Nonlinear Estimation and Control of Wind Turbine

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Abstract—**Wind energy is one of the major renewable energy sources which continue to be one of the fastest growing power generation sectors. For variable speed operation of wind energy conversion system, it is required to generate the maximum power at below the rated speed using an authentic and powerful control strategy. Wind speed has the major impact on the dynamics and control of wind turbines. But in practice there is no accurate measurement of effective wind speed available for direct measurement. In this paper a new technique is proposed for optimal power generation of wind turbine below rated speed without estimating the wind speed. An extended Kalman filter (EKF) is used to estimate the rotor speed and a proportional (P) controller is used to track the error between the measured and estimated rotor speed. The output of the P controller is the estimated aerodynamic torque. The estimated aerodynamic torque and the rotor speed act as an input to the aerodynamic torque feed-forward (ATF) controller. The output of the ATF controller is the generated torque. As the aerodynamic torque is highly dependent on the wind speed so it cannot be controlled. So we have to control the generated torque by using ATF for generating optimal power output. Finally the estimated outputs are validated through correlation analysis.**

***Index Terms*—Extended Kalman Filter, Aerodynamic Torque feed-forward controller, Proportional Controller, Generator torque.**

I . INTRODUCTION

In recent years wind energy has become a popular and a rapidly growing technology for new renewable energy sources due to its environmental, social and economic benefits. Generally wind energy conversion system has been classified into two types namely fixed speed and variable speed wind systems. Different control strategies can be applied to variable speed wind turbines. So at different wind condition the variable speed wind turbine offers a great flexibility over the fixed speed wind turbines [1]. Authors in [2] have discussed about different control strategy i.e. speed control and torque control mode. In torque control mode an electrical torque reference is obtained from the measured shaft speed which gives the optimal tip speed ratio [3]. In speed control mode a rotational speed reference is obtained which gives the optimal tip speed ratio. Different methods are available for getting this speed reference. The rotational speed reference can be derived from the wind speed measurement which is measured by using an anemometer, but not an accurate data. A fuzzy logic based intelligent control of a wind generation system is discussed in [4], where a fuzzy controller tracks the generator speed with the wind velocity to extract the maximum power.

An accurate and reliable measurement of effective wind speed is required to control the wind turbines. The data given by the anemometer reading is not reliable and accurate because it provides the wind speed in the single point of the rotor plane and is distributed by the turbulence from the rotor[5]. The control problem is to track optimal power extraction at below the rated wind speed. This can be achieved by adjusting the generated torque based on the optimum rotor speed. Generally in literature the well known control techniques are Indirect speed control (ISC) [6] and Aerodynamic torque feed forward control (ATF) [7]. A nonlinear approach for a variable speed wind turbine to control the generated torque by using static and dynamic state feedback controllers where the Kalman filter is used to estimate the aerodynamic torque and the rotor speed is given in [8]. In general one approach in the design of dynamic estimators is either to design a linear Kalman filter for estimating the aerodynamic torque and then calculate the effective wind speed [9]. The other way is to combine a linear model of the drive train with the nonlinear aerodynamic model and use nonlinear algorithms such as EKF to estimate the wind speed [10] or by using more dedicated algorithms [11]. The methods discussed above are only for state estimation i.e. aerodynamic torque and the rotor speed. In [12] a dynamic observer based on the Kalman filtering approach is designed for the state estimation and an input observer based on ideas from tracking controllers is designed for estimation the aerodynamic torque. All above techniques discussed are suitable for below the rated wind speed whereas for above rated wind speed pitch control is used.

This paper is based on the rotor speed estimation by using EKF and tracking the error between the measured and estimated rotor speed. The aerodynamic torque is estimated based on the error tracking by using input estimation. The generated torque is controlled by using ATF control. Finally the optimal power output can be obtained at below rated speed by controlling the generated torque without estimating the effective wind speed. Advantage of this method is without estimating the effective wind speed an unknown input based nonlinear estimation is used for estimation of the state variable i.e. the rotor speed.

II. WIND TURBINE MODELLING

Wind turbines produce electricity by using the power of the wind to drive an electrical generator. The wind passes over the blades, generating lift and exerting a turning force. The rotating blades turn a shaft inside the nacelle, which goes into a gearbox. The gearbox increases the rotational speed to that which is appropriate for the generator, which uses magnetic fields to convert the rotational energy into electrical energy. A wind turbine extracts kinetic energy from the swept area of the blades [13].

The aerodynamic power of the wind turbine is given by

$$P_a = \frac{1}{2}\rho\pi R^2 C_P(\lambda,\beta)v^3 \qquad (1)$$

and

$$\lambda = \frac{\omega_r R}{v} \qquad (2)$$

A maximum value of C_P is defined by the Betz limit, which states that a turbine can never extract more than 59.3% of the power from an air stream. In reality, wind turbine rotors have maximum C_P values in the range 25–45%. In equation (1)

λ- Tip-speed ratio
R- Rotor radius (m)
ρ- Air density (Kg/m^3)
v Wind speed (m/s)
β Blade pitch angle (deg)
ω_r Rotor speed (rad/sec)

From equation (2) it is clear that any change in the wind speed variation or rotor speed induces change in the tip speed ratio, thus will lead to the change in power coefficient $C_p(\lambda, \beta)$.

Aerodynamic power

$$P_a = \omega_r T_a \qquad (3)$$

Where T_a is the aerodynamic torque

$$T_a = \frac{1}{2}\rho\pi R^3 C_q(\lambda,\beta)v^2 \qquad (4)$$

C_q is the torque coefficient depending on the nonlinearity upon the tip speed ratio

$$C_q(\lambda,\beta) = \frac{C_p(\lambda,\beta)}{\lambda} \qquad (5)$$

Figure1 shows a single mass model of the wind turbine with suitable assumptions [14].

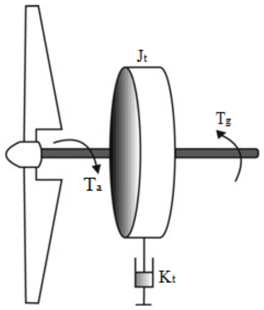

Fig1: Single mass wind turbine model dynamics

The dynamics of the rotor characteristics of a single mass wind turbine model can be expressed by a first order differential equation given as

$$J_t\dot{\omega}_r = T_a - T_g - K_t\omega_r \qquad (6)$$

Where

$$J_t = J_r + n_g{}^2 J_g \qquad (7)$$

$$K_t = K_r + n_g{}^2 K_g \qquad (8)$$

$$T_g = n_g T_{em} \qquad (9)$$

Where
J_r Rotor inertia (Kg m^2)
J_g Generator inertia (Kg m^2)
K_r Rotor external damping (Nm/rad/sec)
K_g Generator external damping (Nm/rad/sec)
T_g Generator torque (Nm)
T_{em} Generator electromagnetic torque(Nm)
n_g Gear ratio
J_t Turbine total inertia (Kg m^2)
K_t Turbine total external damping (Nm/rad/sec)

The above first order differential equation can be modified in the form of state space form with the state variable as ω_r is given in equation (10)

$$\dot{\omega}_r = \frac{1}{J_t}T_a - \frac{1}{J_t}T_g - \frac{K_t}{J_t}\omega_r \qquad (10)$$

III. CONTROL OBJECTIVE

Variable speed wind turbines can be operated in two different modes i.e i) below rated speed ii) above rated speed. For below rated speed there are two major control objectives i.e
1) Maximization of the wind power
2) Minimization of the low speed shaft transients

In most of the time wind speed is less than the rated speed, so it is necessary to capture the maximum power at below the rated wind speed. Energy capture from the aerodynamic power should be maximum below the rated wind speed.

The $C_p(\lambda_{opt}, \beta_{opt})$ curve has a unique maximum corresponding to the optimal power

$$C_p(\lambda_{opt}, \beta_{opt})=C_{popt} \tag{11}$$

$$\lambda_{opt}=\frac{\omega_{ropt}R}{v} \tag{12}$$

To extract the maximum power at below rated wind speed, the blade pitch angle β is to be fixed to optimal value β_{opt} and to maintain the λ to its optimal value λ_{opt}, the rotor speed ω_r must track the optimal rotor speed ω_{ropt}. The objective of the controller is to track the optimal rotor speed which reduces the stress on the dynamic loads [15].

The electrical aspects of the wind turbine response are much faster than the mechanical system of the wind turbine. It is necessary to cascade the two systems (Electrical and Mechanical) through control loops.

1) The inner control loop concerns the electrical generator via power converters

2) The outer control loop concerns the aero turbine that provides reference to the inner loop[15]

IV. CONTROL STRATEGY

In general the wind turbine generator is connected to the grid via rectifier and inverter. When connecting the generator to a grid via the frequency converter, the generator speed will be independent of the grid frequency. The wind turbine is controlled through the generated torque (rotor side). The control input T_{em} is used because in conventional way T_{em} control can be achieved by controlling the firing angle of the converter. In this work we have controlled T_{em} by controlling T_g. As per equation (9) T_g and T_{em} are linearly related though gear ratio n_g. So the controlling T_g is same as controlling T_{em}. Well known control strategy to achieve faster and decoupled response of torque and flux vector control [2] and direct torque control [16].

A. Classical controllers

Two well known classical controllers has been explained in this section, one is an ATF control and another one is Indirect speed control [ISC] or Maximum Power Point Tracking [MPPT]

1). ATF control: In this control the rotor speed and aerodynamic torque are estimated by using the kalman filter as shown in the fig2. The estimated aerodynamic torque is fed back to the generator torque. A proportional control law is used for controlling generated torque control [7]. The aerodynamic torque is fed back to the plant as a part of the control input which cannot be measured directly it can only be estimated by using the EKF. Linearization creates the problems because the aerodynamic torque is a nonlinear function of wind speed and rotor speed.

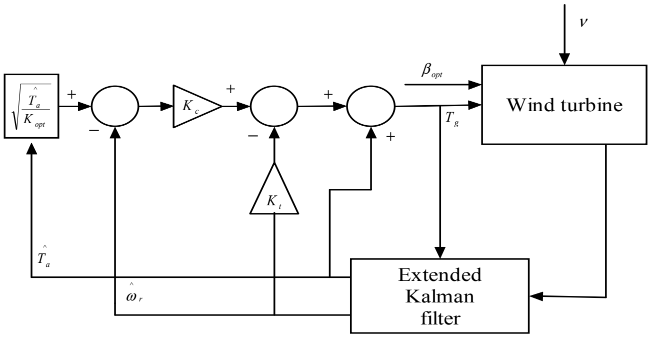

Fig2: Aerodynamic torque feed forward control

$$T_g = K_c(\omega_{ref}-\hat{\omega}_r)+\hat{T}_a-K_t\hat{\omega}_r \tag{13}$$

$$\omega_{ref}=\sqrt{\frac{\hat{T}_a}{K_{opt}}} \tag{14}$$

$$K_{opt}=\frac{\rho}{2}\pi R^5 C_{popt}\frac{1}{\lambda_{opt}{}^3} \tag{15}$$

2. ISC control: Under some specific condition operating point of the wind turbine is stable around the aerodynamic efficiency curve. By means of constant generator torque and wind speed, the wind turbine remains locally stable [6].

$$T_g = K_{opt}\omega_r{}^2 - K_t\omega_r \tag{16}$$

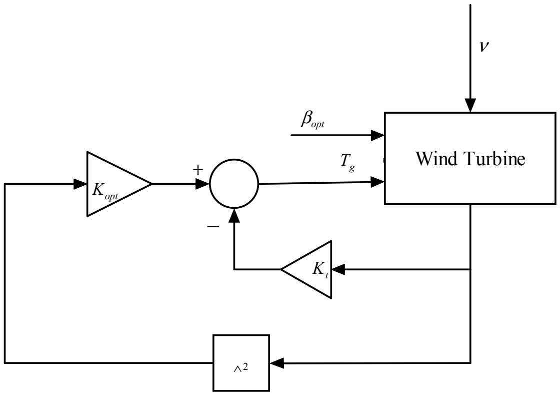

Fig3: Indirect speed control

V. ESTIMATION OF ROTOR SPEED AND AERODYNAMIC TORQUE

The estimation of rotor speed and aerodynamic torque is split into state and input estimation. Two mass drive train models of the wind turbine are converted into single mass model with suitable assumptions [8]. The state space equation is formed with rotor speed as a state variable at the same time aerodynamic and generator torque acts as an input. For state estimation we assume that rotor speed and generator torque are available through measurement. The state equation is updated by a scaling factor K are given in equ (17) and (18)

$$\dot{\omega}_r = A\omega_r + B_1T_g + B_2T_a + K(\omega_r - \hat{\omega}_r) \tag{17}$$

$$y=\omega_r \tag{18}$$

where K is the kalman gain which minimizes the expected value of the square of the estimated value. i.e $E\left[(x-\hat{x})^2\right]$ where x is the state variable i.e ω_r

In practice the aerodynamic torque is not available through measurement, so T_a is to be estimated either by taking it as an augmented state [8] or with an unknown input model [12]. The observer design can be divided into two parts, i.e. 1)The inner loop is the EKF under the assumption of T_a is available 2)The outer loop is the tracking the error between estimated and measured rotor speed. The controller is chosen as proportional controller.

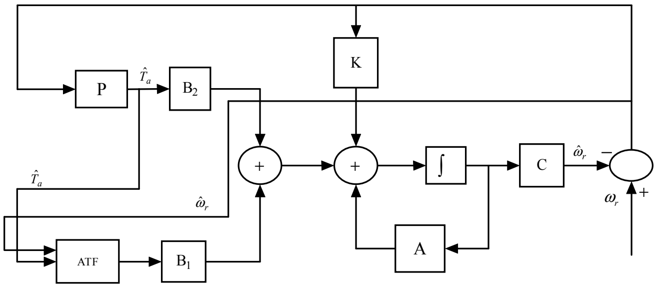

Fig4: Block diagram for observer with ATF control

Figure4 shows the block diagram for an observer with ATF control. In this work EKF is used to estimate the rotor speed and input estimation is used to estimate the aerodynamic torque. Form the state and input based estimation at below the rated wind speed the aim of the controller is to obtain the optimal power. By using aerodynamic torque feed forward controller the generator torque T_g is controlled properly. Figure5 shows the wind profile with a mean wind velocity of 7m/s. Table1 gives the required data for the wind turbine characteristics.

Table 1: Wind turbine characteristics

Rotor diameter (R)	43.164m
Air density (ρ)	1.29 Kg/m^3
Rotor inertia (J$_r$)	3.25.10^5 Kg m^2
Generator inertia (J$_g$)	34.4 Kg m^2
Rotor external damping (K$_r$)	27.36 Nm/rad/sec
Generator external damping (K$_g$)	0.2 Nm/rad/sec
Gear ratio (n$_g$)	43.165
Generator system electrical power	650 KW
Hub height	36.6m

A. Extended kalman filter

The extended Kalman filter is the nonlinear version of kalman filter which linearizes about current mean and variance.

1. The initial step is to guess the initial state x_{init}

$$x_p(0) = x_{init} \tag{19}$$

2. Calculate the predicted measurement state from the predicted state estimation

$$y_p(k) = g[x_p(k)] \tag{20}$$

3. Calculate the innovation variable is nothing but the difference between the measurement $y(k)$ and predicted value $y_p(k)$

$$e(k) = y(k) - y_p(k) \tag{21}$$

4. Calculate the corrected estimated state by adding the corrective term $Ke(k)$ where K is the kalman gain

$$K(k) = P_p C^T [CP_p(k)C^T + R]^{-1} \tag{22}$$

$$P_c(k) = [I - K(k)C]P_p(k) \tag{23}$$

$$P_p(k+1) = AP_c(k)A^T + GQG^T \tag{24}$$

A-Transition Matrix
G-Process noise covariance
C-Measurement gain Matrix
Q-Process noise auto covariance
R-Measurement noise auto covariance

$$x_c(k) = x_p(k) + Ke(k) \tag{25}$$

5. Calculate the predicted state for the next step by using correction state

$$x_p(k+1) = f[x_c(k), u(k)] \tag{26}$$

Assume initial state and the process and measurement noises are zero mean Gaussian noise.

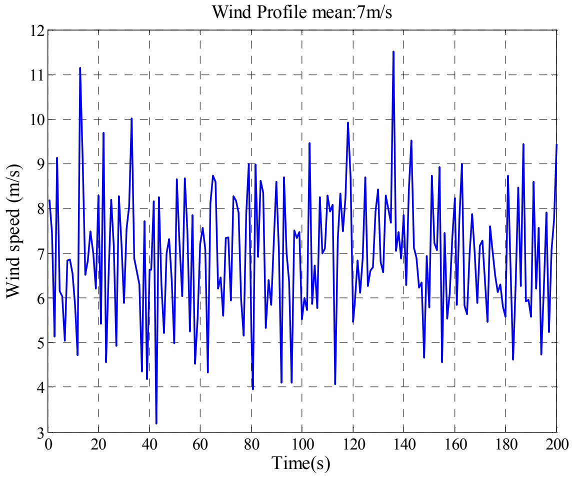

Fig 5: wind profile mean wind speed 7 ms^{-1}

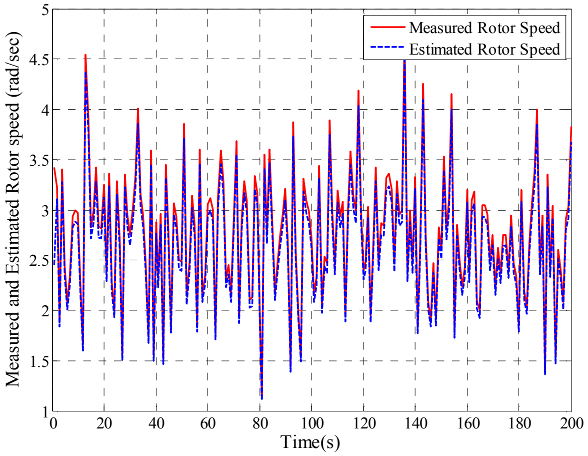

Fig 6: Measured and estimated rotor speed (rad/sec)

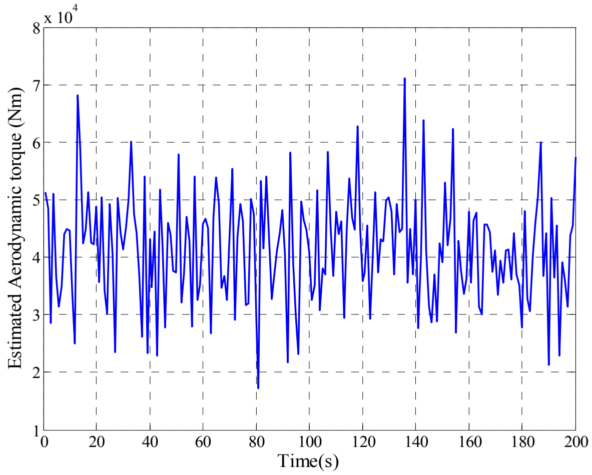

Fig 7: Estimated aerodynamic torque (Nm)

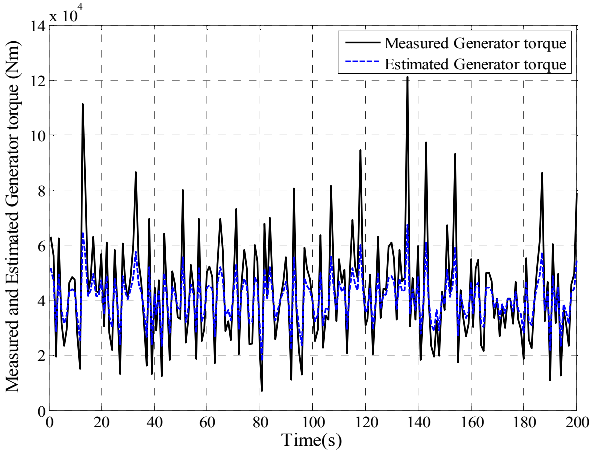

Fig 8: Measured and Estimated Generator torque (Nm)

Figure 6 represents the measured and estimated rotor speeds. It indicates that the estimated rotor speed exactly follows the measured rotor speed. Fig 7 represents the estimated aerodynamic torque by using as an input estimation. Fig 8 represents the measured and estimated generator torque it clear that the estimated generator torque follows the measured generator torque. From the above figures it is concluded that whenever any changes in the wind profile the other parameter of the wind turbines are the estimated rotor speed, aerodynamic torque and generated torque also follow the change in wind speed. The main objective of the controller (ATF) is to optimize the energy capture from the wind. In this work to get more realist condition an additive measurement of noise is introduced in the rotor speed. This measurement noise is assumed to the stationary with signal to noise ratio (SNR) is approximately 10dB.

VI. CORRELATION TEST

Correlation refers to the statistical relation between two sets of data, whereas the correlation coefficient measures the strength and direction of a linear association of two variables. It ranges from +1 to -1. Correlation analysis is used to identify the estimation results to validate the model by using correlation tests. Generally two correlation test are used, i.e the autocorrelation and cross correlation function. The autocorrelation function refers to the general dependence of the value of the samples at one time on the values of the sample at another time. The cross correlation function measures the dependence of the value of one signal to another. A number of auto-correlation and cross-correlation tests given below have been recommended by the authors [17], one of them given in equ (26)

$$\xi_{y_m y_e} = E[y_m(t-\tau)y_e(t)] = \delta(t) \tag{27}$$

Where $\xi_{y_m y_e}$ indicates the cross correlation between the measured and estimated output and $\delta(t)$ is the impulse function, generally correlation functions are within the 95% of the confidence interval then only the estimated results are validated and adequate. In this paper we have considered correlation tests for estimating the rotor speed, aerodynamic and generated torque and validating the model. Fig9 shows cross correlation between measured and estimated rotor speed. Fig10 shows the cross correlation between residual and error derived from actual, measured and estimated rotor speed. Fig11 shows the cross correlation measured and estimated generator torque. From the above figure correlation analysis that all are within the 95% of a confidence interval that shows the estimated variables are more adequate.

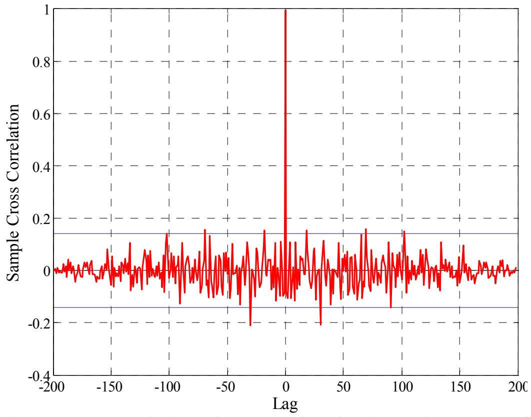

Fig9: Cross correlation of measured and estimated rotor speed

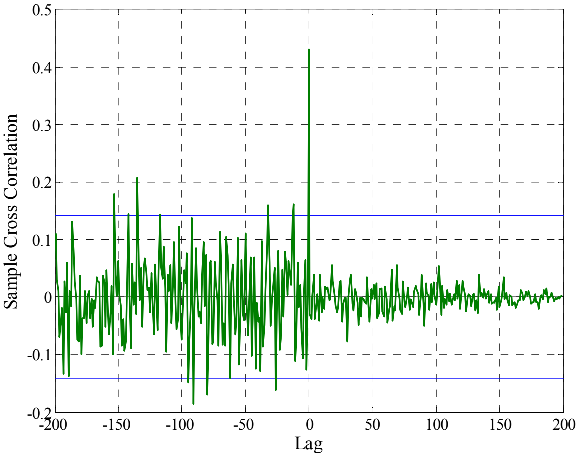

Fig10: Cross correlation of the residuals in rotor speed

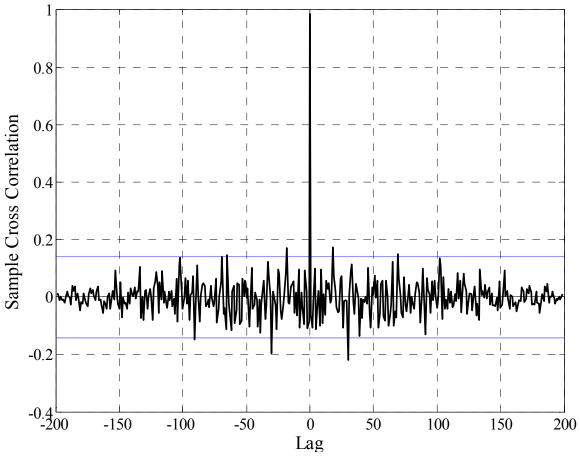

Fig11: Cross correlation of measured and estimated generator torque

VII. CONCLUSION

In variable speed wind turbine the main control objective is to maximize the wind energy at below rated wind speed. Many control techniques are available to operate the wind turbine in a steady state condition. In this work the observer is divided into two parts, state and input observer for estimating the rotor speed and aerodynamic torque. The state and input observer based approach discussed here found to be more approachable rather than taking augmented states as an extra state variable. In this work the input and state estimation based on aerodynamic torque feed forward control with rotor speed and aerodynamic torque estimation is used to control the generated torque without estimating the effective wind speed.

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