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Testing State-Space Controls for the Controls Advanced Research Turbine

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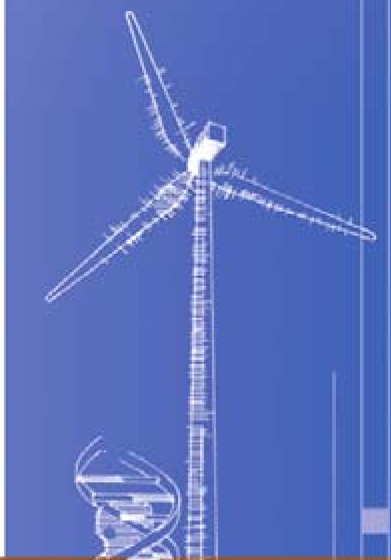

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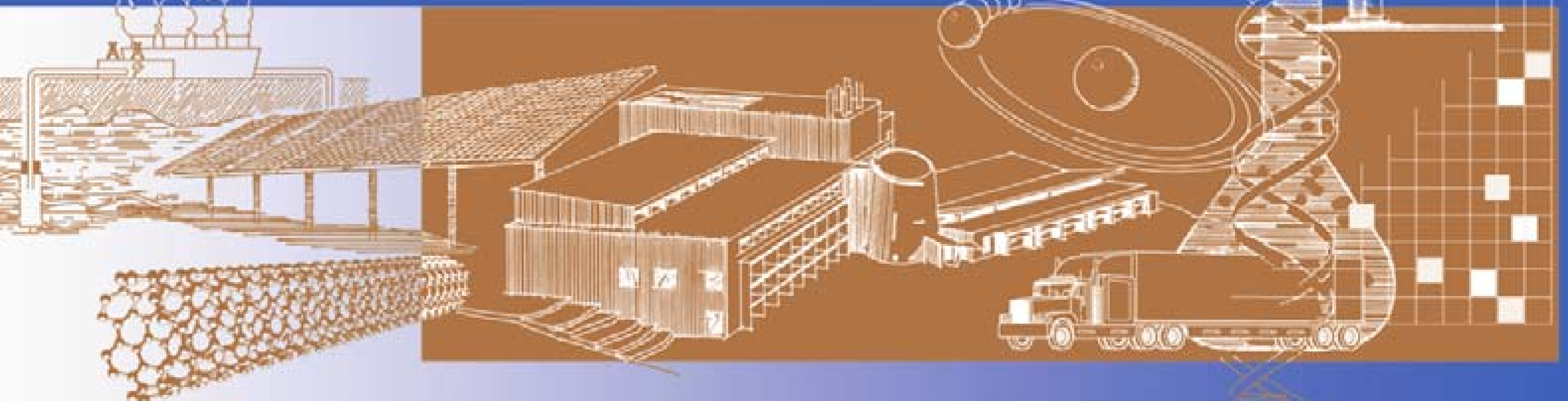

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Testing State-Space Controls for the Controls Advanced Research Turbine

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Control can improve wind turbine performance by enhancing energy capture and reducing dynamic loads. At the National Renewable Energy Laboratory, we are implementing and testing state-space controls on the Controls Advanced Research Turbine (CART), a turbine specifically configured to test advanced controls.

We show the design of control systems to regulate turbine speed in Region 3 using rotor collective pitch and reduce dynamic loads in Regions 2 and 3 using generator torque. These controls enhance damping in the first drive train torsion mode. We base these designs on sensors typically used in commercial turbines.

We evaluate the performance of these controls by showing field test results. We also compare results from these modern controllers to results from a baseline proportional integral controller for the CART. Finally, we report conclusions to this work and outline future studies.

I. Introduction

Typical variable-speed wind turbines have different regions of operation. In Region 2, the goal is to maximize energy production by using generator torque control to operate at optimum tip-speed ratio. In Region 3, generator torque is held constant, and blade-pitch control is used to maintain constant turbine speed. Another important goal of turbine control is to reduce structural dynamic loads.

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] Successful use of state estimation is based on just a few turbine measurements, such as generator speed and tower-top fore-aft acceleration. Other researchers designed controls using state-space methods in Region 2 to maximize energy extraction and reduce fatigue loads with pitch control. [4] In that study, individual pitch control was shown through simulation to reduce fatigue damage equivalent blade loads by 11%.

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There is a great need to implement and test these advanced control algorithms on field-test turbines to demonstrate their load-alleviating capability and to resolve issues regarding implementation of these controls in commercial turbines. Load reduction is important to reduce cost of energy (COE). Performance of these modern control algorithms must be compared to simpler controls based on classical methods to demonstrate intended load reductions. 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,[5] the robust controller produced about the same performance with less pitch activity than the PI controller, but the 3P frequency load attenuation was improved. Further implementation and testing of state-space control designs was reported in (Ref. 7), where two state-space controllers for regulating turbine speed in Region 3 were designed, implemented, and tested in the Controls Advanced Research Turbine (CART) at the National Wind Technology Center (NWTC). These controls were designed to add significant damping to flexible modes which ordinarily have small amounts of damping in open-loop operation. Poor design of controllers can destabilize these modes and increase fatigue loads. It is important that the controllers designed in both Regions 2 and 3 stabilize these modes. A smooth transition between Region 2 and 3 controllers must be achieved to maintain stability of these low-damped modes so that fatigue loads are not increased.

In this paper, we show the design of controls to enhance the damping in the first drive train torsion mode in both Regions 2 and 3, thereby reducing drive train torque loads. These controls must maximize energy in Region 2 and maintain constant turbine speed in Region 3. We show the results of designing a smooth transition between Regions 2 and 3. We then show preliminary results of implementing and testing these controls in the CART. We describe lessons learned from implementing these controls on a field-test turbine, state conclusions, and outline future work. Now we describe the field-test machine.

II. CART Configuration

The CART (Fig. 1) is a two-bladed, teetered, upwind, active-yaw wind turbine. This machine is used as a test bed to study aspects of wind turbine controls technology on medium- to large-scale machines.[8]

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 a low-speed shaft [LSS] speed of 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 to maintain optimum aerodynamic power coefficient C_p.

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

For the baseline turbine controls, the generator torque is varied in Region 2 according to the expression $T = kw^2$, where T is generator torque, k is a constant, and w is rotor speed.[8] In Region 2, blade pitch is constant. In Region 3, generator torque is fixed and blade pitch is varied with a simple PI control loop to maintain constant rotor speed.[8]

One of the challenges of wind turbine control design is meeting multiple control objectives. While maximizing energy in Region 2 and maintaining constant turbine speed in Region 3, we must also reduce dynamic loads to obtain longer turbine lifetimes and reduce COE. If controls are not carefully designed to account for the flexible modes of the wind turbine, we can actually increase dynamic loads through destabilization of low-damped modes. Figure 2 shows excitation of the CART's first drive train torsion mode in Region 3 when controlled with the simple PI baseline controller. It is clear that advanced controls must be designed to enhance damping in these modes. We now describe the design of state-space controls for Region 2 and Region 3 that allow us to meet primary objectives in these regions while also enhancing the damping in the first drive train torsion mode.

III. State-Space Control Design

Our control objective is to maximize power in Region 2 and maintain constant rotor speed in Region 3. We also want to design the controller to enhance damping in the first drive train torsion mode. We must also design a smooth transition between Region 2 and Region 3 to avoid exciting flexible turbine modes, which increase dynamic loads.

In (Ref. 10), a multi-controller approach to state-space control of variable-speed wind turbines over the entire operating envelope was shown. Separate state-space controllers were designed for Region 2 and Region 3. In Region 2, the state-space controller was designed using Disturbance Tracking Control (DTC) theory.[9.] This control design approach allows us to use full-state feedback to achieve desired transient response and stability, while tracking optimum C_p . In Region 3, the controller was designed using Disturbance Accommodating Control (DAC), an approach also allowing full-state feedback. The DTC and DAC controllers were then combined in a multi-controller system that switched between the two controllers when the variable-speed turbine operation transitioned between Regions 2 and 3.

We apply this technique to the design of a generator torque controller to enhance drive train torsion damping in Regions 2 and 3. This controller tracks wind disturbances to maintain constant C_p in Region 2. In Region 3, its only objective is to add damping to drive train torsion. In the transition region, we perform a linear interpolation of generator torque control between Regions 2 and 3 to provide a smooth transition. A pitch controller is also designed using DAC to regulate turbine speed in Region 3 and mitigate the effects of wind speed disturbances.

To apply linear control theory to the design of a Region 2 or 3 controller, a linear state-space turbine model is needed. Such a model is described by

$$\begin{aligned} \dot{\underline{x}} &= A\underline{x} + B\underline{u} + \Gamma\underline{u}_d \\ \underline{y} &= C\underline{x} \end{aligned} \qquad (1)$$

where $\underline{x}$ is the state vector, $\underline{u}$ is the control input, $\underline{u}_D$ is the disturbance input, $\underline{y}$ is the measured output, A is the state matrix, B is the control input distribution matrix, Γ is the disturbance input distribution matrix, and C relates the measured output $\underline{y}$ to the turbine states.

The disturbance inputs $\underline{u}_d$ are derived using a Disturbance Waveform Generator[9.]

$$\begin{aligned} \dot{\underline{z}}_d(t) &= F_d\,\underline{z}_d(t) \\ \underline{u}_d(t) &= \theta_d\,\underline{z}_d(t); \\ \underline{z}_d(0) &= \underline{z}_d^{\,0} \end{aligned} \qquad (2)$$

where $\underline{z}_d$ are the disturbance states, and the matrices F_d, and θ_d are assumed to be known, while $\underline{z}_d^{\,0}$ is unknown (the waveform of the disturbance is known but the amplitude is not). For a step waveform for representing the uniform component of wind speed over the rotor disk, $F_d \equiv 0$, and $\theta_d \equiv 1$.

The control law is assumed to be the superposition of a term corresponding to state feedback of the plant states $\underline{x}$ and a term involving the disturbance $\underline{z}_d$:

$$\underline{u} = G\underline{x} + G_d\,\underline{z}_d \qquad (3)$$

A. Generator Torque Control Design

For the generator torque control design in either Region 2 or 3, a linear model that describes the generator rotational speed as well as first drive train torsion mode is:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} \frac{(\gamma - C_d)}{I_{rot}} & \frac{-1}{I_{rot}} & \frac{C_d}{I_{rot}} \\ K_d & 0 & -K_d \\ \frac{C_d}{I_{gen}} & \frac{1}{I_{gen}} & \frac{-C_d}{I_{gen}} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{-1}{I_{gen}} \end{bmatrix} \delta T_{gen} + \begin{bmatrix} \frac{\alpha}{I_{rot}} \\ 0 \\ 0 \end{bmatrix} \delta w \tag{4}$$

$$y = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} .$$

where,

x_1 = perturbed rotor-speed: $\delta\Omega_{rot}$
x_2 = perturbed drive-train torsion spring force: $K_d(\delta\psi_{rot} - \delta\psi_{gen})$
x_3 = perturbed generator speed: $\delta\Omega_{gen}$

Here $\delta\psi_{rot}$ is the perturbed rotor azimuth angle, $\delta\psi_{gen}$ the perturbed generator azimuth angle, $\delta\Omega_{rot}$ the perturbed rotational speed of the rotor, and $\delta\Omega_{gen}$ the rotational speed of the generator. I_{rot} is the rotor rotational inertia, I_{gen} is the generator rotational inertia, K_d is the spring constant describing the torsional stiffness of the LSS, C_d is the torsional damping constant, α is the partial derivative of rotor aerodynamic torque with respect to blade pitch angle, and γ is the partial derivative of rotor aerodynamic torque with respect to rotor speed.

We model the disturbance state in (1) with just one state: perturbation of the uniform wind speed over the rotor disk δw. Our control input is δT_{gen}, perturbation in generator torque. State estimation is used to estimate unmeasured plant states using the single turbine measurement perturbed generator rotational speed x_3.

We designed the Region 2 generator torque controller from this state-space model generated by FAST [13] at the turbine operating point:

Wind speed = 8 m/s
Rotor speed = 27.1 RPM
Pitch angle = -1 degree (normal Region 2 "run-pitch").

The goal of state-space control design is to use state feedback to place the poles of the plant to obtain desired stability and transient response. In open-loop, the eigenvalues of the A matrix at this operating point have the values -0.0004 ± 3.57i (Hertz [Hz.].), -0.0044. The pole pair corresponds to the first drive train torsion mode, having a natural frequency of 3.57 Hz. We chose the gains G in the feedback law so that the closed-loop eigenvalues were -0.6 ± 3.57i (Hz.), -0.1. This resulted in greatly enhanced damping in the first drive train torsion mode. The gain G_d corresponding to the uniform wind disturbance was chosen to track wind speed disturbances using the theory of DTC. [9.]

For the Region 3 generator torque controller, a linear model with the same states as in (4) was generated by FAST at the turbine operating point.

Wind speed = 18 m/s
Rotor speed = 41.7 RPM
Pitch angle = 11 degrees.

The goal is to again use state feedback to place the poles of the plant to obtain desired stability and transient response. In open-loop, the eigenvalues of the A matrix had the values -0.0016±3.5712i (Hz.), -.016. We chose the gains G in the feedback law so that the closed-loop poles would have values -0.6±3.57i (Hz.), -0.15.

In Region 3 control, the generator torque is usually constant. Blade-pitch control is then used to maintain a constant turbine rotational speed, thereby fixing power at "rated power." Here we allow only small perturbations in generator torque to enhance damping in the first drive train torsion mode. The gain corresponding to the uniform wind disturbance (G_d) was set to zero for the Region 3 torque controller to prevent tracking or canceling wind speed disturbances, which would cause large variations in generator torque.

B. Region 2 to 3 Generator Torque Control Transition

In the Region 2 to 3 transition, we switched between the Region 2 and Region 3 generator torque controllers based on the equation:

$$T = (T_2 - T_1)(\Omega_{rot} - \Omega_1)/(\Omega_2 - \Omega_1) + T_1 \tag{5}$$

where T is generator torque, T_1 is the Region 2 torque, T_2 is the Region 3 torque, Ω_{rot} is rotor speed, Ω_1 is the rotor speed at the start of Region 2 to 3 transition (39.2 RPM), and Ω_2 the rotor speed at the start of Region 3 (41.3 RPM).

C. Region 3 Pitch Controller

Control of turbine speed in Region 3 is performed by the rotor collective pitch controller. Here we use DAC to design the controller to mitigate wind speed disturbances. The rotor collective pitch controller is designed from a state-space model with the following states:

x_1 = perturbed rotor symmetric flap displacement
x_2 = perturbed rotor symmetric flap velocity
x_3 = perturbed generator speed
x_4 = perturbed actuator pitch angle
x_5 = perturbed actuator pitch rate
x_6 = perturbed uniform wind disturbance over the rotor disk

We found it necessary to include actuator dynamics in the model for control design as described in (Ref. 7), as reflected in selection of states x_4 and x_5 above.

For design of this controller, this state-space model was generated by FAST at a turbine operating point of

Wind speed = 18 m/s
Rotor speed = 41.7 RPM
Pitch angle = 11 degrees.

We chose the gains G in the feedback law so that the closed-loop poles would have values -4.6±13.5i (Hz.), -2, -10, and -59. The first pair of poles corresponds to the perturbed rotor first symmetric flap mode. The next pole corresponds to the perturbed rotor rotational speed state, and the next two states correspond to the perturbed actuator blade-pitch angle and perturbed pitch rate. In this operating region, the control objective for the pitch controller is to regulate speed in the presence of persistent wind disturbances. The gain corresponding to the wind disturbance G_d is chosen to mitigate wind disturbances uniform over the rotor disk using DAC.[9]

We ran test simulations in FAST before implementing these controllers on the real machine. During one test, we wanted to compare the rotor speed predicted by FAST when using the state-space controllers to the baseline Region 2 and Region 3 controllers. Figure 3 shows this comparison. In this simulation, we input step winds, beginning with a wind speed of 6 m/s and increasing to 12 m/s in steps during 60 seconds of simulation. Over the entire wind speed range, the state-space controller results in slightly higher rotor speeds compared to the baseline controller. The larger discrepancy at the low end of Region 2 may be a result of designing only one controller in Region 2, at one operating point (wind speed of 8 m/s). A solution may be to design several controllers at different Region 2 operating points and to transition between controllers using gain scheduling. In addition, it was shown in (Ref. 4) that certain state-space models may result in imperfect optimum tip-speed ratio tracking using Disturbance Tracking Control Theory. We will investigate these issues in future work.

We now describe various implementation issues regarding testing this Region 2 and Region 3 controller in the CART.

IV. Implementation Issues and Lessons Learned

There are various issues in implementing and testing wind turbine controls. Sensor limitations, data sampling rates, and actuator dynamics are important, as reported in (Ref. 7). In addition, the control algorithm must be correctly coded in the turbine-control software. Each of the previously described controllers is implemented into the CART-control software. 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 uses a lookup table for aerodynamic torque. These tests are useful for 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 in which the simulator predicts dynamic instability when the other simulator models (FAST) or actual turbine do not. However, this is a very useful test to conduct before the controller is tested on the real machine.

There are also situations in which testing a new controller on the real machine results in unstable behavior, even though the simulations do not reveal this behavior. When first testing a new controller, turbine behavior must be closely monitored to ensure stable operation. The first Region 2 generator torque controller we implemented and tested in the CART resulted in unstable generator torque upon startup, as shown in Fig. 4. None of our simulations predicted this behavior. This controller was designed from a linear model generated at a turbine operating point closer to Region 3 than the final design. When the controller was redesigned at the operating point described in the control design section above, we obtained stable generator torque upon startup.

Another issue was correctly implementing the Region 2 to 3 transition. Early implementation of these generator torque controls resulted in a rough transition. Instead of adding damping to the first drive train torsion mode, we were actually destabilizing this mode. Figure 5a shows turbine response while being controlled by the first implementation of the transition Eq. (5). In this first implementation, we used unfiltered rotor rotational speed in (5). This signal (LSS RPM) contains high-frequency noise, as seen in the figure. Figure 5a also shows commanded generator torque and LSS torque. Between 160 and 163 seconds, the turbine is entirely in transition since the rotor speed is above the entrance to transition (39.2 RPM). The resulting demanded generator torque (Torque Demand) contains much of the same high-frequency content as the LSS RPM signal. This noise acts to excite the drive train torsion instead of adding damping, as seen in the LSS torque signal in Fig. 5a. We then filtered rotor speed in Eq. (5) with a first-order filter with a time constant of 1 second. The resulting measured demanded generator torque, LSS torque, and LSS RPM (unfiltered LSS RPM values shown in this plot) are shown in Fig. 5b. Now, except for the point at which the turbine enters transition, the commanded generator torque is much smoother than in Fig. 5a. The LSS Torque signal shows much less response at the first drive train torsion mode.

A further problem occurred at the limit points of the Region 2 to 3 transition (lower limit 39.2 RPM, upper limit 41.3 RPM). Figure 5b shows discontinuities in demanded generator torque when the lower limit of 39.2 RPM is reached. These discontinuities are caused by a mismatch of rotor speed used in Eq. (5) and rotor speed used in the decision to enter transition. At any instant of time, the unfiltered and filtered values of rotor speed will be unequal. From Eq. (5) we see that for a rotor speed of 39.2 RPM, the demanded generator torque should equal T_1 (Region 2 torque at 39.2 RPM). If there is a mismatch in the rotor speed used in Eq. (5) and the rotor speed used in the decision to enter transition test, the demanded generator torque will not equal T_1, and there will be a discontinuity in demanded generator torque upon entering or exiting the transition region. Figure 5c shows the result of using filtered rotor speed in both Eq. (5) and the decision test. In this figure, the rotor speed passes through both the lower and upper limit points (39.2 and 41.3 RPM). Now the commanded generator torque is smooth without discontinuities.

Another problem concerned interaction between the Region 3 torque controller and the Region 3 pitch controller. Previous control simulation tests failed to show this interaction[3] (Fig. 6). Both the generator torque and blade pitch controllers were designed assuming generator speed (HSS RPM) as the control input. As can be seen from Fig. 6a, the HSS RPM signal contains high cyclic amplitude at the first drive-train torsion frequency. Also from Fig. 6a, we see that the LSS Torque and the demanded Generator Torque all contain response at this frequency. Because HSS rotational speed is the input to the pitch controller as well, the pitch controller also responds at this natural frequency. The pitch controller and torque controller interact in an undesirable way.

We then changed the control input to the blade pitch controller to LSS RPM instead of HSS RPM. This signal does not contain a response at the first drive-train torsion frequency because the large rotor inertia acts as a filter, filtering out response at this frequency (3.5 Hz). Now, the blade pitch controller no longer responds at the first drive-train torsion frequency, and the generator torque controller no longer interacts with the pitch controller (Fig. 6b). Even though the pitch controller was not designed from a state-space model containing a description of the first drive-train torsion mode, it interacts with the torque controller when high-speed RPM is used as the control input. Inputting rotor speed (LSS RPM) instead of generator speed (HSS RPM) solves this problem.

We now make some preliminary comparisons of the state-space controller to the baseline controller in Regions 2 and 3.

V. Field Test Results and Comparisons

We collected data on the CART while testing the Region 2 state-space controller. We then compared the test results to a case from the baseline control in Region 2. Because these controllers were tested at different times, a direct results comparison is difficult. Our objective was to show trends, such as load mitigation. We attempted to examine both datasets and extract smaller sections of data in which turbine operating parameters (such as wind speed and direction, yaw error, etc.) were similar. The results of our comparison are preliminary, and we need many more hours of operation for realistic statistical comparisons between the controllers.

Table 1 shows the statistics of two datasets used for comparison. Each dataset consisted of 300 seconds of data. Listed in this table are the mean and standard deviation (std) of the wind speed (at a height of 36.6 meters [m]), rotor speed (LSS RPM), generator torque (Torque Demand), and LSS torque.

Figure 7 shows plots of wind speed, LSS rotational speed, LSS torque, and demanded generator torque for the two datasets. Figure 7a corresponds to the baseline controller and Fig. 7b the state-space controller. Although the wind speeds do not match, the deviations in wind speed for the two cases are similar, with somewhat greater deviations occurring during operation with the state-space controller. We also calculated the Damage Equivalent Load (DEL) for the LSS torque for the two datasets.[14] The state-space controller resulted in slightly lower DEL than the baseline controller.

We also calculated the power spectral density (PSD) of the LSS and demanded generator torque for the two cases, as shown in Fig. 8. The peak in the PSD for the LSS torque (Fig. 8a) corresponds to the first drive-train torsion natural frequency. It is interesting to note that this peak is lower for the state-space control case because we have used full state feedback to place the poles corresponding to this mode to have higher damping, resulting in reduced loads at this frequency. The peak for the state-space control case is displaced slightly to the right of the baseline case because we have placed the pole to have a natural frequency at 3.57 Hz. The natural frequency of the first drive-train torsion mode in open-loop is probably about 3.3 Hz., as seen by the peak response for the baseline case. This represents a slight discrepancy between the FAST-predicted natural frequency (3.57 Hz.) and the open-loop natural frequency of this mode in the real machine, due to modeling uncertainty.

Table 1: Preliminary Comparison of Baseline and FAST State-Space Controllers for Region 2 Operation

Statistics and Performance Measure	Baseline Control (05031750.DAT)	State-Space Control (07191751.DAT)
Wind speed (m/s)	mean 8.45 std 1.44	mean 8.22 std 1.53
Rotor speed (rpm)	mean 28.53 std 3.86	mean 27.3 std 3.35
Generator torque (kNm)	mean 1340 std 361	mean 1190 std 341
Low-speed shaft torque (kNm)	mean 59.4 std 15.9 fatigue DEL 7.63	mean 53.3 std 14.1 fatigue DEL 6.83

Figure 8b shows the PSD of the demanded generator torque. For the baseline control case, the peak at 3.57 Hz. is absent because the controller is not adding damping to this mode. For the state-space case, the large peak at 3.57 Hz. indicates the action of the generator controller to add damping to this mode as desired. Table 1 indicates (std of demanded generator torque) that the generator torque activity is actually lower for the state-space case compared to the baseline case. Further data collection and comparisons are needed before we can assess the effects of these additional control objectives on the actuator duty cycle of the generator.

Table 2. Comparison of Baseline and FAST State-Space Controller for Region 3 Operation

Statistics and Performance Measure	Baseline Control (05212101.DAT)	State-Space Control (09092110.DAT)
Wind speed (m/s)	mean 15.85 std 2.31	mean 15.74 std 2.11
Rotor speed (rpm)	mean 41.67 std 0.30	mean 41.26 std 0.49
Generator torque (kNm)	mean 3501 std 112.9	mean 3409 std 160.2
Low-speed shaft torque (kNm)	mean 154.10 std 8.08 fatigue DEL 18.27	mean 149.84 std 7.92 fatigue DEL 8.92

Next we compared the Region 3 state-space controller to the Region 3 baseline PI controller. Table 2 compares statistics of 300 seconds of CART data during operation with the PI controller and the state-space controller. Figure 9 shows plots of different data channels for these two cases. The mean and std of wind speed are slightly lower for the state-space controller, as seen in the table. The mean rotor speed is also slightly lower, although the std is slightly higher than for the baseline case. A lack of turbine data for the turbine operating entirely in Region 3 meant that there was some operation in the transition region. The std of demanded generator torque is higher for the state-space controller than for the baseline case. This may be due to operation in the transition region. For the baseline controller operating entirely in Region 3, the standard deviation of demanded generator torque should be zero. A direct assessment of actuator duty for the state-space controller is difficult. We also calculated the DEL for the LSS torque, with a large reduction in load for the state-space controller compared to the baseline controller.[14]

Figure 10 shows the PSDs of LSS and generator torque for the two control cases. Again, we see in Fig. 10a a significant reduction in the peak at the first drive-train torsion mode for the state-space case because of the damping enhancement provided by the generator controller. The PSD of generator torque shows a peak at 3.57 Hz. for the state-space case, indicating that the generator is adding damping to the first drive-train torsion mode.

Although these results are preliminary, Tables 1 and 2 seem to show the potential to reduce LSS torque loads with the state-space controllers. This is due to the enhanced damping of the first drive-train torsion mode with these controllers. The load reduction seems to be greater in Region 3 than in Region 2. This may be due to nonlinear behavior of the turbine in Region 2. Improved performance might be obtained by designing controllers at several operating points in Region 2 and transitioning between them using gain scheduling. In this study we designed a controller at a single operating point in Region 2. In addition, we need to re-design the Region 2 controller to place the poles farther to the left in the complex plane, further increasing the damping in the first drive-train torsion mode. More data must be collected with the state-space controllers and comparisons made to the baseline controller before firm conclusions can be reached. In this preliminary study, the trends indicate potential for load alleviation using state-space control designs.

VI. Conclusions

In this paper, we have shown the design, implementation, and testing of controls using generator torque in Regions 2 and 3 to enhance damping in the first drive-train torsion mode. Rotor collective pitch control is used in Region 3 to regulate turbine speed. We described various controls implementation issues, such as Region 2 to 3 transition. We also described correctly implementing the generator torque control and blade pitch control in Region 3 to prevent interactions between these two controllers. We showed preliminary test results after implementing and testing these controls in the CART in both Regions 2 and 3, indicating that these state-space controls reduce structural dynamic loads compared to a baseline PI controller. 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 baseline 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 and blade pitch to add damping to the tower side-side and fore-aft modes 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).

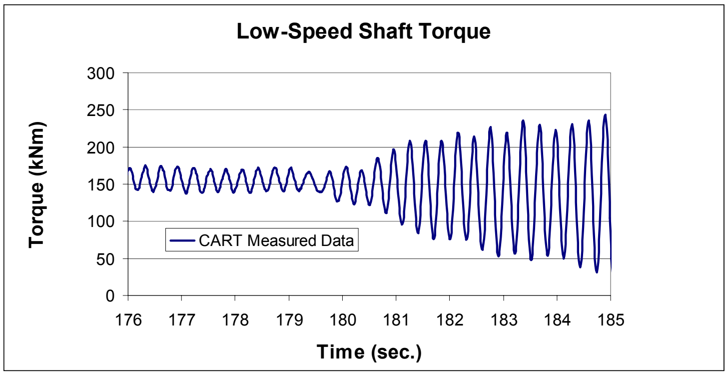


Figure 2. Measured shaft torque showing drive train excitation in Region 3 using classical control.

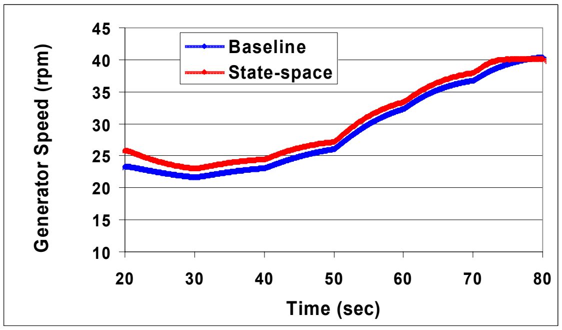


Figure 3. FAST-simulated generator speed for the baseline and state-space controllers excited by step winds spanning Regions 2 and 3.

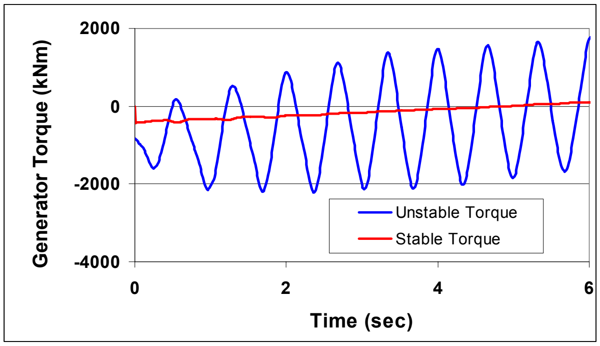


Figure 4. Measured generator torque showing stable and unstable behavior during startup for two implemented controllers.

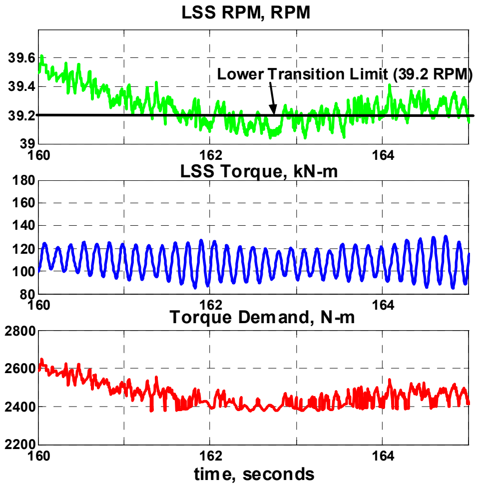


Fig 5a.

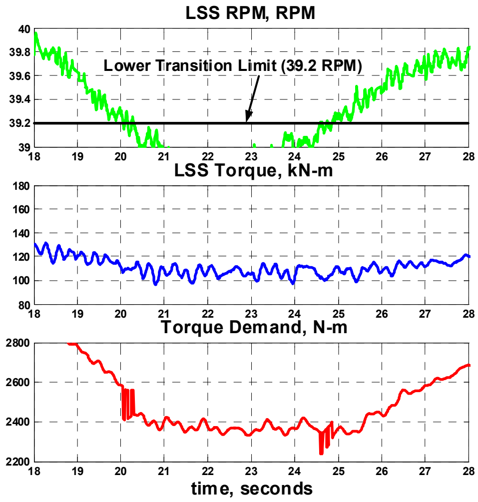


Fig 5b.

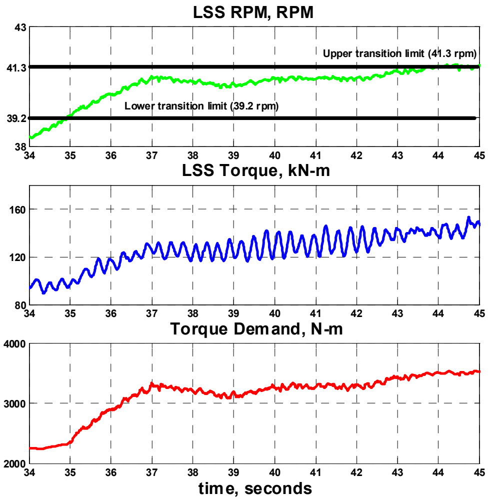
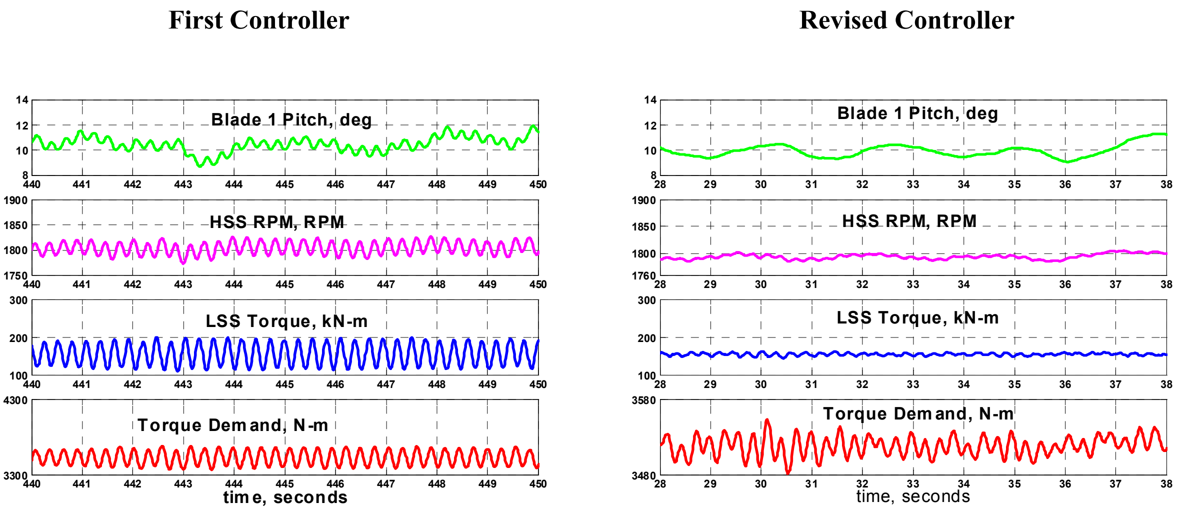


Fig 5c.

Figure 5. Measured CART data during transition from Region 2 to Region 3.

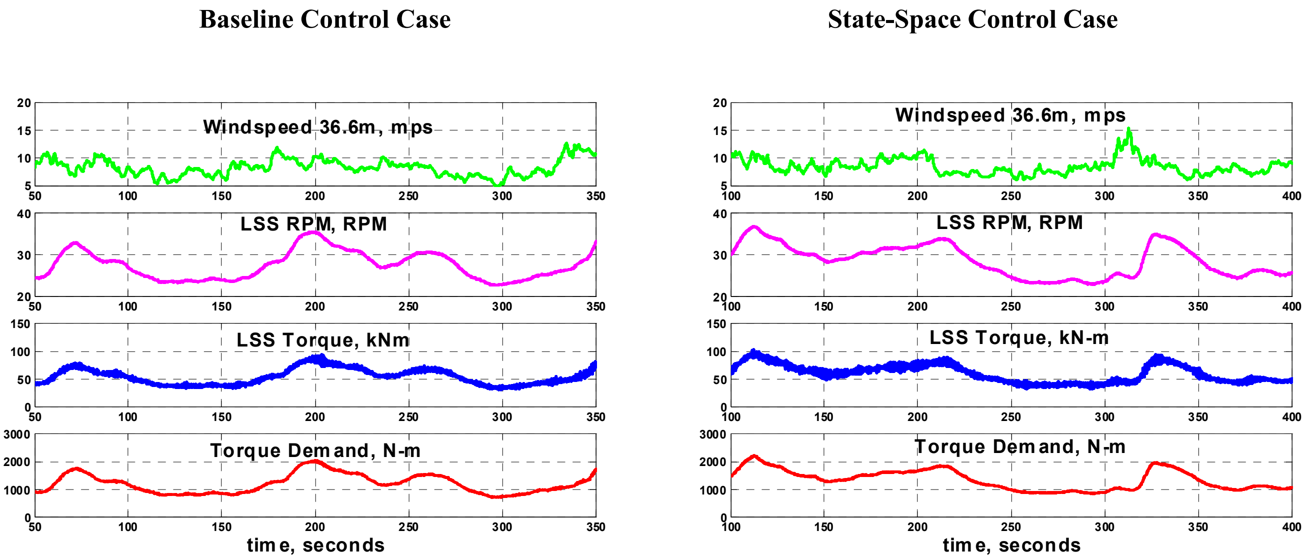

First Controller

Revised Controller

Fig 6a.

Fig 6b.

Figure 6. Measured CART data during operation in Region 3, showing generator pitch interaction in first controller.


Baseline Control Case

State-Space Control Case

Fig 7a.

Fig 7b.

Figure 7. Measured CART data for Region 2 control for the baseline and state-space case.

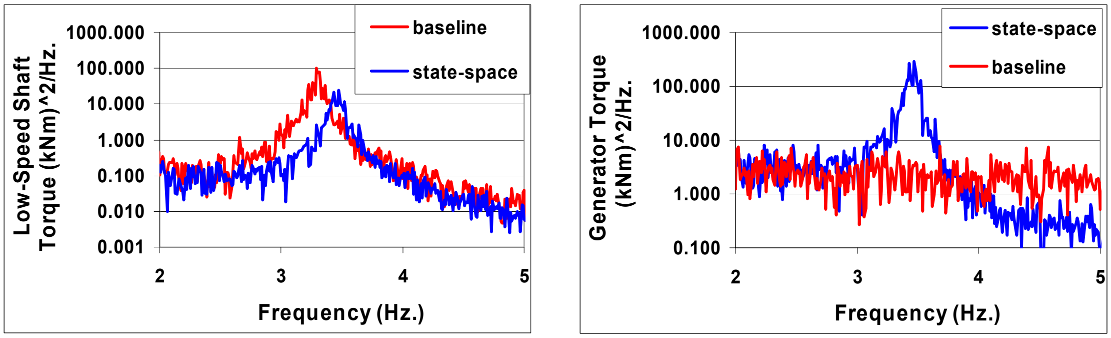


Fig 8a. Fig 8b.

Figure 8. Power spectral density of low-speed shaft and generator torque for the Region 2 baseline and state-space cases.

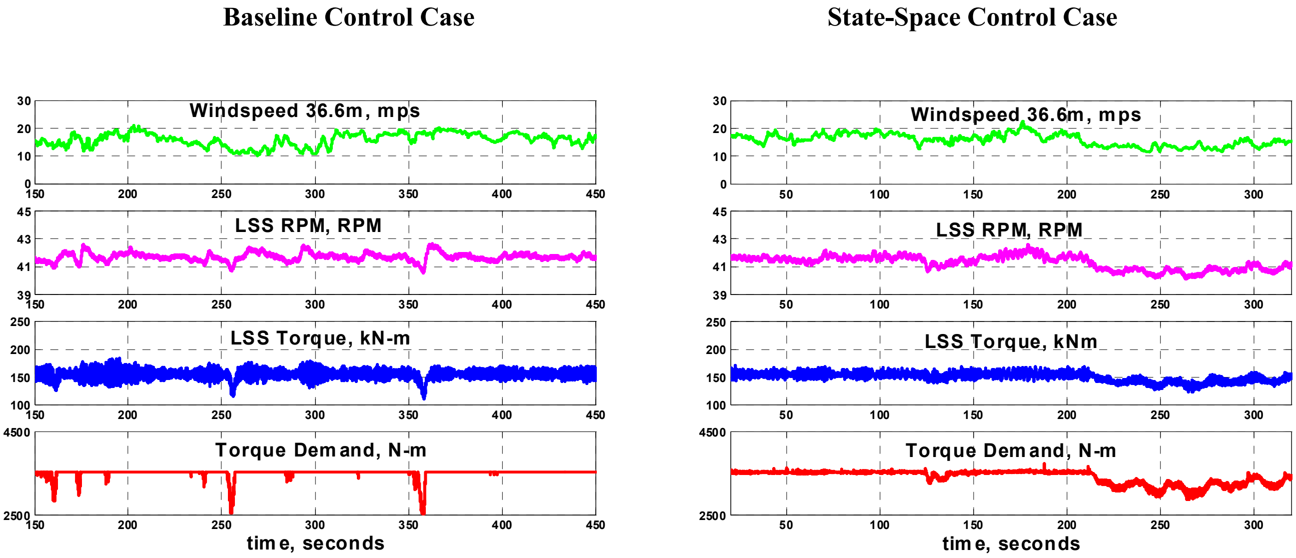


Fig 9a. Fig 9b.

Figure 9. Measured CART data for Region 3 control for the baseline and state-space case.

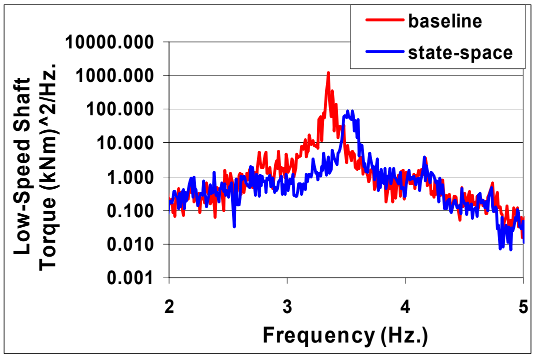


Fig 10a.

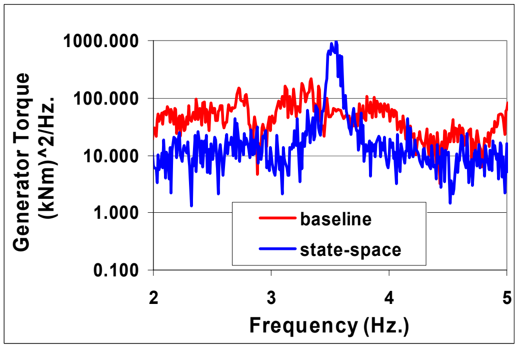


Fig 10b.

Figure 10. Power spectral density of low-speed shaft and generator torque for the Region 3 baseline and state-space cases.

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14. ABSTRACT *(Maximum 200 Words)*

Control can improve wind turbine performance by enhancing energy capture and reducing dynamic loads. At the National Renewable Energy Laboratory, we are implementing and testing state-space controls on the Controls Advanced Research Turbine (CART), a turbine specifically configured to test advanced controls. We show the design of control systems to regulate turbine speed in Region 3 using rotor collective pitch and reduce dynamic loads in Regions 2 and 3 using generator torque. These controls enhance damping in the first drive train torsion mode. We base these designs on sensors typically used in commercial turbines. We evaluate the performance of these controls by showing field test results. We also compare results from these modern controllers to results from a baseline proportional integral controller for the CART. Finally, we report conclusions to this work and outline future studies.

15. SUBJECT TERMS

wind energy; wind turbines; control systems; CART; Controls Advanced Research Turbine

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