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Adaptive Disturbance Tracking Control to Maximize the Power Capture of Large Wind Turbines in Below Rated Wind Speed Region

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Abstract The amount of power captured by wind turbine depends on the wind speed and the power coefficient (C_p). When wind speed is above rated value, the rated amount of power is captured but in below rated wind speed operation or Region II operation, the power captured must be maximized.

The power coefficient (C_p) further depends on the blade pitch angle and the Tip Speed Ratio (TSR). For a fixed blade pitch angle there exist an optimum TSR for which the power coefficient becomes maximum. In Region II turbine operation, blade pitch is kept constant and TSR is tracked to its optimum value to maximize the power capture.

In this paper we introduce an Adaptive Disturbance Tracking Control (ADTC) Theory and make some modifications to implement it to maximize the power capture by tracking the optimum TSR in Region II operation of large wind turbines. Since ADTC requires measurement of wind speed, a wind speed and partial state estimator based on linearized lower-order model of wind turbine at Region II operating point was developed. The estimated wind speed was then used with the adaptive controller and the states were used for state feedback. The combination of partial state feedback and adaptive disturbance tracking control is implemented in National Renewable Energy Laboratory (NREL)'s 5 MW offshore wind turbine model and simulated in MATLAB/Simulink. The simulation result was then compared with existing fixed gain controller.

1 Introduction

Depending on the available wind speed, wind turbines operate in three different regions. In the first region, also called the startup region, the wind speed is just sufficient to turn on the wind turbine. When the wind speed is enough to produce the power but not enough to produce rated power, the wind turbines operate in Region II. In Region III, the wind speed is more than rated value and the turbine operates in its rated speed producing the rated power.

The amount of power, that can be extracted using wind turbine, can be expressed as [1]:

$$P=\frac{1}{2}\rho A C_p w^3, \tag{1}$$

where, P is the power, A is the area of the rotor disc, C_P is the power coefficient, ρ is the air density, w and is the free-stream wind velocity.

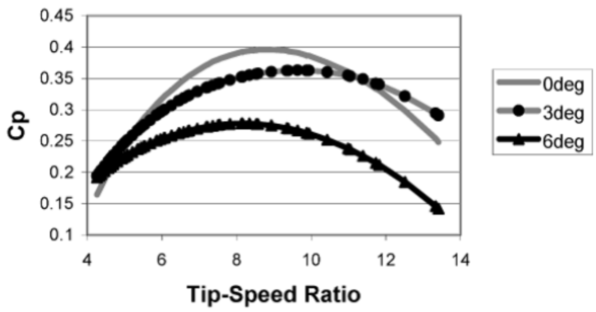
The power coefficient C_P is the function of tip-speed ratio (λ) and the blade pitch angle (β). The Tip Speed Ratio (TSR) can be expressed as:

$$\lambda = \frac{\Omega R}{w} \quad , \tag{2}$$

where, Ω is the rotor speed, R is the rotor radius.

The variation of power coefficient with the TSR for fixed sets of blade pitch angles are in figure 1. When wind speed is not sufficient to produce the rated power, the power capture can be maximized by operating the wind turbine at optimum TSR with fixed blade pitch angle which is the main concern in the Region II operation

Fig. 1. Variation of Tip Speed Ratio with power coefficient for a fixed blade pitch angle



An idea for counteracting persistent disturbance was developed by Johnson in [2]. Theory of Disturbance Tracking Control was developed by Balas [3]. This theory has been explored by Wright in [4] where he used fixed gain disturbance tracking controller to address the Region II control problem of CART-II. Adaptive Disturbance Tracking Control was first used in [5] where the wind speed was assumed to be available for measurement. In [6], [7] a simple wind speed estimator was introduced which uses only the generator speed information to estimate the wind speed. This simple estimator was implemented for linearized version of CART – II for the Region II control. Since simple wind speed estimator introduces a non-minimum phase zero, this drawback has been addressed in [8], where a nominal plant model is used to estimate the wind speed. In this paper we further investigate the ADTC theory and modify it to incorporate the wind speed estimator, partial state estimator and partial state feedback from a lower order model of the turbine.

The motivation behind the theory of Adaptive Disturbance Tracking Control is to make the wind turbine track the wind speed, which ultimately tries to keep the TSR constant at some optimum value. The TSR tracking error (ε) is introduced as the deviation of the actual TSR (λ) from the operating or optimum TSR (λ_{OP}).

$$\varepsilon \equiv \lambda - \lambda_{op} = \frac{\Omega R}{w} - \frac{\Omega_{op} R}{w_{op}}$$
$$= \frac{R}{w}\left(\Omega - \frac{\Omega_{op}}{w_{op}} w\right) \tag{3}$$

where (Ω_{op},w_{op}) is the desired turbine operating point corresponding to the desired TSR (λ_{OP}). We let the **Output Tracking Error** be

$$\begin{cases} e_y \equiv \Omega_T - Q * w \\ \text{with } Q \equiv \dfrac{\Omega_{op}}{w_{op}} \end{cases} \tag{4}$$

and think of (Ω), the turbine speed variation, as a measured output of the turbine and (w), the wind speed fluctuations, as a disturbance on the turbine. Then DTC choose a feedback control law that produces:

$$e_y = \Omega - Q * w \xrightarrow[t \to \infty]{} 0 \tag{5}$$

this (approximately) produces tracking of the desired TSR[5] :

$$\varepsilon = \lambda - \lambda_{op} \xrightarrow[t \to \infty]{} 0 \tag{6}$$

2 Adaptive Disturbance Tracking Control (ADTC) Theory

In this section we introduce further modification of the theory presented in [5] with addition of wind speed and partial states estimation, and partial state feedback.

The wind turbine is assumed to be modeled by a linear, time-invariant, finite-dimensional system:

$$\begin{cases} \dot{x} = Ax + Bu_p + \Gamma u_D \\ y = Cx; x(0) = x_0 \end{cases}$$

(7a)

and the plant model with partial states of (6a) is expressed as:

$$\begin{cases} \dot{x}_m = A_m x_m + B_m u_p + \Gamma_m u_D \\ y_m = C_m x_m ; x_m(0) = x_0 \end{cases} \tag{7b}$$

where, the plant state, x, is an N_p-dimensional vector, the control input vector, u_p , is M-dimensional, the sensor output vector, y , is P-dimensional. x_m is m-dimensional (m<n) lower order plant model state vector, y_m is the P_m dimensional model output vector. A, B, C, Γ are the state, input, output and disturbance matrix of plant with appropriate dimensions. A_m, B_m, C_m, Γ_m are the state, input, output and disturbance matrix of the lower order plant model with appropriate dimensions. The disturbance input vector, u_D, is M_D-dimensional and will be thought to come from the Disturbance Generator:

$$\begin{cases} u_D = \Theta z_D \\ \dot{z}_D = F z_D ; z_D(0) = z_0 \end{cases} \tag{8}$$

where, the disturbance state,z_D , is N_D-dimensional.

All matrices in Eqs. (7)-(8) have the appropriate compatible dimensions. Such descriptions of persistent disturbances were first used in [5] to describe signals of known form but unknown amplitude. Equation (8) can be rewritten in a form that is not a dynamical system, which is sometimes easier to use:

$$\begin{cases} u_D = \Theta z_D \\ z_D = L \phi_D \end{cases}$$

(9)

where, φ_D is a vector composed of the known basis functions for the solution of $u_D = \Theta z_D$, i.e., φ_D are the basis functions which make up the known form of the disturbance, and L is a matrix of appropriate dimension. The method for tracking persistent disturbances used in this paper requires only the knowledge of the form of the disturbance, the amplitude of the disturbance does not need to be known, i.e.(L,Θ) are unknown. In this paper, we will be interested in rejecting step disturbances of unknown amplitude which can be represented in the form of Eq. (9) as $\varphi_D=1$, with (L,Θ) unknown. This has been a viable model for wind fluctuations in our previous work.

Now combining equation (7b) and (8) we get a new augmented plant model [6]:

$$\begin{bmatrix} \dot{x}_m \\ \dot{z}_D \end{bmatrix} = \begin{bmatrix} A_m & \Gamma_m \Theta \\ F & 0 \end{bmatrix} \begin{bmatrix} x_m \\ z_D \end{bmatrix} + \begin{bmatrix} B_m \\ 0 \end{bmatrix} u \tag{10}$$

In equation (10) we used the lower order plant model to estimate the partial state and use the partial state feedback.
using the augmented plant model in (10) , a state estimator can be designed as:

$$\begin{bmatrix} \dot{\hat{x}}_m \\ \dot{\hat{z}}_D \end{bmatrix} = \begin{bmatrix} A_m & \Gamma_m \Theta \\ F & 0 \end{bmatrix} \begin{bmatrix} \hat{x}_m \\ \hat{z}_D \end{bmatrix} + \begin{bmatrix} B_m \\ 0 \end{bmatrix} u + \begin{bmatrix} K_x \\ K_D \end{bmatrix} (y_p - \hat{y}_m) \tag{11}$$

The estimator equation (11) can also be broken down into wind disturbance estimator and state estimator as:

$$\begin{aligned} \dot{\hat{x}}_m &= A_m \hat{x}_m + B_m u + \Gamma_m \Theta \hat{z}_D + K_x (y_p - \hat{y}_m) \\ \dot{\hat{z}}_D &= F \hat{z}_D + K_D (y_p - \hat{y}_m) \end{aligned} \tag{12}$$

Using the wind disturbance state estimation, the estimated wind speed can be expressed as:

$$u_D = \Theta \widehat{z}_D \tag{13}$$

Our control objective will be to cause the output of the plant, y_p, to asymptotically track some linear function of estimated disturbances of the form given by the disturbance estimator. We define the estimated output tracking error vector as:

$$\hat{e}_y \equiv y_p - Q u_D \tag{14}$$

To achieve the desired control objective, we want $\hat{e}_y \xrightarrow[t \to \infty]{} 0$

this aligns with the TSR tracking in Region II described by equation (5).

Consider the plant given by Eq. (7a) with the disturbance generator given by Eq. (8) and respective disturbance and state estimator given by (11) and (12). Our control objective for this system will be accomplished by an Adaptive Control Law of the form:

$$u_P = G_e \hat{e}_y + G_D \phi_D + G_x x_m \tag{15}$$

where G_e and G_D are adaptive gain matrices of the appropriate compatible dimensions, and G_x is the state feedback gain matrix.

Now we specify the *Adaptive Gain Laws*, which will produce asymptotic tracking:

$$\begin{cases} \dot{G}_e = -\hat{e}_y \hat{e}_y^T \gamma_e \\ \dot{G}_D = -\hat{e}_y \phi_D^T \gamma_D \end{cases} \tag{16}$$

where γ_e, γ_D are arbitrary, positive definite matrices. Our Adaptive Controller is specified by Eq. (15) with the above adaptive gain laws Eq. (16).

3 Implementation of ADTC Theory

The ADTC theory with low order state estimation and wind speed estimation discussed in previous section was designed and implemented to the National Renewable Energy Laboratory (NREL)'s 5 MW onshore wind turbine model to track the optimum TSR and maximize the power capture in below rated wind speed region.

3.1 Simulation setup

NREL's 5 MW wind turbine model is the three bladed horizontal axis upwind wind turbine with 63 meter of rotor radius and 5 MW of rated power. The cut-in, rated and cut-out wind speed are 3 m/s, 11.4 m/s and 25 m/s respectively. Also, cut-in and rated rotor speeds are 6.9 m/s and 12.1 m/s respectively. It has rated Tip Speed of 80 m/s with a Tip Speed Ratio of 7.55.

Depending upon which Degree Of Freedom (DOF) we need, it has eleven switches which can be switched on and off to add the complexity in operation. When all DOF's are switched on the wind turbine model has 31 states. The detailed description of this wind turbine can be found in [9].

To design the wind speed and partial state estimation of wind turbine, the turbine is linearized at constant wind speed of 8 m/s with blade pitch held at 0 degree. During the linearization Drive Train and Generator DOF switch were turned on which gave four states with two states due to the Generator DOF and two states due to Drive Train DOF. The first state (generator azimuth position) was removed to get the three state model of wind turbine. This three state model is then augmented with wind disturbance model given by equation (8) and state estimator was designed using equation (11).

3.2 Simulation results

We simulated the wind turbine model with existing baseline PID controller and the adaptive controller with partial state observer and state feedback we designed with step wind profile. The TSR performance and the amount of power captured were compared.

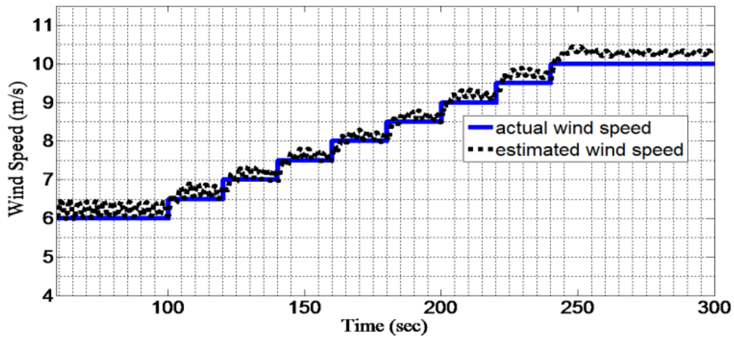


Fig. 2. Actual vs estimated wind speed

The estimated wind speed is in fig. 2. The estimated wind speed is close enough to the estimated speed. The noise in estimated wind speed may be because of the flexibility of wind turbine structures.

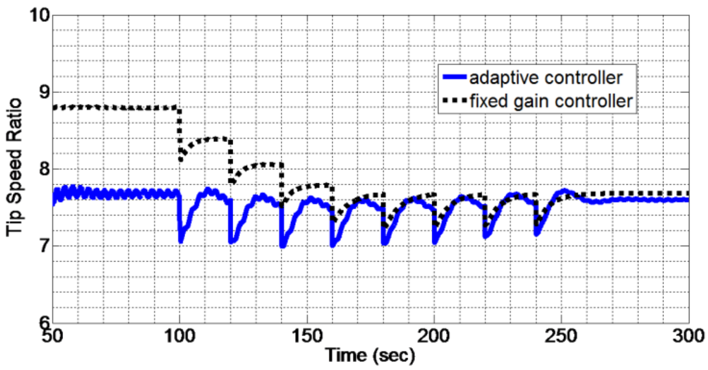


Fig. 3. Comparison of Tip Speed Ratio (TSR)

The main aspect of the Region II control is TSR tracking or keeping TSR constant at its optimum value, which ultimately maximizes power captures. The TSR tracking performance of ADTC with partial order estimator and state feedback is compared in fig. 3. with the existing fixed gain PID controller. The optimum TSR for the 5 MW wind turbine model used for simulation is 7.55 and the ADTC is performing relatively better.

The TSR has the huge effect on the power output. Its deviation from the optimum value, either larger or smaller, reduces the power capture. The fixed gain controller has slightly high deviation from the optimum TSR hence the power captured is slightly less than that of ADTC in steady state.

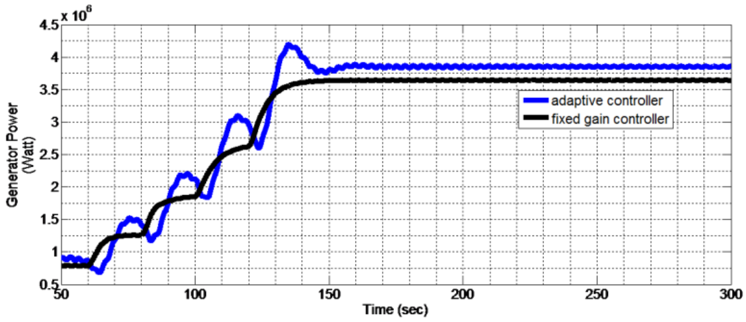


Fig. 4. Comparison of Generator Power in Region II operation

4 Conclusion

We introduced the theory of adaptive disturbance tracking and used it to track the TSR of large wind turbines. Since the ADTC theory requires wind speed information, we used low order plant model to combine the disturbance model with it and designed the estimator based on this augmented plant, which estimates few selected states as well as the wind speed. From the simulation, we found that the ADTC and partial state estimator/state feedback has comparatively better performance in both TSR tracking and power generation compared to the existing fixed gain controller. Also, the wind speed estimator closely estimates the wind speed which can be used with ADTC.

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