinging vortices

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