NREL/CP-500-24378 • UC Category: 1211

Wind Turbine Control System Modeling Capabilities

Kirk Pierce
Lee Jay Fingersh

Presented at
American Controls Conference
Philadelphia, PA
June 24–26, 1998

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under contract No. DE-AC36-83CH10093

Work performed under task number WE801340

April 1998

Available to DOE and DOE contractors from:
Office of Scientific and Technical Information (OSTI)
P.O. Box 62
Oak Ridge, TN 37831
Prices available by calling (423) 576-8401

Available to the public from:
National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

WIND TURBINE CONTROL SYSTEM MODELING CAPABILITIES

Kirk Pierce
Lee Jay Fingersh
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401

Abstract

At the National Renewable Energy Laboratory's (NREL's) National Wind Technology Center we are continuing to make progress in our ability to model complete wind turbine systems. An ADAMS® model of the NREL variable-speed test bed turbine was developed to determine whether wind turbine control systems could be simulated and to investigate other control strategies for this turbine. Model simulations are compared with data from the operating turbine using the current mode of operation. In general, the simulations show good agreement with test data. Having established confidence in our ability to model the physical machine, we evaluated two other control methods. The methods studied are a generalized predictive control method and a bias estimation method. Simulation results using these methods are compared to simulation results of the current mode of operation of the turbine.

Introduction

Control systems have been incorporated into wind turbine designs throughout much of their long history, although the earliest systems were manual. Early modern-era wind turbines used passive controls to regulate power, yawing, and rotor braking. As the size of turbines and the knowledge of automatic control systems increased, tail vanes and other passive devices became impractical, and active control systems arose. Today, a 100-1000 kW wind turbine often has active pitch control, and in the case of upwind rotors, active yaw control. The future promises a further increase in the use of control systems as new designs investigate controlling load and power excursions by using variable-speed operation, aerodynamic controls, and other devices in more complex schemes.

Aerodynamic and power control systems can enhance power production, prevent overloading, and reduce fatigue loads of the turbine, but how best to control these complex nonlinear systems to achieve these goals has yet to be determined. Overuse of the controls increases maintenance needs of the turbine, although underuse would not result in the desired goals. Ideally, we would like to maximize the power produced while minimizing damaging loads and the effort needed by the controls. These are difficult objectives to realize, since the wind input to the turbine can be highly turbulent and varied over the rotor disk.

At the National Wind Technology Center (NWTC) at NREL, we are continuing to make progress in our ability to model complete wind turbine systems. The commercially available ADAMS[1] dynamics analysis program, combined with the AeroDyn [Hansen 1996] aerodynamics code, provides great flexibility in the modeling of these complex systems. An ADAMS model may have many hundreds of degrees of freedom, including elastic blades, towers, and drive train components. ADAMS also allows modeling of control systems. These control systems can be quite complex, and can be implemented as either continuous or discrete time systems. Control systems evaluated with these models produce, as accurately as currently possible in computer simulations, the behavior of the complete system over the dynamic range of operation.

Computer simulations provide unique control over otherwise uncontrollable parameters. For example, it is possible to repeatedly use the same wind as input to the model. By using the same wind with the same model and varying control strategies, differences in power output and loads can be attributed directly to changes in control strategies. This provides a relatively quick means of evaluating control methods. In contrast, in order to evaluate various strategies on an operating turbine, one would need to collect many hours of test data and use statistical methods to determine effects.

While computer simulations can provide useful insight into the effects of control systems, it is necessary that the simulation accurately represent the physical system being modeled. To gain confidence in our ability to model wind turbine control systems, we developed an ADAMS model of the NREL variable-speed test bed turbine [Carlin and Fingersh 1997]. This turbine is operated at the National Wind Technology Center.

---

[1] ADAMS is a registered trademark of Mechanical Dynamics Inc. Further references denote ADAMS linked with AeroDyn.

Test Data Comparisons

The ADAMS model of the NREL variable-speed test bed was developed to determine our ability to model wind turbine control systems. This is a three-bladed, downwind turbine, with a rotor diameter of 10 m. Test data from this turbine are readily available for comparison to predictions. As the name indicates, the turbine operates in variable speed, and utilizes full-span blade pitch to regulate rotor speed in high winds.

There are two modes of operation for this turbine. In low winds the pitch of the blades is held constant while the generator torque is regulated to allow the turbine to operate near the most efficient tip-speed ratio. In high winds the generator torque is held constant and the blades are controlled in pitch to maintain the rotor near constant speed. This paper investigates control methods for regulating rotor speed in the high-wind-speed region of operation. At present, the method used for control of blade pitch on the turbine is a PID-type algorithm. The current methods of operation of the turbine pitch control system and generator were modeled as accurately as possible in ADAMS to compare results of the simulations with test data.

Comparisons with a section of test data, including variable speed and speed regulation regions of operation, are shown in Figures 1 and 2. Figure 1 is a plot of simulated and measured blade pitch versus time. Figure 2 is a plot of simulated and measured rotor speed versus time. The simulation was performed using wind speed and direction data measured from an array of anemometers located 2.5 rotor diameters upwind of the turbine. The data were time-shifted by the ratio of the distance between the array of anemometers and the turbine rotor, and the average wind speed for the data set, for comparison to the simulation results. As we see in the figures, the match between the simulated data and the test data is quite good, indicating that the model can accurately predict the behavior of the actual turbine. Several additional simulations resulted in good comparisons for turbine speed and pitch as well. Having established this confidence in our ability to model the turbine in the present configuration, we proceeded to investigate other control methods as well.

Control Method Investigation

The current PID method used on the turbine works quite well for speed regulation in low winds; however, oscillations in pitch were observed for operation in high winds. We thought that a different method of control might produce better overall turbine performance. The methods we investigated in this study were the generalized predictive control method and the bias estimation method. The control objectives for the power regulation region were to maintain the rotor speed between 100 and 110 rpm, near 105 rpm, with low pitch actuation. Also, the dynamic behavior of the turbine was to remain fairly constant with changing wind conditions.

The basic dynamic equation for the wind turbine, neglecting viscous damping, which is low for this direct-drive turbine, is given by

$$T_{aero} - T_{gen} = I\dot{\omega} \qquad (1)$$

where T_{aero} is the aerodynamic torque generated by the rotor, T_{gen} is the generator torque, I is the inertia of the rotating system, and $\dot{\omega}$ is the rate of change of rotor speed. Taking the derivative with respect to time of equation 1, and since T_{gen} is constant in the power regulation region,

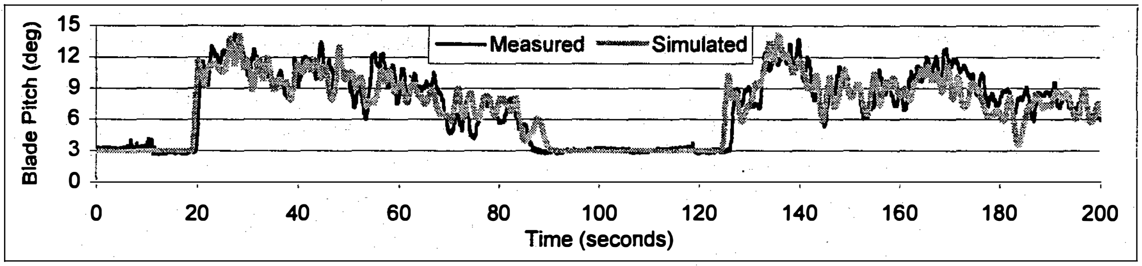

Figure 1: Simulated and measured blade pitch angle versus time

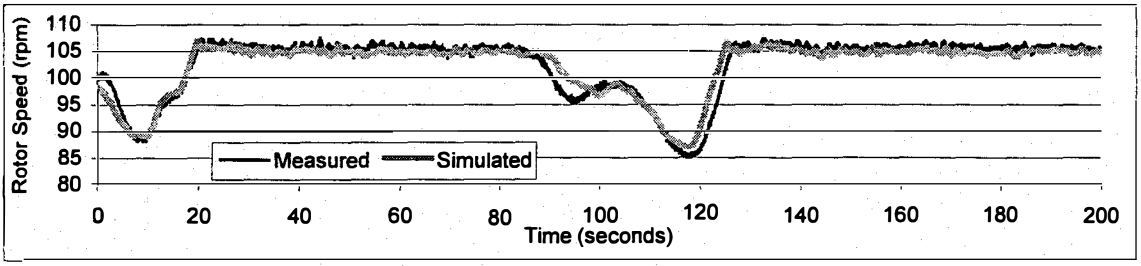

Figure 2: Simulated and measured rotor speed versus time

produces

$$\dot{T}_{aero} = I\ddot{\omega} \tag{2}$$

The change in aerodynamic torque depends upon the change in wind speed, the change in pitch angle of the rotor blades, and also on the current operating point of the turbine. For this representation of the turbine dynamics, the transfer function from the rate of change of aerodynamic torque to rotor speed is a double integrator, scaled by the inverse of the rotating system inertia.

For the turbine under consideration, the drive train is very stiff and, therefore, drive train dynamics need not be included. Also, the pitch actuation system used on the turbine is very fast, accurately following the desired pitch rate, so that including actuator dynamics was not necessary. For other systems, these dynamics may be important, and so they should be included in the control model.

Two 10-minute data sets were chosen for the initial evaluation of the control methods. The first data set was for a relatively low wind case with an average wind speed of 7.7 m/s and a turbulence intensity of 13%. The second data set was for a moderately high wind case with an average wind speed of 12 m/s and a turbulence intensity of 16%. In this higher wind speed case, oscillations in pitch were observed.

Generalized Predictive Control

Generalized predictive control (GPC) [Clarke et al. 1987] uses estimates of the future output of the plant to calculate the current control signal. The discrete model of the turbine used for the method is shown in Figure 3, which is a finite difference approximation of the double integrator model. Δp is the change in blade pitch angle, Δv is the change in hub-height wind speed, and ω is the rotor speed. The coefficients b and c of the model are adapted using a recursive least-squares (RLS) filter with forgetting factor. Low pass filtered values of the signals were used in the RLS filter and as input to the control systems to eliminate high-frequency noise. This model of the turbine produced an accurate prediction of rotor speed, with coefficients that varied reasonably and as expected with wind speed. As others have noted Leith and Leithead 1994], the coefficients b and c increase in magnitude as the wind speed increases. The increase in b produces an increase in gain for the pitch system, which results in the marginally stable system in high winds for the PID control used on the turbine.

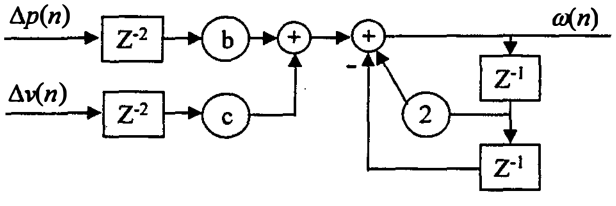

Figure 3: Wind turbine model.

The equations for the GPC method used in this study are given by

$$W = GP + F \tag{3}$$

Where

$$W = \begin{pmatrix} \omega(n+1) \\ \omega(n+2) \\ \Delta\omega(n+1) \\ \Delta\omega(n+1) \end{pmatrix} \quad P = \begin{pmatrix} \Delta p(n) \\ \Delta p(n+1) \end{pmatrix}$$

$$G = \begin{bmatrix} 0 & 0 \\ b & 0 \\ 0 & 0 \\ b & 0 \end{bmatrix} \tag{4}$$

$$F = \begin{pmatrix} 2\omega(n) - \omega(n-1) + b\Delta p(n-1) + c\Delta v(n-1) \\ 2F(1) - \omega(n) + c\Delta v(n) \\ \Delta\omega(n) + b\Delta p(n-1) + c\Delta v(n-1) \\ F(3) + c\Delta v(n) \end{pmatrix}$$

The equations for $\omega(n+1)$ and $\omega(n+2)$, given above, are the standard GPC method of order two. The standard method was found to produce an unsatisfactory transient response because of the double integrator and the short control horizon used for the method. The additional equations for $\Delta\omega$ were added to provide derivative type control to improve the transient response.

The cost function to be minimized, J, was chosen to be

$$J = (W - W_D)^T Q(W - W_D) + \sigma P^T P \tag{5}$$

The weighting matrix, Q, was included so different weighting factors could be used for ω and $\Delta\omega$. W_D is the desired response vector, which is known for all time since the desired rotor speed is a constant in the power regulation region. σ is the decision factor that weights the use of control against the error in the desired response. For Q positive semidefinite the cost function above produces the control law

$$P = \left[\sigma I + G^T Q G\right]^{-1} G^T Q\left[W_D - F\right] \tag{6}$$

The matrix to be inverted is diagonal for this system making calculation of the inverse straightforward. The desired change in pitch for the current time step is given by the first element of P.

The GPC method has the ability to adjust control as the system coefficients vary with changing conditions. However, the change in control that occurs is not the preferred change. As the wind speed and b increase, the method uses the additional gain in the pitch system to more accurately control the rotor speed. To enable the system to perform similarly for all wind speeds, the decision factor, σ, was scaled by b. That is $\sigma = \sigma_0 b$, where σ_0 is a constant.

Bias Estimation Model

In the bias estimation model (BEM) [Franklin et al. 1990] the state estimator is augmented with additional equations that estimate unmodeled disturbances acting on the system. This method was investigated because the wind speed for this turbine is not measured very near the rotor, and if it were, it may not accurately represent the wind speed over the rotor disk. Therefore, the bias term to be estimated is the effect of wind speed changes acting on the turbine.

The same model of the turbine used for GPC was used for this method as well, including average values of the coefficients b and c, determined from the RLS filter for 12 m/s average wind speed. These average values are denoted by b_M and c_M. This model, minus the wind input, was used as the linear model for calculating of the feedback gains.

The state estimator was augmented with a state to estimate Δv assuming step changes. This estimate of Δv is included in the control law to cancel the disturbance. The system under consideration is shown in Figure 4. The estimator used for this system produced a fairly accurate estimate of the change in wind speed, as shown in Figure 5. The line labeled "estimate" in the plot is obtained from shifting the sum of the estimated Δv. Over time, the wind speed estimated by this method drifts, since only Δv is estimated. The state estimator for this low-order system was found to perform fairly well over the range of wind speeds investigated.

Results

The control methods were implemented in user written subroutines that are linked to ADAMS. Simulations were performed using wind speed measurements from the two selected 10-minute data sets for the GPC and BEM control strategies. Results of these simulations were compared with simulation results for the current PID algorithm to ensure direct comparison. Histograms of rotor speed and blade pitch rate were calculated to compare the control methods.

Normalized histograms of rotor speed and pitch rate for the low wind speed cases are shown in Figure 6 and Figure 7. Only data from the speed regulation region of operation were used in calculating the histograms. The PID method maintains the rotor speed closest to the desired value of 105 rpm, and has the highest pitch actuation. The GPC method has the lowest pitch actuation and the largest variation in rotor speed from the set point value. Results of the BEM simulation lie between the results of the other methods. For this case, the results are as expected: the distribution of rotor speed from the desired value decreases with increasing control.

Normalized histograms of rotor speed and pitch rate for the higher wind speed cases are shown in Figures 8 and 9. For this case, BEM produces the least deviation in rotor speed from the desired value. The rotor speed distribution for the PID method is similar to that of the BEM, maintaining the rotor speed close to the desired value. However, in this higher wind speed case the PID method shows excessive pitch actuation. Again, GPC shows the largest spread in rotor speed and the least pitch actuation.

With GPC, the distributions in rotor speed and pitch rate are very similar for both cases in this study. The distributions could be adjusted by changing the decision factor, thus producing similar results in changing wind conditions. Rotor speed distribution for BEM decreases with increasing wind speed because of the increased gain of the pitch system. Pitch actuation for this method may become excessive in high winds. The increased gain of the pitch system with increasing wind speed produces a marginally stable system for the PID method in higher winds.

Conclusions

A modified generalized predictive control method and the bias estimation control method were compared in an ADAMS model of the NWTC variable-speed test bed turbine. Simulations were performed using measured wind data from two 10-minute data sets. Comparisons were then made of the GPC, BEM, and PID control methods. The gain of the pitch system increased with increasing wind speed, which is one of the difficulties associated with speed control for this turbine. The other major difficulty is the turbulent nature of the wind input.

The GPC method demonstrated similar distributions of rotor speed for the wind cases in this study. The decision factor was adjusted as the pitch gain varied with changing wind conditions, resulting in the similar distributions.

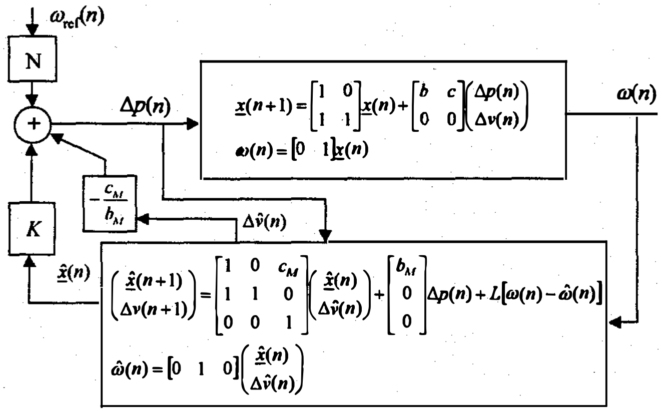

Figure 4: BEM control system

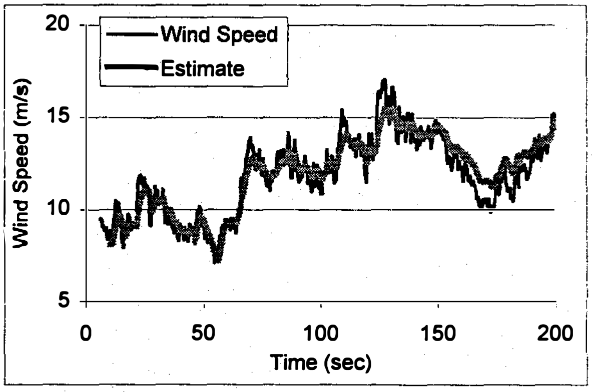

Figure 5: Measured and estimated wind speed

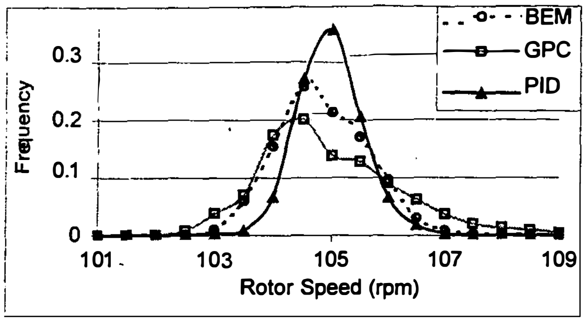

Figure 6: Rotor speed histogram (low wind case)

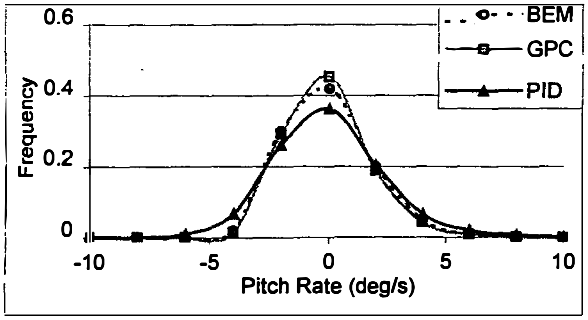

Figure 7: Blade pitch rate histogram (low wind case)

However, this method requires a wind speed measurement for implementation

BEM demonstrated a decreased rotor speed distribution and increased pitch actuation as the pitch system gain increased with increasing wind speed. Pitch actuation may become excessive at high wind speeds. Gain scheduling techniques used with this method may provide more similar distributions over a range of wind speeds.

Acknowledgements

DOE has supported this work through the National Renewable Energy Laboratory under contract number DE-AC36-83CH10093.

References

Carlin, P. W., and Fingersh, L. J., 1997, *Some Preliminary Results from the NWTC Direct Drive, Variable-Speed Test Bed*, AIAA 97-0966, 35th Aero-space Sciences Meeting & Exhibit, AIAA, Reno, Nevada.

Clarke, D. W., Mohtadi, C., and Tuffs, P. S., 1987, *Generalized Predictive Control - Part I. The Basic Algorithm*, Automatica v 23 n 2, Mar 1987, pp. 137-148.

Connor, B., and Leithead, W. E., *The Effect of Rotor Characteristics on the Control of Pitch Regulated Variable Speed Wind Turbines*, Wind Energy Conversion 1994, Proceedings of the 16th British Wind Energy Association Conference, Sterling, UK.

Franklin, Gene F., Powell, J. David, and Workman, Michael L., 1990, *Digital Control of Dynamic Systems*, Second Edition, Reading, Massachusetts, Addison-Wesley.

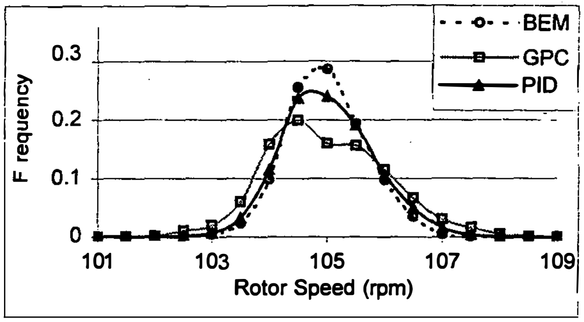

Figure 8: Rotor speed histogram (high wind case)

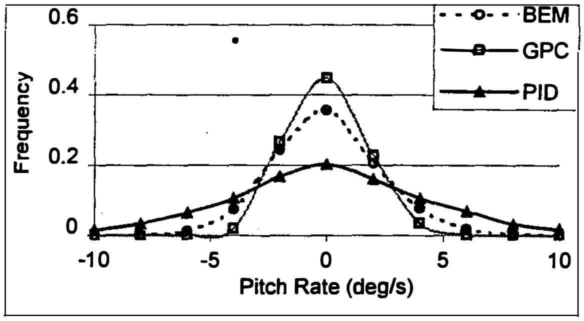

Figure 9: Blade pitch rate histogram (high wind case)

Hansen, A. C., 1996, *Users Guide to the Wind Turbine Dynamics Computer Programs YawDyn and AeroDyn for ADAMS®*, Mechanical Engineering Department, University of Utah, Salt Lake City, Utah.

Leith, D. J., and Leithead, W. E., 1994, *Comparisons of Various Control Strategies for a Two Bladed Wind Turbine*, Wind Energy Conversion 1994, Proceedings of the 16th British Wind Energy Association Conference, Sterling, UK.

Pierce, Kirk G., and Laino, David J., 1996, *Modeling the Effects of Control Systems on Wind Turbine Fatigue Damage*, Proceedings of Windpower '96, AWEA, Denver Colorado.

Sastry, Shankar and Bodson, Marc, 1989, *Adaptive Contro. Stability, Convergence, and Robustness*, Englewood Cliffs, New Jersey, Prentice Hall,.