Araştırma Makalesi

NONLINEAR CONTROL OF POWER COEFFICIENTS IN WIND TURBINES

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ABSTRACT

Wind speed above rated value causes high power and generator over speed. This leads to overloading and breakdown of the generator. As a result, control is required to maintain the desired generated electrical power. Many papers use the blade pitch angle, which is highly non-linear as control input to achieve this goal. In this paper, the power coefficient is used for the first time as the control input due to its simplicity, noting that power coefficient is a linear coefficient of the rotor power. A non-linear controller called Sliding mode is used to command the power coefficient to regulate the rotor speed to the desired value. The actual pitch angle for every wind speed is determined by designing some algorithms which are used with the power coefficient from the controller. The simulation results show that this control strategy is able to regulate the generator power by setting the rotor speed to its desired value. Another non-linear controller called feedback linearization is also used to compare its results to the sliding mode controller. This is to show that other controllers can also be used. The simulation results of the two controllers are indistinguishable.

Keywords: Wind turbine electrical power, generator speed, power coefficient, pitch angle, sliding mode control

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1. INTRODUCTION

To improve the stability and reliability of wind Turbines, advance control systems should be designed. This improves the behaviour of wind turbines making them more profitable.

Compared to fixed speed turbines, variable speed wind turbines feature higher energy yields, lower component stress, and fewer grid connection power peaks (Boukhezzar and Siguerdidjane, 2005). Researches in wind energy control have shown many ways of controlling wind turbines. (Hwas and Katebi, 2012) introduced PI control and used analytical and simulation methods to calculate the gains. (Hand and Balas, 1999) used PID controller with the gain design performed using a non-linear turbine model and two linear models. Optimal control has been introduced in (Martinez, 2007). In (Jing, et al., 2017), a quasi-continuous high-order sliding mode method is used to design controllers. In (Boukhezzar and Siguerdidjane, 2005), 2 nonlinear controllers were investigated using the generator torque to track the power output. (Mullane et al, 2001) used an adaptive feedback linearization controller. (Boukhezzar, et al., 2007) used a multivariable control strategy by combining a nonlinear dynamic state feedback torque control strategy with a linear control strategy for blade pitch angle. Model predictive control (MPC) was applied to (Wijewardana, et al., 2016) to guarantee the stability of the equilibrium point.

In most of these papers, the controller uses the pitch angle of the blades which is highly non-linear as control input. These controllers are used when the wind speed is above its rated value. This is to ensure that constant desired generator power and speed are obtained to maintain grid stability energy supply. When the wind turbine is running below rated wind speed (variable rotor speed), no pitch controller is needed. Generator torque is used to help obtain maximum available power.

In this work, the power coefficient Cp is used for the first time as control input to regulate the generator speed when the wind speed is above the rated value. Algorithms are developed and used with the Cp to determine the required pitch angle for every wind speed above its rated value. Another non-linear controller is also used to further validate the control strategy implemented in this paper.

This paper is organized as follows: Section 2 describes the modelling of the wind turbine system. Section 3 discusses the methodology used to control the wind turbine. Section 4 discusses the simulation and results and Section 5 gives the discussion and conclusion.

2. MODELING OF THE SYSTEM

2.1. Wind and Rotor Aerodynamics

Wind turbines extract energy from the wind through the rotors and convert them to mechanical energy. This energy is then used to turn a shaft connected to a generator through a gear box which steps up the rotation speed to the generator desired value. In (Martinez, 2007), Figure 1 shows the global scheme of a variable speed wind turbine.

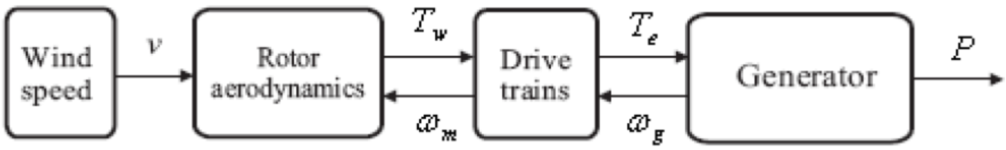


Figure 1. Wind turbine scheme.

Betz's Elementary Momentum Theory shows that the maximum amount of energy that can be extracted from the wind and converted to mechanical energy is 16/27 (59.3%) of the wind energy (P_w).

$$P_w = \frac{1}{2}\rho A V^3 \quad (1)$$

Where ρ is the air density, V is the wind speed and A is the area of the blade given as $A = \pi R^2$, Where R is the blade radius.

The ratio between the mechanical energy extracted P_t and P_w is called power coefficient (Cp). The power coefficient (Cp) depends on the tip speed ratio (λ) and the pitch angle (β), where

$$\lambda = \frac{\omega_r R}{V} \tag{2}$$

ω_r is the rotational speed of the rotor. P_t is then given as:

$$P_t = \frac{1}{2}\rho\pi R^2 V^3 Cp \tag{3}$$

The power coefficient (Cp) is written in (Martinez, 2007) as

$$Cp\,(\lambda,\beta) = 0.5(116\frac{1}{\gamma} - 0.4\beta - 5)e^{-21\frac{1}{\gamma}} \tag{4}$$

Where $\frac{1}{\gamma} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{1+\beta^3}$ and β is in degree. The Cp curve is shown in Figure 2.

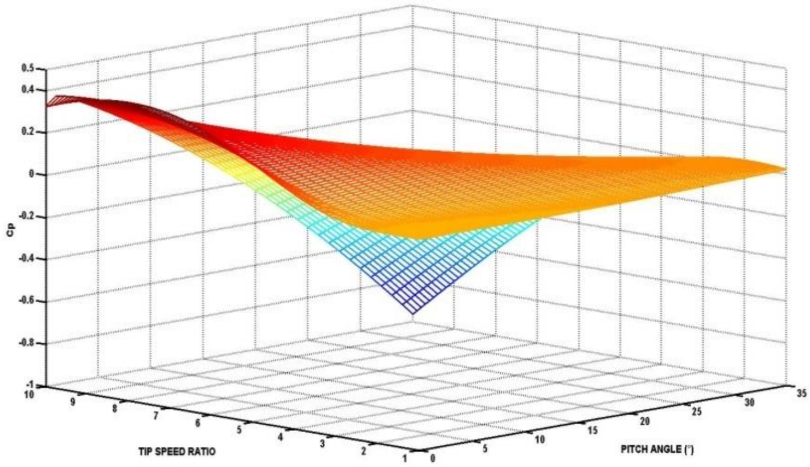


Figure 2. Power coefficient (Cp) curve.

The aerodynamic torque T_a is given as

$$T_a = \frac{1}{2}\rho\pi R^3 V^2 \frac{Cp}{\lambda} \tag{5}$$

2.2. Drive Trains

The two-mass model of the horizontal axis wind turbine is shown in Figure 3. This system includes a turbine rotor, gearbox and a generator.

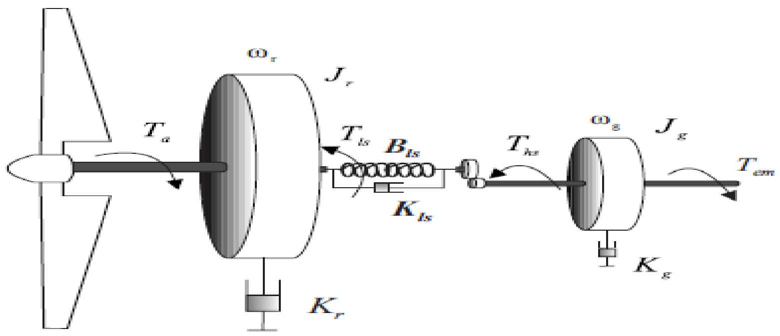


Figure 3. Two-mass-model (Boukhezzar and Siguerdidjane, 2005).

2.2.1.Turbine Motor

The turbine is driven by the aerodynamic torque T_a and braked by the low speed shaft torque T_ls, with its external damping b_r to damp the rotor. The dynamics is given by:

$$J_r \dot{\omega_r} = T_a - b_r \omega_r - T_{ls} \tag{6}$$

where $T_{ls} = b_{ls}(\omega_r - \omega_{ls}) + k_{ls}(\theta_r - \theta_{ls})$. J_r is the rotor inertia, b_{ls} is the low speed shaft damping coefficient, k_{ls} is the low speed shaft spring constant, ω_{ls} is the low speed shaft rotational speed, θ_r is the rotor position and θ_{ls} is the low speed shaft position.

Note: b_r is represented in Figure 3 as K_r.

2.2.2.Generator

The Generator is driven by the high speed shaft torque T_{hs} and braked by the generator electromagnetic torque T_{em}, with its external damping b_g to damp the generator. The dynamics is given by

$$J_g \dot{\omega_g} = T_{hs} - b_g \omega_g - T_{em} \tag{7}$$

where $T_{hs} = b_{hs}(\omega_g - \omega_{hs}) + k_{hs}(\theta_g - \theta_{hs})$. ω_g is the rotational speed of the rotor, J_g is the generator inertia, b_{hs} is the high speed shaft external damping, k_{hs} is the high speed shaft spring constant, ω_{hs} is the high speed shaft rotational speed, θ_g is the generator position and θ_{hs} is the high speed shaft position.
Note: b_g is represented in Figure 3 as K_g.

2.2.3.Gear Ratio

The gear ratio n, is used to step up the rotor rotational speed to the desired generator rotational speed. The gear ratio n is given as;

$$n = \frac{T_{ls}}{T_{hs}} = \frac{\omega_g}{\omega_{ls}} \tag{8}$$

With a rigid low speed shaft, $\omega_{ls} = \omega_r$. The gear ratio n will increase the rotor speed ω_r to reach the desired generator speed ω_g value. Transferring the generator dynamics to the rotor side using equation (8) and adding it to equation (6) gives:

$$J_t \dot{\omega_r} = T_a - b_t \omega_r - T_g \tag{9}$$

where $J_t = (J_r + J_g n^2)$, $b_t = (b_r + b_g n^2)$, $T_g = nT_{em}$.

3. METHODS

3.1. Control Aim

The aim of the controller is to make sure that the system works according to the system requirements. Variable Speed Wind Turbine operates in three modes: mode 1, mode 2 and mode 3 as shown in Figure 4 (Verdonschot, 2009).

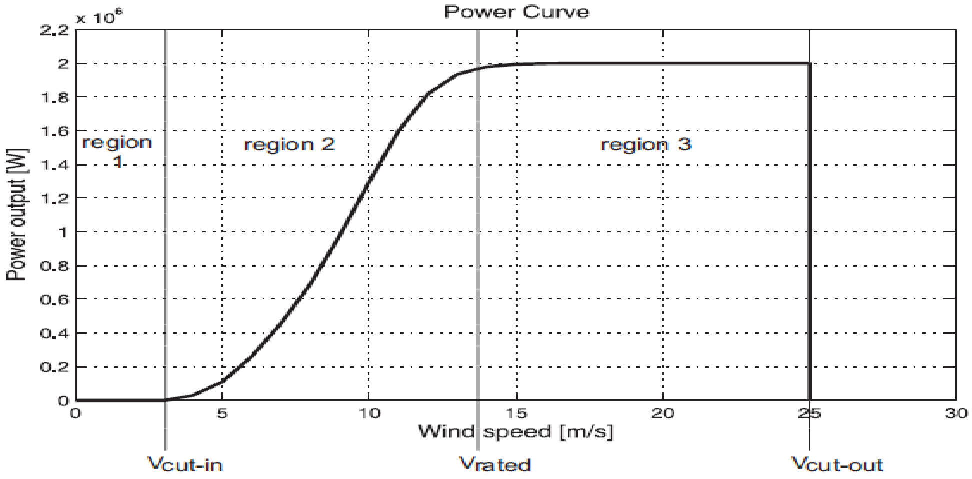


Figure 4. Wind turbine operation modes.

In mode 1, wind speed is below the cut-in value (5m/s). Wind turbine is not in operation in this mode therefore both power and rotor speed are zero.

In mode 2, wind speed is below rated wind speed (10m/s) but above the cut-in value. When operating in this mode, wind turbine runs with constant blade pitch angle (0°) and tip speed ratio (optimum value) λ_{opt}. This ensures that Cp is always constant in this mode at its optimum value (Cpmax).

$$\lambda_{opt} = \frac{\omega_{ropt}*R}{V} \quad (10)$$

where ω_{opt} is the rated rotor speed.

This is the mode where the turbine runs at variable speed. The generator torque is used as control input to extract maximum power by adjusting the rotor speed. This is called indirect speed control (ISC) (Boukhezzar and Siguerdidjane, 2005). With this control technique, the power electronics can be used to set the generator torque to almost any desired value as they determine the frequency and phase of the current flowing from the generator (Manwell, et al., 2002).

$$T_g = K\omega_r^2 - b_t\omega_r \quad (11)$$

where $K = \frac{1}{2}\rho\pi R^5 \frac{Cpmax}{\lambda_{opt}^3}$.

In mode 3, wind speed is above rated wind speed. This is where the controller is needed to ensure that power is constant. In this mode, both the generator torque and speed are made constant at their rated values. In this study, the generator torque control technique used is similar to the one adopted in (Mullane et al, 2001) while the generator speed is made constant by using a novel approach to control the Cp. Non-linear sliding mode control technique is used to achieve this. The sliding mode controller will make the generator speed constant by regulating the Cp value. These control techniques will ensure safe operation of the wind turbine when running in this mode.

3.2. Control Methodolgy

Cp as a control input. A nonlinear controller called Sliding mode controller is designed by using matlab/simulink to command the Cp to regulate the rotor speed. Note from equation (4) that $Cp\,(\lambda,\beta) = 0.5(116(\frac{1}{\lambda+0.08\beta} - \frac{0.035}{1+\beta^3}) - 0.4\beta - 5)e^{-21(\frac{1}{\lambda+0.08\beta} - \frac{0.035}{1+\beta^3})}$, is a highly non-linear function of λ and β. Therefore, given Cp and λ, computation of β is a root finding problem which requires initial estimation of β. To obtain the initial estimation of β, a lookup table is designed and used. Thus, for each Cp obtained from the controller, the corresponding pitch angle must be calculated for every wind speed. For this reason, an algorithm

is designed and used with the lookup table. Using Cp as a control input and designing these algorithms to obtain β are the main contribution of this paper.
An alternative non-linear controller called feedback linearization is also designed to compare its results with the sliding mode controller. This is to further validate the control strategy (using Cp as a control input) implemented in this paper. A switch is also used to make sure that the pitch angle is always at 0° when operating in mode 2 as shown in Figure 5.

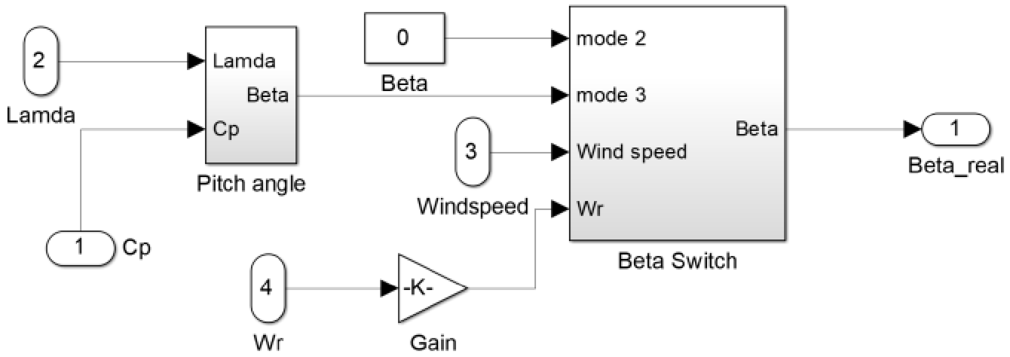


Figure 5. Pitch angle simulink model.

Sliding Mode Control (SMC) is a robust control used to make the generator speed reach its desired value. For SMC, let us first define the error rate ω_e as the difference between the actual rotor angular velociy ω_r and desired rotor angular velocity ω_d.

$$\omega_e = \omega_r - \omega_d \tag{12}$$

Noting that ω_d is constant and using equation (9), we obtain

$$\dot{\omega_e} = \dot{\omega_r} = \frac{T_a}{J_t} - \frac{b_t}{J_t}\omega_r - \frac{T_g}{J_t} \tag{13}$$

From equations (12) and (13)

$$\dot{\omega_e} = \dot{\omega_r} = \frac{k_o V^3 u}{J_t(\omega_e+\omega_d)} - \frac{b_t}{J_t}(\omega_e + \omega_d) - \frac{T_g}{J_t} \tag{14}$$

where $k_o = \frac{1}{2}\rho\pi R^2$ and control input $u = Cp$. Let the sliding variable "s" as

$$s = \omega_e \tag{15}$$

The two main rules of the sliding mode control are:

- As $s \to 0$, the error $\omega_e \to 0$.
- $\dot{s}$ must contain the control input, u.

$$\dot{s} = \dot{\omega_e} \tag{16}$$

$$\dot{s} = (\frac{k_o V^3 u}{J_t(\omega_e+\omega_d)} - \frac{b_t}{J_t}(\omega_e + \omega_d) - \frac{T_g}{J_t}) \tag{17}$$

From equation (17), assuming $u \to \hat{u}$ as $\dot{s} \to 0$. Thus, we obtain

$$\begin{cases} \hat{u}\left(\frac{k_o V^3}{(\omega_e+\omega_d)}\right) = b_t(\omega_e + \omega_d) + T_g \\ \hat{u} = \left(\frac{\omega_e+\omega_d}{k_o V^3}\right)(b_t(\omega_e + \omega_d) + T_g) \end{cases} \tag{18}$$

Using Lyapunov theorem, we get

$$\begin{cases} \frac{1}{2}\frac{d}{dt}(s^2) = -|s| \\ s\dot{s} = -|s| \ \rightarrow \dot{s} = -k\ sgn(s) \end{cases} ,k > 0 \tag{19}$$

From equation (17) and (19) and, noting that $u \rightarrow U$ as $\dot{s} \rightarrow -sgn(s)$, we solve for the control.

$$\begin{cases} \frac{1}{2}\frac{d}{dt}(s^2) = -|s| \\ s\dot{s} = -|s| \ \rightarrow \dot{s} = -k\ sgn(s) \end{cases} ,k > 0 \tag{20-a}$$

To avoid the chattering caused by the “sign” function, we use the following “sat” function to obtain smooth responses.

$$\begin{cases} U = \left(\frac{\omega_e+\omega_d}{k_o V^3}\right)(b_t(\omega_e + \omega_d) + T_g) - ksat(s) \\ C_p = \ U = \left(\frac{\omega_r}{k_o V^3}\right)(b_t(\omega_r) + T_g) - ksat(\omega_r - \omega_d\ ) \end{cases} \tag{20-b}$$

Feedback Linearized Control first linearizes the system and then uses equation (14)
$\dot{\omega_e} = \dot{\omega_r} = \frac{k_o V^3 u}{J_t(\omega_e+\omega_d\ )} - \frac{b_t}{J_t}(\omega_e + \omega_d\ ) - \frac{T_g}{J_t}$

To eliminate the non-linear terms such as $\frac{k_o v^3 u}{J_t(\omega_e+\omega_d\ )}$,we choose the control input u $= u_{fb}$ so that the resulting equations become a stable linear system. For a stable error rate dynamics;

$$\begin{cases} \dot{\omega_e} + K_c\omega_e = 0\ ,\ K_c > 0 \\ \dot{\omega_e} = -K_c\omega_e \\ \frac{k_o v^3 u}{J_t(\omega_e+d\ )} - \frac{b_t}{J_t}(\omega_e + \omega_d\ ) - \frac{T_g}{J_t} = -K_c\omega_e \end{cases} \tag{21}$$

$$\begin{cases} u_{fb} = \frac{J_t(\omega_e+\omega_d\ )}{k_o v^3}\left[\frac{b_t}{J_t}(\omega_e + \omega_d\ ) + \frac{T_g}{J_t} - K_c\omega_e\right] \\ C_p = \ u_{fb} = \frac{\omega_r}{k_o v^3}\left[b_t\omega_r + T_g - J_t K_c(\omega_r - \omega_d)\right] \end{cases} \tag{22}$$

Regarding the **Torque controller** in mode 3,

$$T_{hs} = J_g v + b_g\omega_g + \hat{T}_{em} \tag{23}$$

Where v is the additional input (Mullane et al, 2001) and $\hat{T}_{em}$ is the estimated generator electromagnetic torque.

In this study, $\hat{T}_{em}$ is assumed to be constant which is equal to the rated generator torque of 2533.25N.m.

Putting equation (23) in (7) yields

$$\begin{cases} J_g\dot{\omega_g} = J_g v + \hat{T}_{em} - T_{em} \\ J_g\dot{\omega_g} = J_g v - \tilde{T}_{em} \end{cases} \tag{24}$$

Where $\tilde{T}_{em}$ is the error between the actual and estimated generator electromagnetic torque.

$$\dot{\omega_g} = v - \frac{\tilde{T}_{em}}{J_g} \tag{25}$$

As $\tilde{T}_{em}$ approaches zero, v approaches $\dot{\omega_g}$

$$e = \ \omega_g - {\omega_g}^* \tag{26}$$

Where $\omega_g{}^*$ is the desired generator speed. For a stable error dynamics; $\dot{e} + K_1 e = 0$, $K_1 > 0$

$$\dot{e} = \dot{\omega_g} - \dot{\omega_g}^* \tag{27}$$

$$v = \dot{\omega_g}^* - K_1 e \text{ (When v approaches } \dot{\omega_g}) \tag{28}$$

Putting (25) in (28)

$$\begin{cases} \dot{\omega_g} + \frac{\tilde{T}_{em}}{J_g} = \dot{\omega_g}^* - K_1 e \\ \dot{e} = -\frac{\tilde{T}_{em}}{J_g} - K_1 e \end{cases} \tag{29}$$

Using a Lyapunov equation,

$$V = \frac{1}{2} P e^2 + \frac{\tilde{T}_{em}{}^2}{2} \ , P > 0 \tag{30}$$

$$\begin{cases} \dot{V} = Pe\left(-K_1 e - \frac{\tilde{T}_{em}}{J_g}\right) + \tilde{T}_{em}\dot{\tilde{T}}_{em} \\ \dot{V} = -PK_1 e^2 - \tilde{T}_{em}\left(\frac{Pe}{J_g} - \dot{\tilde{T}}_{em}\right) \end{cases} \tag{31}$$

In equation (31), by letting

$$\dot{\tilde{\boldsymbol{T}}}_{\boldsymbol{em}} = \frac{\boldsymbol{P}}{\boldsymbol{J_g}}\boldsymbol{e} - \boldsymbol{K_2}\tilde{\boldsymbol{T}}_{\boldsymbol{em}} \tag{32}$$

$$\begin{cases} X = \begin{bmatrix} e \\ \tilde{T}_{em} \end{bmatrix} \\ \dot{X} = \underbrace{\begin{bmatrix} -K_1 & -\frac{1}{J_g} \\ \frac{P}{J_g} & -K_2 \end{bmatrix}}_{A} \begin{bmatrix} e \\ \tilde{T}_{em} \end{bmatrix} \end{cases} \tag{33}$$

For the linear state equation (33) to be stable, all the eigenvalues of A must have negative real parts. Thus,

$$|A - \lambda I| = 0 = \begin{bmatrix} -K_1 & -\frac{1}{J_g} \\ \frac{P}{J_g} & -K_2 \end{bmatrix} - \begin{bmatrix} \lambda & 0 \\ 0 & \lambda \end{bmatrix} \tag{34}$$

Using the pole placement theory and selecting the eigenvalues as $\lambda_1 = -5$ and $\lambda_2 = -10$, we obtain

$$\begin{cases} K_1 K_2 + \frac{P}{J_g{}^2} = 50 \\ K_1 + K_2 = 15 \end{cases} \tag{35}$$

Letting P = $36 J_g{}^2$ yields $K_1 = 14$ and $K_2 = 1$. Hence, it is guaranteed that X→ 0 which implies that $\omega_g \to \omega_g{}^*$ and $T_{em} \to \hat{T}_{em}$.

In mode 3, using these control techniques, the power, rotor speed and torque can be made constant to their desired values. At the same time by controlling Cp the corresponding pitch angle is determined for a given wind speed. The controllers are designed in such a way that the torque controller will be faster than the Cp controller.

4. SIMULATION AND RESULT

The wind turbine considered uses a “G22R 355 MX4” 400KW generator (VEM, 2000) connected to a rotor through a gearbox. The simulation was done using matlab/simulink as shown in Figure 6.

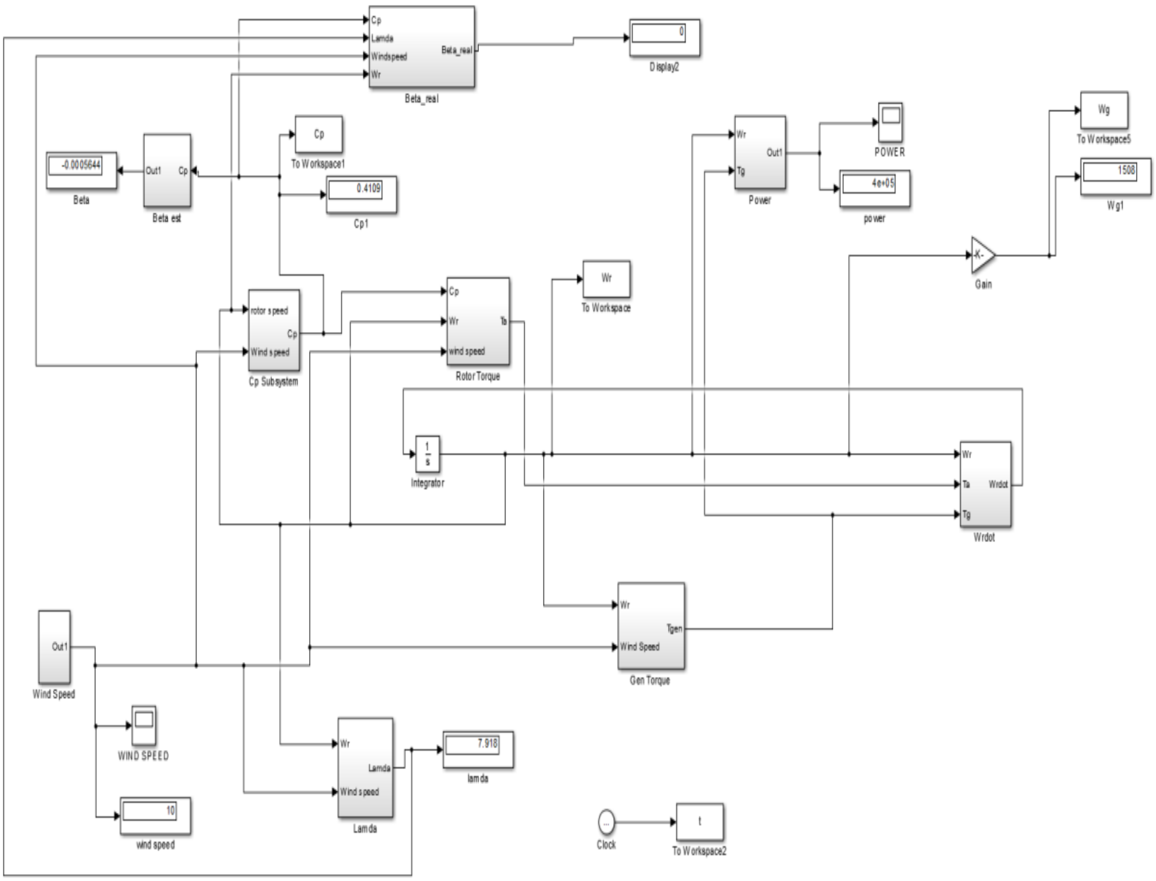


Figure 6. Simulink model of the wind turbine.

The simulation was done using the parameters in Table 1. Running the simulation at rated values shows that the maximum Cp (Cpmax) is 0.4109 with an optimum tip speed ratio of 7.918.

Table 1. Wind turbine parameters.

Name	Value	Unit
Rated wind speed	10	m/s
Air density	1.225	kg/m^3
Rotor radius	29.5	m
Rotor inertia	1.6×10^6	kg. m^2
Rated rotor speed	2.6838	rad/s
Gear box ratio	58.84	----
Rated generator power	400	KW
Rated generator speed	1508	rpm
Rated generator torque	2533.25	N.m
Generator inertia	9.5	kg. m^2
Total external damping	4×10^4	N.m/rad/s

4.1. Wind Speed from 5m/s to 10m/s (Mode 2)

In mode 2, Cpmax and optimum tip speed ratio are kept constant without any power control. To achieve maximum extraction of the available power, the demanded generator torque Tc(same as Tg in this mode) is used to adjust the rotor speed.

The graph of the wind speed, power, generator speed and demanded generator torque in mode 2 is shown in Figure 7.

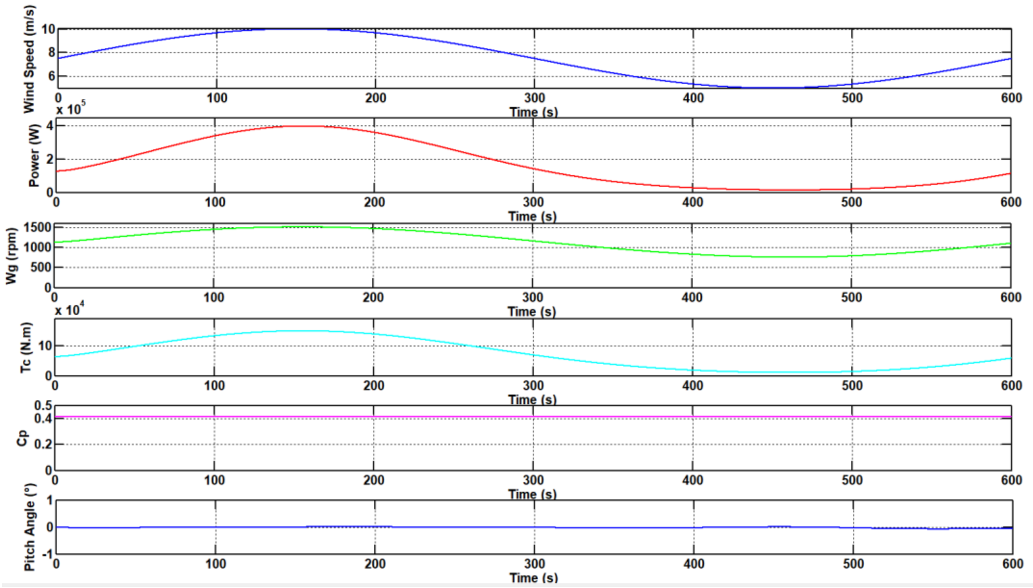


Figure 7. Wind speed, power, generator speed and demanded generator torque in mode 2.

The simulation results in Figure 7 shows the characteristics of the wind turbine in mode 2. The pitch angle was kept constant at zero while Cpmax and optimum tip speed ratio were kept constant.

4.2. Wind Speed from 10m/s to 25m/s (Mode 3)

In mode 3, the control techniques are used when the wind speed is above the rated value to make the generator power, torque and speed constant at their rated values. The graph of the wind speed, power, generator speed, generator torque, Cp and pitch angle in mode 3 is shown in Figure 8. For smooth transition between mode 2 and mode 3, the initial rotor speed, ω_r (0) is set to 2.6838rad/s.

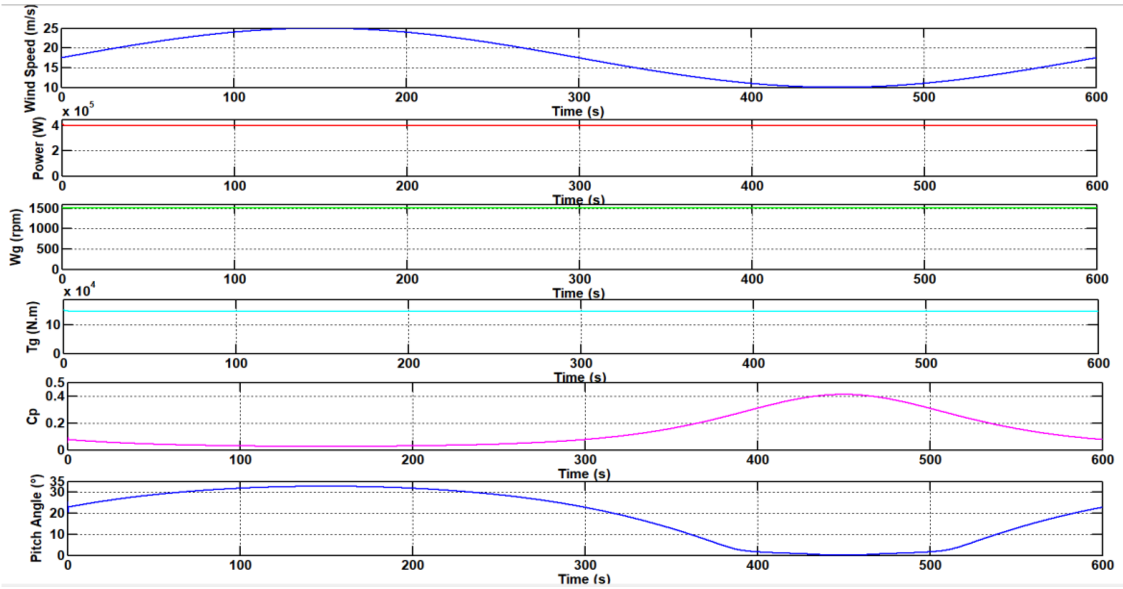
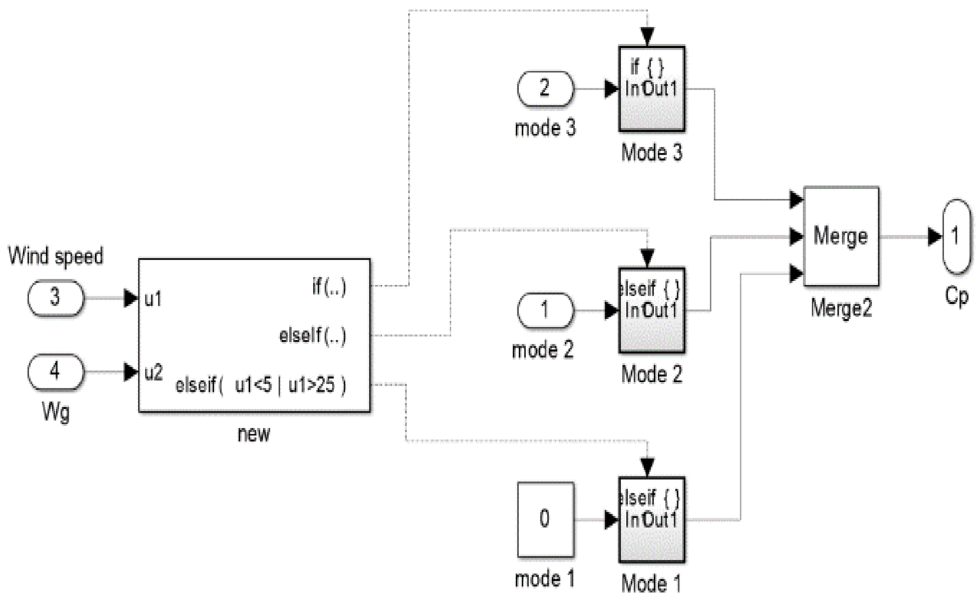


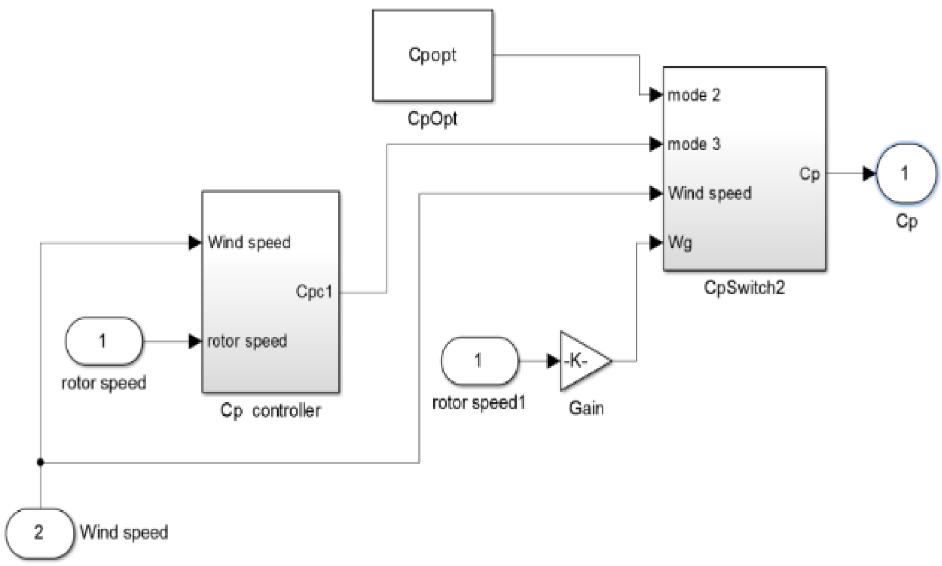
Figure 8. Wind speed, power, generator speed, demanded generator torque, Cp and pitch angle in mode 3.

4.3. Switching Between Mode 2 and 3

When the wind speed is moving from mode 2 to mode 3, power fluctuations must be limited as much as possible. Figure 9 shows the simulink model of the switching logic used.



(a)

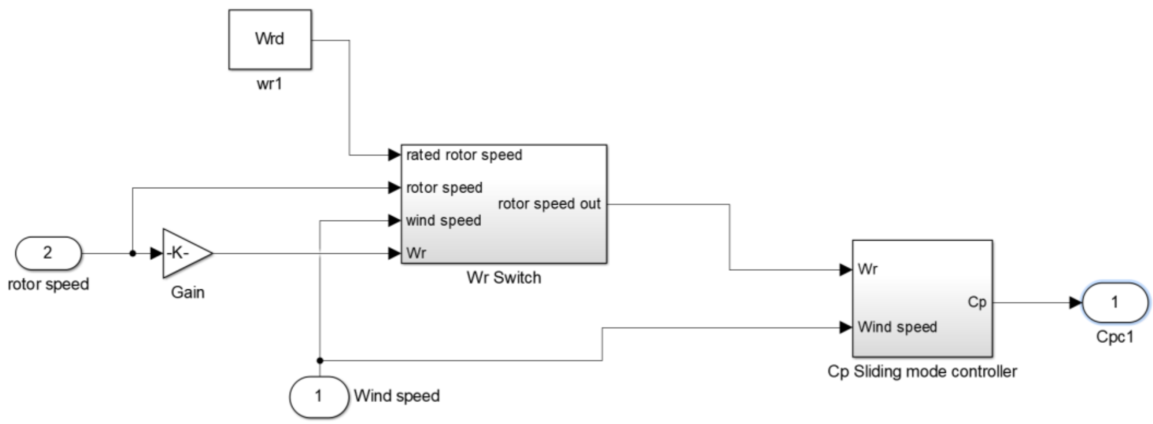


(b)

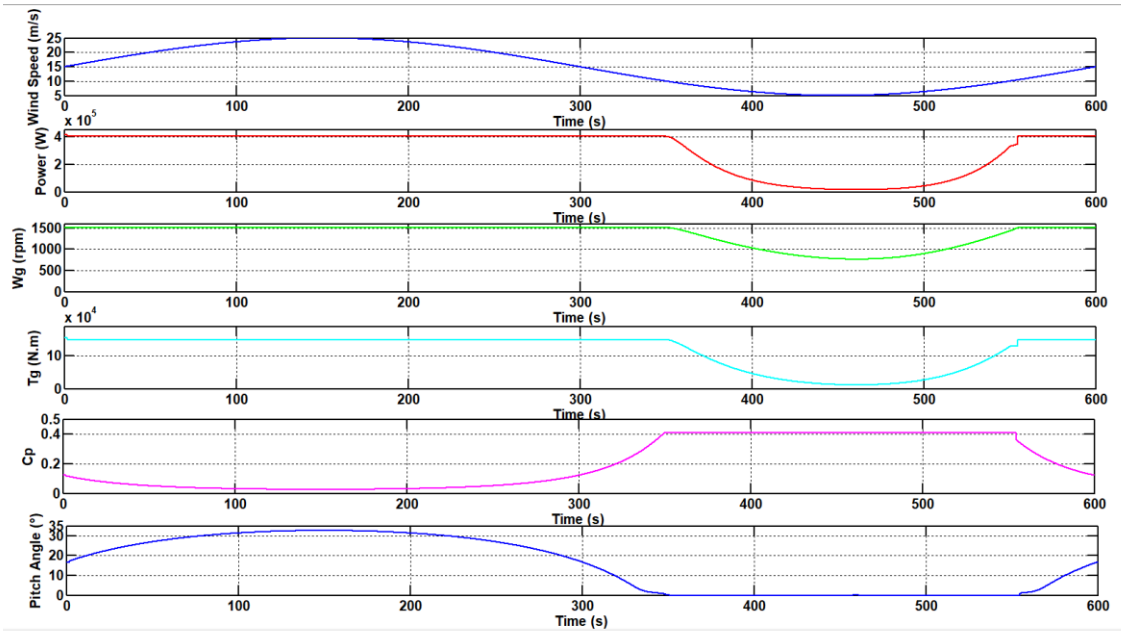
Figure 9. (a) Switching logic, (b) Cp controller switch.

The switching logic shown in Figure 9 is to make the wind turbine move from mode 2 to mode 3 or vice versa. Figure 9 doesn't guarantee smooth transition. Its only function is to switch between the modes. Fluctuations/overshoot must be avoided after the transition line from mode 2 to mode 3. This can disrupt the entire connected electrical grid. As a result, the transition between the modes must be smooth.

For a smooth transition, an extra switch was added between the rotor speed measured and the controller as shown in Figure 10(a). This is to make sure that the controller will receive the rated rotor speed when the turbine is running in mode 2 even though the controller will not be used. With this technique, the fluctuation or overshoot after the transition is unnoticeable therefore it won't disrupt the synchronized system. This is shown in Figure 10(b).



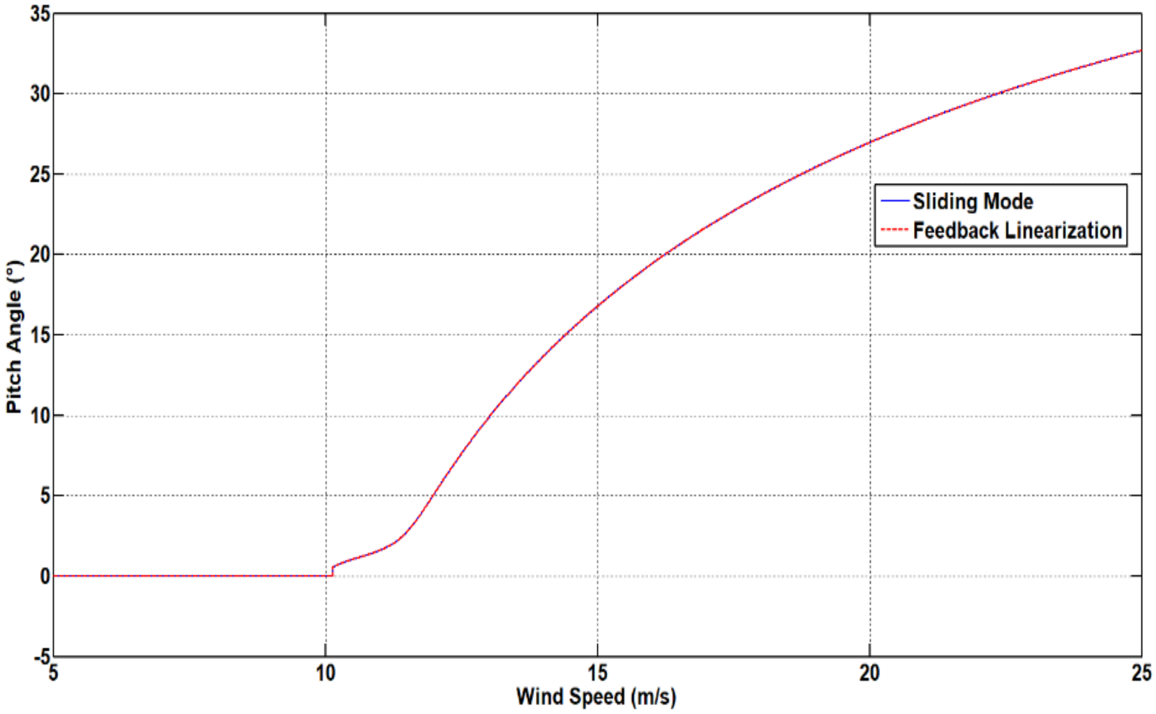
(a)



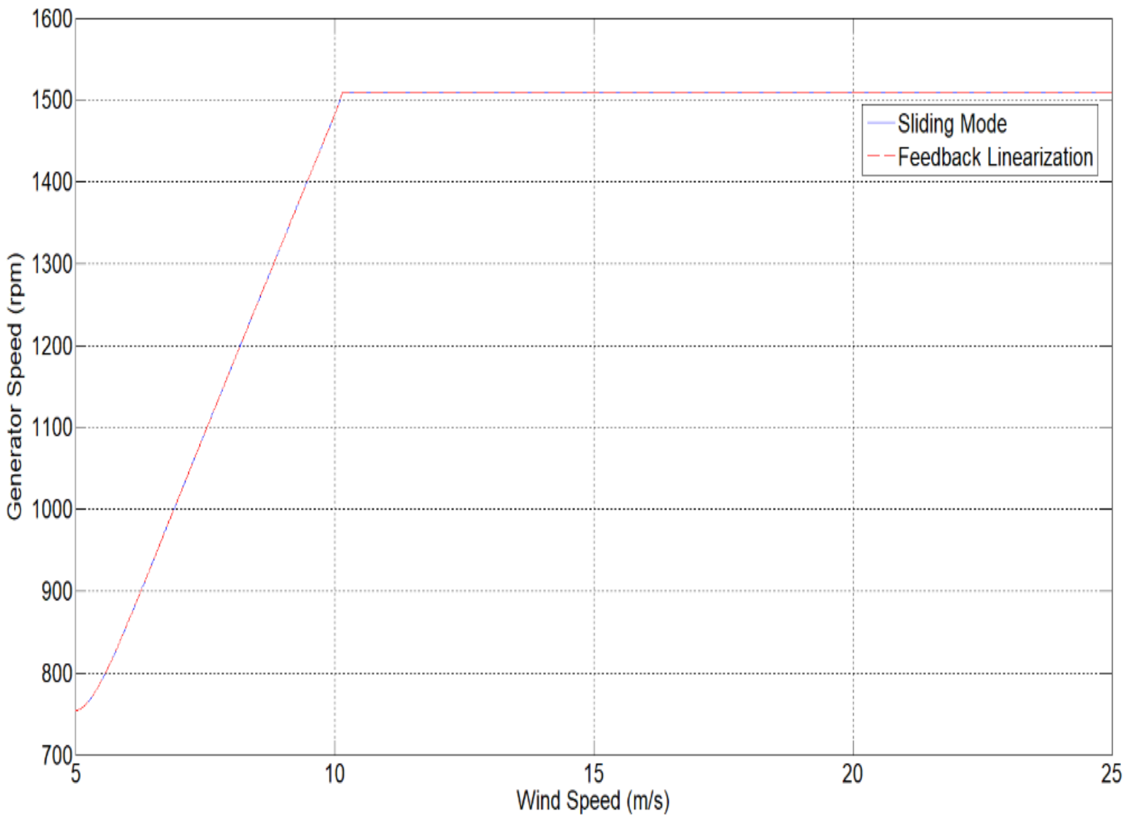
(b)

Figure 10. Smooth transition between mode 2 and 3 (a) simulink model, (b) change in wind speed.

The two non-linear controllers, namely, feedback linearization controller and sliding mode controller are compared in Figure 11. It is obvious that the response of the two controllers is fully coinciding such that they are indistinguishable.



(a)



(b)

Figure 11. (a) Generator speed (b) Pitch angle, using feedback linearization and sliding mode controls.

5. DISCUSSION AND CONCLUSION

In this work, the following two issues are considered and studied in detail.

- When the wind speed is below the rated value, the conditions under which the maximum generator power can be obtained.
- When the wind speed is above the rated value, how to control the generator speed and the generator torque in order to maintain a constant generator power and keep it at that value

In order to control the generator speed and the generator torque, a mathematical model of the wind turbine control system based on the power coefficient Cp, as a control input has been developed and displayed in Matlab/Simulink environment. “Cp as a control input” is selected rather than “ β as a control input” since $Cp\ (\lambda, \beta)$, as seen from equation (4), is a highly non-linear function of λ and β. For each Cp obtained from the two controllers, namely, Sliding Mode Control and Feedback Linearized Control, the corresponding pitch angle β is calculated for every wind speed. For this reason, an algorithm is designed and used with the lookup table. The algorithm uses fzero function, which handles the non-linear root finding problem for the pitch angle. Using “Cp as a control input” and using lookup table with the specifically designed algorithm to obtain β are the main contribution of this paper.

In this study, demonstration through analytical work, through the required simulation results that the two non-linear controllers, where Cp is chosen as control input, performed as desired. The results also show that feedback linearization controller acts almost like the sliding mode controller such that the responses are indistinguishable. The switching logic used in this paper guarantees smooth transitions when the turbine is operating from a low to high wind speed. The generator speed curve in Figure 11(a) satisfies the characteristics of a typical variable speed wind turbine. Considering the time interval 470s(cut-in value) <time< 600s(cut-off value) in Figure 10(b), the power curve resembles that of Figure 4 (power curve for a 2MW, three-bladed turbine), where the transition is smooth and the power is maintained at the rated value.

In conclusion, the two non-linear controllers (sliding mode control and feedback linearized control), where Cp is chosen as control input, performed as desired.

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