December 2004 • NREL/CP-500-36818

Conference Paper

Progress in Implementing and Testing State-Space Controls for the Controls Advanced Research Turbine

Preprint

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To be presented at the 24th ASME Wind Energy Symposium
Reno, Nevada
January 10–13, 2005

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Contract No. DE-AC36-99-GO10337

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Progress in Implementing and Testing State-Space Controls for the Controls Advanced Research Turbine

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Designing wind turbines with maximum energy production and longevity for minimal cost is a major goal of the federal wind program and the wind industry. Control can improve the performance of wind turbines by enhancing energy capture and reducing dynamic loads. At the National Renewable Energy Laboratory (NREL) we are designing state-space control algorithms for turbine speed regulation and load reduction and testing them on the Controls Advanced Research Turbine (CART). The CART is a test-bed especially designed to test advanced control algorithms on a two-bladed teetering hub upwind turbine. In this paper we briefly describe the design of control systems to regulate turbine speed in region 3 for the CART. These controls use rotor collective pitch to regulate speed and also enhance damping in the 1st drive-train torsion, 1st rotor symmetric flap mode, and the 1st tower fore-aft mode. We designed these controls using linear optimal control techniques using state estimation based on limited turbine measurements such as generator speed and tower fore-aft bending moment. In this paper, we describe the issues and steps involved with implementing and testing these controls on the CART, and we show simulated tests to quantify controller performance. We then present preliminary results after implementing and testing these controls on the CART. We compare results from these controls to field test results from a baseline Proportional Integral control system. Finally we report conclusions to this work and outline future studies.

I. Introduction

In previous papers we have shown the design of state-space controllers to regulate turbine speed in region 3 and enhance damping of flexible turbine modes.[1,2] Those papers showed the advantages of using full state feedback to place turbine plant poles to enhance transient response and increase stability. When limited turbine measurements are available, state estimation must be used to estimate plant states.[3] The successful use of state estimation is based on just a few turbine measurements such as generator speed and tower-top fore-aft acceleration.[3] The design of periodic controls for two-bladed wind turbines is also based on state estimation.[4,5]

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It is well known that the impact of wind disturbances on the rotor degrades controller performance and should be accounted for in its design. Disturbance accommodating control (DAC) was used to account for the uniform hub-height wind component across the rotor disk.[1,2] It has been shown that this disturbance can be estimated using a limited set of turbine measurements, allowing the use of full state feedback and state estimation. Disturbance effects can also be mitigated, and in some cases completely cancelled, through proper selection of the disturbance gain.

Designing control for wind turbines necessitates the use of special tools, both for control design and the testing of the control algorithms through simulation. A linear model of a wind turbine is needed to design a turbine controller using state-space methods. Past work has highlighted the use of FAST and SymDyn to extract linear models of a wind turbine.[3,2] Once the control algorithm is designed using these linear models, it can be incorporated back into the codes for simulation purposes. These same codes are also used to simulate closed-loop behavior of the controlled turbine to test controller performance before implementation on the real machine.

To date, few sources have published results on the implementation and testing of state-space controls on a real turbine. When a robust pitch controller was compared to a proportional integral (PI) controller through full-scale tests,[6] the robust controller produced about the same performance with less pitch activity than the PI controller, but the 3P frequency load attenuation was improved.

There is a great need to further implement and test state-space control algorithms on field-test turbines. Performance of these modern control algorithms must be compared to simpler controls based on classical methods. This paper describes the implementation and testing of state-space control algorithms and presents the preliminary results.

One control objective is to regulate turbine speed in region 3 using rotor collective pitch, assuming constant generator torque. Another control objective is to mitigate loads by enhancing damping in low-damped modes of the turbine, such as 1st drive-train torsion, and tower 1st fore-aft bending.

We compare the preliminary test results from controls designed using these state-space methods to results from a baseline PI controller. We also discuss implementation issues and their effect on controller performance.

II. CART Configuration

The Controls Advanced Research Turbine (CART), shown in Fig. 1, is a two-bladed, teetered, upwind, active-yaw wind turbine. This machine is used as a test bed for studying a number of aspects of wind turbine controls technology on medium- to large-scale machines.[7]

The two-bladed teetering upwind turbine is variable speed and each blade is capable of being independently pitched with its own electromechanical servo. The pitch system can pitch the blades up to 18 degrees per second (deg/s) with pitch accelerations up to 150 degrees per second per second (deg/s/s). The squirrel cage induction generator with full power electronics can control torque from minus rating (motoring) to plus rating (generating) at any speed. The torque control loop has a very high rated bandwidth of 500 radians per second.

Rated electrical power (600 kW at 41.7 RPM) is maintained in region 3 in a conventional variable-speed approach. Power electronics are used to command constant torque from the generator and full-span blade pitch controls the rotor speed. In region 2, the machine torque is varied to produce variable rotor speed in order to maintain optimum aerodynamic power coefficient C_p.

The machine is equipped with a full complement of instruments that gather upwind meteorological data at four heights. Blade root flap and edge strain gauges, tower-bending gauges, and low- and high-speed shaft torque transducers gather loads data. Absolute position encoders gather data on pitch, yaw, teeter, low-speed shaft, and high-speed shaft positions.

All of this data is sampled at 100 Hz. The custom-built control system collects this data and controls the turbine at a control loop cycle rate of 100 Hz. This system is PC-based and is very flexible.

There are various issues, such as actuator dynamics, sensor limitations, and data sampling rates, which must be addressed in implementing state-space controls. In addition, the control algorithm must be correctly coded in the turbine control software. Additional implementation issues specific to wind turbines include effects of steady-state speed errors in region 3 performance, and transition issues between region 2 and 3. Errors in implementing these control algorithms into the turbine software can cause the control software to fault, leaving the turbine in an uncontrolled state. The second issue (steady-state speed errors) is important, because we want the controller to regulate speed precisely at the desired set-point. The region transition issues ensure a smooth transition between control of maximum power capture in region 2 and control of rotor speed to maintain constant power in region 3.

Designing, implementing, and testing state-space controllers on a real machine such as the CART involves various steps. These steps include:

1) Design a controller using analytical control design tools,
2) Incorporate the control algorithm into codes and test the closed-loop system through simulation,
3) Implement the control algorithm into the turbine control software and perform simple checkout tests,
4) Field test the control algorithm in the turbine,
5) Examine performance and refine control algorithm as appropriate and then verify through further tests.

III. Control Design and Simulation Tests

The first step is to design the control algorithm. One important implementation issue is the effects of actuator dynamics. Previous studies neglected the effects of the actuator, assuming that the actuator acted "infinitely fast."

The dynamics of an electromechanical pitch servo are influenced by many subsystems, including: internal servo controllers (converting pitch-rate commands to motor current), motor dynamics, blade torsional stiffness, and aeroelastic coupling. Individual servomotors pitch each blade based on rate (not angle) commands from the CART control software. Separate hardware controllers convert these pitch-rate signals into pitch torque commands and, at a lower level, motor current. A model that includes all these elements could be complex. Alternatively, because the actuator dynamics are fast relative to those of the rest of the turbine, it is convenient to use a first-order linear model relating pitch rate commands and actual pitch rates. From least-squares fitting to field-test data of the CART, a time constant for this model is calculated to be 1/60 seconds.[8] The dynamics of the pitch actuator can be simplified to the following first-order transfer function involving pitch rate

$$\frac{\dot{\theta}(s)}{\dot{\theta}_{com}(s)} = \frac{60.0}{s+60.0} \tag{1}$$

where $\dot{\theta}_{com}(s)$ is the commanded pitch rate.

The actuator effects can be accounted for in the control design by appending the turbine linear model with extra states representing the actuator. If the resulting composite system is controllable then full state feedback can be applied to place plant and actuator poles to obtain desired performance. If the resulting system is observable, state estimation can be successfully used to estimate plant states with limited turbine measurements.

A. Linearized State-Space Models Including Actuator and Disturbance States

We first describe the linear model of the turbine plant without actuator states. This linear model can be expressed in state-space form as

$$\begin{aligned} \dot{\underline{x}}_m &= A_m \underline{x}_m + B_m \underline{u}_m + \Gamma_m \underline{u}_d \\ \underline{y}_m &= C_m \underline{x}_\mathrm{m} \end{aligned} \tag{2}$$

where $\underline{x}_m$ is the state vector, $\underline{u}_m$ is the rotor collective pitch control input, $\underline{u}_d$ is the uniform wind disturbance input, $\underline{y}_m$ is the measured output, A_m is the state matrix, B_m is the control input distribution matrix, Γ_m is the disturbance input distribution matrix, and C_m relates the measured output $\underline{y}_m$ to the turbine states. The states, control input, disturbance input, and measurement are perturbations from the model linearization point.

As discussed, we model the collective pitch actuator as a first-order linear system, which determines actual pitch rate given pitch-rate commands. Because we are interested in pitch angle as the interface to our plant model, we construct a state-space actuator model with two states (pitch angle and pitch rate).

Such a model is described by:

$$\begin{aligned} \dot{\underline{x}}_a &= A_a \underline{x}_a + B_a \underline{u}_a \\ \underline{y}_a &= C_a \underline{x}_\mathrm{a} \end{aligned} \tag{3}$$

where,

$$\underline{x}_a = \begin{bmatrix} \Delta\theta \\ \Delta\dot{\theta} \end{bmatrix}, \ \underline{u}_a = \theta_{com}, \underline{y}_a = \Delta\theta,$$

$$A_a = \begin{bmatrix} 0 & 1 \\ 0 & -60 \end{bmatrix}, B_a = \begin{bmatrix} 0 \\ 60 \end{bmatrix}, C_a = \begin{bmatrix} 1 & 0 \end{bmatrix}. \tag{4}$$

Combining the plant model Eq. (2) and actuator model Eq. (3) gives:

$$\begin{aligned} \dot{\underline{x}} &= A\underline{x} + B\underline{u} + \Gamma\underline{u}_d \\ \underline{y} &= C\underline{x} \end{aligned} \tag{5}$$

where

$$A = \begin{bmatrix} A_m & B_m C_a \\ 0 & A_a \end{bmatrix}, \ B = \begin{bmatrix} 0 \\ B_a \end{bmatrix}, \ C = \begin{bmatrix} C_m & 0 \\ 0 & C_a \end{bmatrix}, \text{ and } \begin{bmatrix} \Gamma_m \\ 0 \end{bmatrix}.$$

We have also incorporated a wind disturbance state representing the hub-height component of wind uniform over the rotor disk into some of these models (not shown). This model is also described by a state-space system with the disturbance waveform modeled as a step function.[5,9] One complication of including this actuator model in the state-space system is that rigorous calculation of the disturbance gain is not possible.[9] Still, a trial and error approach of manually selecting the disturbance gain can be used to obtain improved controller performance compared to the case in which this gain is set to zero.

If the resulting system is controllable and observable, then full state feedback and state estimation can be used to design the controller to achieve desired performance, including actuator effects. To describe various control designs in the following sections, we refer to Eq. (5), with various states in the state vector $\underline{x}$ denoted by x_1, x_2, etc. We now present two linear models that we use to design controls for implementation on the CART. The first model is based on the FAST code, while the second is based on SymDyn.

B. Linear FAST Model

The first controller is designed using a linear time-invariant model generated from FAST.[10] We generated periodic linear models at several points around the rotor disk and averaged them to obtain a state-space model averaged with respect to blade azimuth position. This model contains the following turbine states:

x_1 = perturbed drive-train torsional deflection,

x_2 = perturbed rotor 1st symmetric flap mode displacement,

x_3 = perturbed generator rotational speed,

x_4 = perturbed drive-train torsional velocity,

x_5 = perturbed rotor 1st symmetric flap mode velocity,

x_6 = perturbed actuator pitch angle,

x_7 = perturbed actuator pitch rate,

x_8 = perturbed hub-height wind speed disturbance.

This linear model is generated at a wind speed of 18m/s with a pitch angle of 11° and a rotor speed of 41.7 RPM. Eigenanalysis of the A matrix gives the open-loop poles at -.02 ± 22.6i, -3.6 ± 13.5i, -0.1, 0., -60. The first pole pair corresponds to the 1st drive-train torsion mode, while the second pole pair corresponds to the rotor 1st symmetric flap mode. The next pole corresponds to the generator speed state. The next two poles (at 0 and –60) correspond to the actuator states. We note that the 1st drive-train torsion mode is very lightly damped, by noting the real part of this complex eigenvalue (-0.02).

The advantages of using state-space control design methods are highlighted here. A goal in state-space control design is to move the plant poles further to the left in the complex plane so as to greatly increase damping and improve transient response. For example, if we move the poles corresponding to the 1st drive-train torsion mode so that the real parts have a value of –2 instead of -.02, then damping is greatly increased. This is very straightforward in state-space control design and much more difficult using classical control design methods.

In the next linear model, we include the tower 1st fore-aft bending mode.

C. Linear SymDyn Model

The second controller we present and implement on the CART is designed using a linear time-invariant model from the SymDyn code.[**] A larger number of states are chosen for the model than used in the FAST model above because here we are investigating the potential to reduce tower dynamic loads in addition to the other performance objectives. The following states are chosen:

x_1 = perturbed tower fore-aft deflection,

x_2 = perturbed generator azimuth position,

x_3 = perturbed drive-train torsional deflection,

x_4 = perturbed blade #1 flap deflection,

x_5 = perturbed blade #2 flap deflection,

x_6 = perturbed tower fore-aft velocity,

x_7 = perturbed generator rotational speed,

x_8 = perturbed drive-train torsional velocity,

x_9 = perturbed blade #1 flap velocity,

x_{10} = perturbed blade #2 flap velocity,

x_{11} = perturbed actuator pitch angle,

x_{12} = perturbed actuator pitch rate,

x_{13} = perturbed hub height wind speed.

The linear SymDyn model is generated at the same linearization point in region 3 as the FAST model (wind speed at 18 m/s, etc.) The model becomes time-invariant upon averaging the periodic state-space matrices over one rotation period.

Now that these linear models have been generated, we proceed with control design, by first calculating gains.

D. Calculation of Controller Gains

Previous studies[1, 3, 9] have shown control design using pole placement to place both plant and state estimator poles. Other methods use optimal control techniques,[2,5] such as linear quadratic regulation (LQR). In the control designs to be shown in the next sections, we used LQR to calculate gains.

With LQR, we find a unique linear feedback control signal that will minimize the following quadratic cost function.

$$J = \int_0^\infty \left(\underline{x}(t)^T Q \;\; \underline{x}(t) + \;\; \underline{u}(t)^T R \;\; \underline{u}(t) \right) \; dt \tag{6}$$

The matrix Q contains weightings for the states and the matrix R contains weightings for actuator pitch rate. Fast state regulation and low actuator usage are competing objectives; therefore the Q and R weightings allow us to trade-off different performance objectives with actuator usage.

E. Turbine Measurements and State Estimation

Due to limited turbine measurements, state estimation must be used to estimate plant states. For the FAST model, successful state estimation was applied by using the following turbine measurements:

[**] Stol, K. and Bir, G., "User's Guide for SymDyn, version 1.2," http://wind.nrel.gov/designcodes/symdyn/symdyn.pdf, accessed July 1, 2004.

y_1 = perturbed high-speed shaft (HSS) rotational speed,

y_2 = perturbed pitch angle.

Previous studies using FAST included only a measurement of generator speed for state estimation. Now that actuator states are included in the model for control design, an additional measurement is needed to ensure that the model/ blade pitch angle may be observed.

Another issue is the method in which HSS rotational speed is measured in the CART. The azimuth position of the HSS is first measured. HSS rotational speed is then derived from this measurement by taking its derivative and applying a low-pass filter to remove high-frequency quantization noise effects.

For the SymDyn model, additional measurements are needed due to the additional complexity and number of states in this model, such as:

y_1 = perturbed HSS azimuth position,

y_2 = perturbed pitch angle,

y_3 = perturbed drive-train torsional deflection,

y_4 = perturbed tower fore-aft bending moment,

y_5 = perturbed blade #1 flap bending moment,

y_6 = perturbed blade #2 flap bending moment.

Drive-train torsional deflection is measured by dividing low-speed shaft (LSS) torque by the stiffness of the LSS. This static approach is acceptable for measuring deflection, because the LSS torque transducer is adjacent to the flexible shaft and, therefore, inertia effects are negligible.

F. Discrete-Time Equivalent Controllers

We have presented a state-space control methodology that assumes continuous-time operation. However, the CART control algorithm must run on a digital computer that refreshes all measurements and command signals at the rate of 100 Hz, i.e. with a 0.01-second sampling period. To operate in discrete-time, an equivalent control system is generated from the continuous-time version. Once the continuous time state-space model or equivalent transfer function is calculated, an equivalent discrete-time state-space model can be easily calculated using MATLAB.

G. Specific Control Designs for Implementation

We implement controls for the CART based on the two linear models just discussed. The first is the FAST control model, and the second is the SymDyn control model.

1. FAST Control Model

The first control system is designed using the FAST generated linear model just described. The objective is to regulate the speed at 41.7 RPM in region 3, enhance the damping of the 1st drive-train torsion mode, and stabilize the blade 1st flap.

After checking controllability of the FAST generated state-space system shown above, we calculate the gains using LQR. The resulting closed-loop system increases the damping in the 1st drive-train torsion mode and improves the transient response of the other states, with poles now located at -1.3 ± 22.6i, -3.9 ± 13.5i, -2, -10, and -60. The gain, corresponding to the wind disturbance, is adjusted to give good speed regulation behavior and is manually selected at 0.28.

State estimator gains are calculated with resulting pole locations at –15 ± 22.5i, -9 ± 13i, -32, -10, -11, and -7, corresponding to the 1st drive-train torsion mode, the 1st rotor symmetric flap mode, actuator deflection and rate, generator speed, and uniform wind disturbance.

The discrete time controller is incorporated into the FAST control subroutine to simulate the closed-loop response.

One implementation issue is steady state speed errors. This is important to obtain good performance and to prevent triggering turbine over-speed in region 3. Over-speed occurs in the CART when the rotor speed reaches 43 RPM. In this control design, the linearization point is at 18m/s, a point midway between the highest and lowest wind speeds in region 3. We can expect deviation from the desired 41.7 RPM set point for wind speeds above and below 18m/s. To check this, test step winds are input to FAST as shown in Fig. 2, providing wind speeds below and above the 18m/s linearization point. After implementing the controller into FAST and simulating closed-loop, Fig. 3 shows that the generator speed varies from 41 RPM to 42.5 RPM. The simulated generator speed matches the 41.7 RPM set-point only at a wind speed of 18m/s. We can see that the controller maintains rotor speed below the 43 RPM over-speed point for this range of tested wind speeds.

Additionally, we tested the closed-loop performance using turbulent wind inputs to excite the turbine model. Figure 4 shows speed regulation for this case again showing good speed regulation to 41.7 RPM and maintaining speed below the 43 RPM over-speed point. The controller should also reduce low-speed shaft torque loads because it was designed to increase damping of drive-train torsion. Figure 5 shows simulated low-speed shaft torque loads, showing the load alleviation effect of increasing the damping in the 1st drive-train torsional mode.

Before implementing this controller into the CART, we investigated the effects of discretizing the continuous time controller into a discrete time controller. We implemented both forms of the controller into FAST, ran simulations, and found very little difference in the simulated results between the two forms of the controller. In addition, we investigated the effect of deriving HSS rotational speed from the HSS position measurement. We conducted FAST simulations with the HSS speed derived from HSS azimuth position. In general, we found very little difference between this simulation and the simulation with HSS speed taken directly from FAST. After we conducted these thorough investigations, we proceeded to implement this controller in the CART.

2. SymDyn Control model

We are now prepared to implement the SymDyn controller. The objectives of the controller are the same as the FAST controller: to regulate speed at 41.7 RPM and enhance the drive-train torsion damping and blade flap modes. An additional objective is to reduce the tower fatigue loads in the fore-aft direction. The selection of the 13 model states and 6 turbine measurements defined earlier reflect these objectives.

The design of full-state feedback gains and state estimator gains are performed using LQR methods. While we added a disturbance state estimate to the controller – as we found this improved the estimator performance – it did not directly contribute to the control input, i.e. the DAC is not fully employed.

We ran simulations with both a SymDyn nonlinear model of the CART and an ADAMS® model. ADAMS, by The MSC Software Corporation, is a commercial multi-body dynamics code capable of modeling the structure of a wind turbine with high fidelity. We had to tune the control gains between simulation runs to account for nonlinearities and unmodeled higher-order structural dynamics. For each simulation, we used a 100-second turbulent wind input with dynamic stall and generalized dynamic wake options.

We compared the final SymDyn state-space controller to the baseline PI controller by incorporating it into an ADAMS model and simulating before implementing the controller on the real turbine. Table 1 uses statistical performance measures to compare the controllers. The fatigue damage equivalent load (DEL) measures are calculated using rain-flow counting, Miner's linear damage rule, and a reference frequency of 1.0 Hz. We measured tower bending moments at 9.3 m from the ground to correspond to strain gauge locations on the CART. The simulation showed us that while speed regulation and pitch rates are the same between the controllers, the state-space controller is indeed capable of reducing fatigue damage in the flexible components. This gives us confidence to test the controller on the CART.

Table 1: ADAMS Simulation Results for the SymDyn State-Space Controller

Performance Measure	Baseline PI Controller	SymDyn State-Space Controller
RMS speed error [RPM]	0.389	0.380
Max. pitch rate [deg/s]	14.9	15.5
Tower fore-aft fatigue DEL [kNm]	2266	1586 (-30%)
Low-speed shaft torque fatigue DEL [kNm]	42	25 (-40%)
Blade-root flap fatigue DEL [kNm]	385	306 (-21%)

IV. Implementation and Field Test Results

Now we describe the last three steps involved with designing, implementing and testing controls. Each of the previously described controllers is implemented into the CART control software. Care is taken to be sure that all programming bugs are removed. Before these algorithms are field tested, the control code is tested using a simple simulator built into the control software. This simulator integrates a single-state (rotor speed) and a lookup table for aerodynamic torque. These tests are useful for further catching C-code implementation bugs, highlighting region transition problems, and as an independent check of speed regulation performance. One weakness of this simulator is that it does not account for turbine flexible modes. In addition, because the simulator does not produce many of the measurement signals that the more complex state-space controllers assume, there are situations when the simulator predicts dynamic instability when the other simulator models (FAST and SymDyn simulations) or actual turbine do not. Still, this is a very useful test to conduct before the controller is tested on the real machine.

Another issue, already addressed with the FAST controller, is steady state speed errors. This issue is addressed differently in the SymDyn controller than in the FAST controller.

An alternative method to address this issue is by feeding back the integral of speed error, as is achieved by the integral term in the PI baseline controller. The controller based on SymDyn does this by feedback of the generator azimuth error state (x_2), which is the natural integral of generator speed error (x_7). The consequence of this approach is that at low wind speeds when the pitch angle can saturate at -1°, the generator is running at just below rated speed and the azimuth error state gets larger in the negative direction. It is not until generator speed is greater than rated speed that the magnitude of the azimuth error will decrease. Meanwhile pitch angles will remain saturated, leading to the likely possibility of over-speed. This condition is commonly called wind-up. The current working solution for this problem is to saturate the azimuth error state so that it cannot continue to grow. This has proved satisfactory.

A. FAST State-Space Designed Controller Results

We collected several 10-minute datasets on the CART while implementing the FAST controller. We then compared the test results to a case with simple PI control to regulate speed in region 3. Because these controllers were tested at different times, a direct comparison between results is difficult. Our objective was to show trends, such as speed regulation, load mitigation, etc. We attempted to examine both datasets and extract smaller sections of

Table 2: Comparison Between Baseline PI and FAST State-Space Controller

Performance Measure	Baseline PI Controller	FAST State-space Designed Controller
RMS speed error [RPM]	0.233	0.214
Max pitch rate [deg/s]	13.7	12.1
RMS pitch current [A]	28.8	20.7
Tower fore-aft fatigue DEL [kNm]	578	525
Low-speed shaft torque fatigue DEL [kNm]	15.8	3.04
Blade-root flap fatigue DEL [kNm]	126	135

data in which turbine operating parameters (such as wind speed and direction, yaw error, etc.) are similar. The results of our comparison are preliminary and we need many more hours of operation for realistic statistical comparisons between the controllers. In the next few paragraphs, data in the figures corresponds to the same data summarized in Table 2.

Figure 6 shows the hub-height winds during turbine operation with these two controllers. Although the winds do not match, the deviations in wind speed for the two cases are similar, with somewhat greater deviations occurring during operation with the FAST controller.

Figure 7 shows speed regulation. Deviations in low-speed shaft rotational speed are seen using both controllers, with the greatest deviations seen for the PI controller. We note that the FAST state-space controller seems to regulate speed to values below those of the PI controller. This is probably due to design of the controller at the 18m/s and 41.7 RPM linearization point. We would expect regulated speed to be less than 41.7 RPM for wind speeds less than 18m/s. Figure 7 shows that as the wind speed increases to 18m/s at about 23 seconds, the speed increases to about 41.7 RPM in that range.

Figure 8 shows low-speed shaft torque during operation with each controller. The trend shows reductions in cyclic loads during operation with the state-space controller. This result is expected, because this controller was explicitly designed to increase damping in the 1st torsional mode of the drive-train.

Figure 9 shows measured pitch rates from the CART during operation with each controller. The figure shows similar values of pitch rate for each controller. The trend indicates that the state-space controller, with its added drive-train load mitigation, does not significantly increase pitch rates compared to the PI controller. Actual pitch rate limits of ±18deg/s are implemented in the CART. As can be seen from the figure, these pitch rates are well within these limits.

Table 2 compares statistics of the CART data during operation with the PI controller and the FAST controller. The FAST controller produces slightly lower RMS speed errors compared to the PI controller. The maximum pitch rate is slightly reduced with the FAST controller compared to the PI controller. The most notable difference between the two controllers is the reduction in low-speed shaft torque fatigue loads using the FAST controller because of its design to add damping to the 1st drive-train torsion mode. The blade root flap and tower fore-aft loads are comparable to the results from the PI controller. The next section shows results from a controller designed with additional states, which allows damping to be enhanced in other modes of the turbine.

B. SymDyn State-Space Designed Controller Results

To compare the SymDyn state-space controller with the PI baseline controller, we used the same baseline PI control results as used in the FAST controller comparison. Table 3 compares the performance of each controller using the metrics that were introduced in the section containing ADAMS simulation results. We added the RMS pitch current to further compare actuator usage. The pitch servos must not exceed a pitch rate of 18 deg/s or a current of 35 Amps RMS.

The statistical results in Table 3 are consistent with those obtained from the simulation. They show that the state-space controller regulates turbine speed at the level of the baseline controller while significantly reducing fatigue damage in the tower fore-aft direction, drive-train torsion, and blade flap direction. Pitch rate and RMS pitch current are well below the operational limits and, in fact, are lower for the state-space controller. These results are preliminary and certainly many more hours of operation are needed for realistic statistical comparisons between the controllers. In the next few paragraphs, data in the figures corresponds to the same data summarized in Table 3.

We also performed a graphical comparison between the results from the baseline controller and SymDyn state-space controller. We chose a 30-second subset of data for each controller with approximately the same wind conditions. Figure 10 illustrates the variation of hub-height wind speed. This shows that the mean and range of wind speed are approximately matched, permitting the comparison of other turbine measurements.

Figure 11 shows speed regulation performance of the two controllers. Speed deviation from the desired 41.7 RPM set point is similar for each, as expected from the statistical results. Figures 12, 13, and 14 compare loads in the low-speed shaft, tower, and blades respectively. Although it is clear that the state-space controller reduces cyclic loads in the drive-train, it is not so clear in the plots for the tower and blades, because the mean loads vary differently. In tower fore-aft bending, there are instances when the state-space controller appears to dampen sudden changes in load. At 6 seconds, 11 seconds, and 17 seconds, rapid changes in bending moment are followed immediately by rapid attenuation over about 3 seconds. Such consistent attenuation does not appear in the results from the PI controller. After 22 seconds, the magnitude of cyclic load remains high. These observations are consistent with the addition of damping to the 1st fore-aft bending mode in the state-space control design. Similar trends are also seen in the plot for the flap-bending moment, seen in Fig. 14.

Table 3: Preliminary CART Field-Test Results for the SymDyn State-Space Controller

Performance Measure	Baseline PI Controller	SymDyn State-Space Controller
RMS speed error [RPM]	0.233	0.213
Max. pitch rate [deg/s]	13.7	9.4
RMS pitch current [A]	28.8	16.0 (-44%)
Tower fore-aft fatigue DEL [kNm]	578	272 (-53%)
Low-speed shaft torque fatigue DEL [kNm]	15.8	7.7 (-51%)
Blade-root flap fatigue DEL [kNm]	126	86 (-32%)

V. Conclusions

In this paper we have shown the design, implementation and testing of controls using rotor collective pitch in region 3 to regulate turbine speed and enhance damping in low-damped flexible modes. We described various controls implementation issues and steps. We showed preliminary test results after implementing and testing these controls in the CART; the trend for these state-space controls to reduce structural dynamic loads by comparison to results from a baseline PI controller; and that the state-space controls regulate turbine speed with about the same precision as the PI control algorithm. We also showed that these state-space controllers performed these control objectives without increasing actuator duty compared to the PI control algorithm. These results are preliminary and many more hours of operation are needed for realistic statistical comparisons between the controllers.

Future Work

Directions for future work include further field-testing of the controls already implemented in the CART. We need to obtain many more hours of test data to show statistically that loads are reduced compared to simple PI control results. Implementation and testing of independent pitch control to mitigate spatially varying wind disturbances across the rotor disk will be tested. Design of controls using generator torque to add damping to the drive-train torsion mode in region 3 will be implemented and tested. Controls will also be designed and implemented on a 3-bladed version of the CART.

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Figure 1. The Controls Advanced Research Turbine (CART).

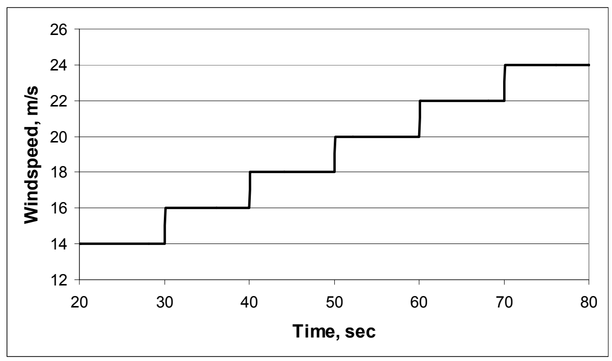


Figure 2. Test wind applied to CART FAST models.

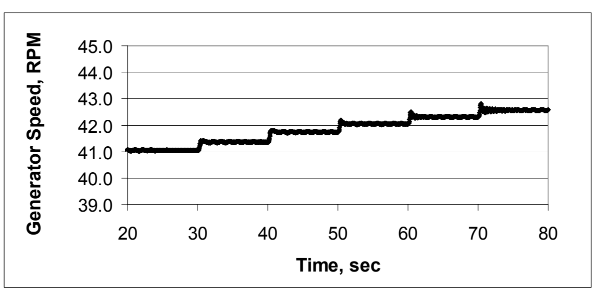


Figure 3. FAST simulated generator Speed excited by step winds.

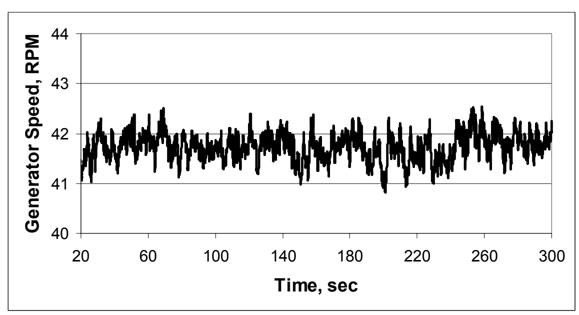


Figure 4. FAST simulated generator Speed excited by turbulent winds.

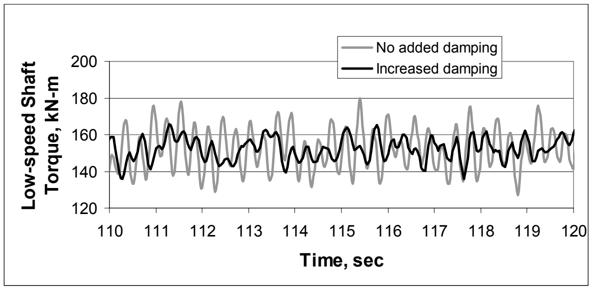


Figure 5. Simulated shaft torque showing effects of increased torsional damping added by controller.

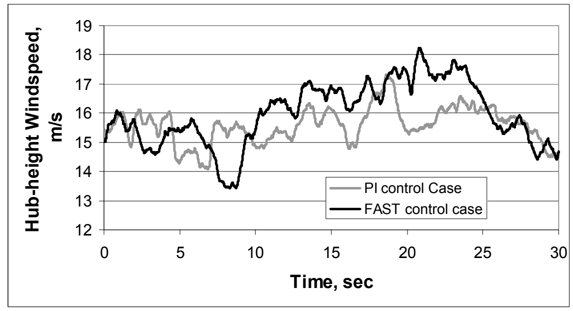


Figure 6. Measured hub-height wind speed during the PI control case and the FAST control case.

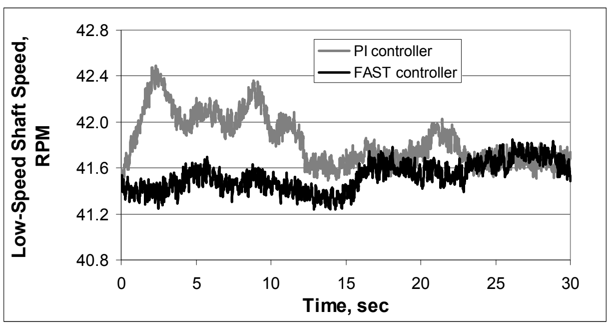


Figure 7. Measured Low-speed Shaft Rotational Speed during CART operation using the PI controller and the FAST controller.

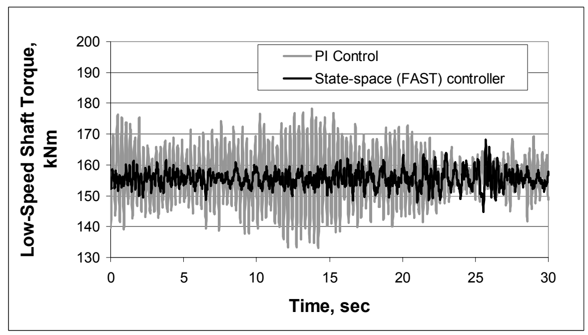


Figure 8. Measured low-speed shaft torque during CART operation using the PI controller and the FAST controller.

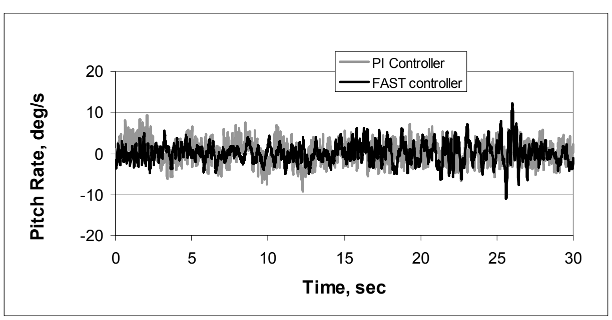


Figure 9. Measured pitch rates during CART operation using the PI controller and the FAST controller.

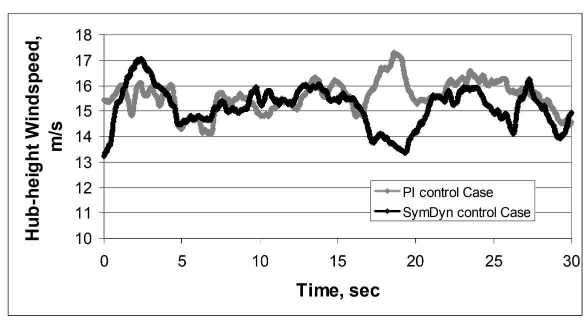
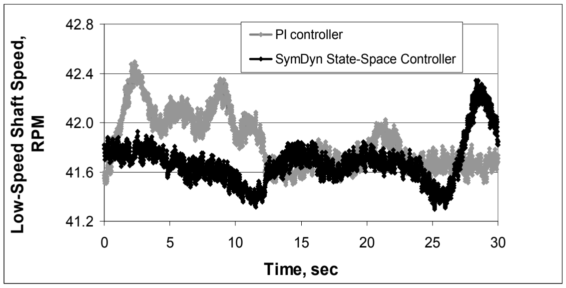


Figure 10. Measured hub-height wind speed during CART operation using the PI controller and the SymDyn controller.



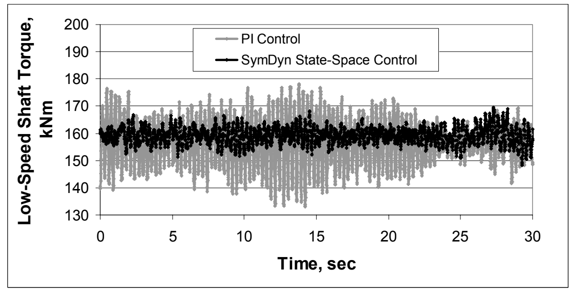
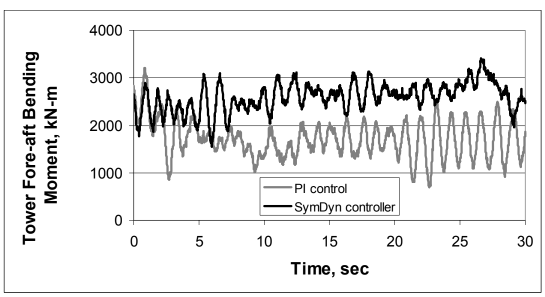


Figure 11. Measured low-speed shaft speed during CART operation using the PI controller and the SymDyn controller.

Figure 12. Measured low-speed shaft torque during CART operation using the PI controller and the SymDyn controller.



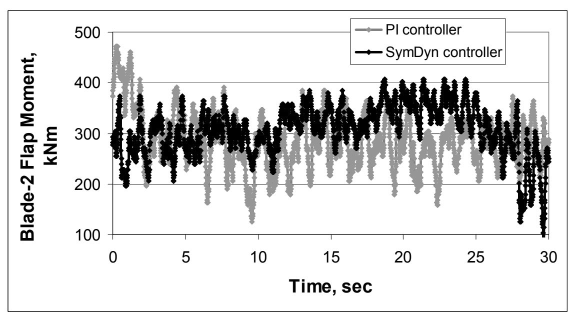


Figure 13. Measured tower fore-aft bending moment during CART operation using the PI controller and the SymDyn controller.

Figure 14. Measured blade flap-bending moment during CART operation using the PI controller and the SymDyn controller.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
December 2004	Conference paper	January 10–13, 2005

4. TITLE AND SUBTITLE
Progress in Implementing and Testing State-Space Controls for the Controls Advanced Research Turbine: Preprint

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
A.D. Wright, L.J. Fingersh, and K.A. Stol

5d. PROJECT NUMBER
NREL/CP-500-36818

5e. TASK NUMBER
WER4.3301

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-500-36818

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)*
Designing wind turbines with maximum energy production and longevity for minimal cost is a major goal of the federal wind program and the wind industry. Control can improve the performance of wind turbines by enhancing energy capture and reducing dynamic loads. At the National Renewable Energy Laboratory (NREL) we are designing state-space control algorithms for turbine speed regulation and load reduction and testing them on the Controls Advanced Research Turbine (CART). The CART is a test-bed especially designed to test advanced control algorithms on a two-bladed teetering hub upwind turbine. In this paper we briefly describe the design of control systems to regulate turbine speed in region 3 for the CART. These controls use rotor collective pitch to regulate speed and also enhance damping in the 1st drive-train torsion, 1st rotor symmetric flap mode, and the 1st tower fore-aft mode. We designed these controls using linear optimal control techniques using state estimation based on limited turbine measurements such as generator speed and tower fore-aft bending moment. In this paper, we describe the issues and steps involved with implementing and testing these controls on the CART, and we show simulated tests to quantify controller performance. We then present preliminary results after implementing and testing these controls on the CART. We compare results from these controls to field test results from a baseline Proportional Integral control system. Finally we report conclusions to this work and outline future studies.

15. SUBJECT TERMS
wind turbines; wind turbine controls; wind turbine speed regulation; controls advanced research turbine

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
Unclassified	Unclassified	Unclassified	UL		19b. TELEPHONE NUMBER (*Include area code*)