Nonlinear Pitch Control Based Variable Speed Operation of Wind Turbines

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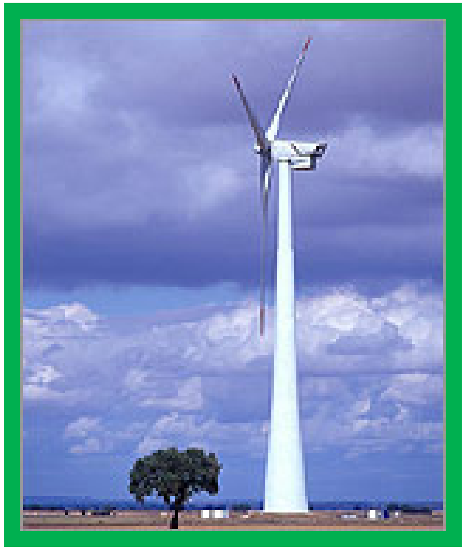
Outline

- Introduction
- System Modeling
- Algorithms and Stability Analysis
- Simulation Result
- Conclusion

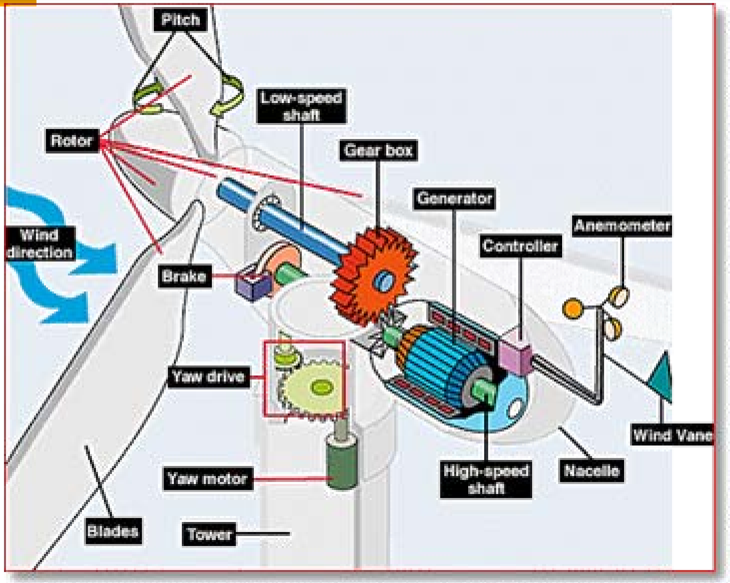
Wind Energy

- Current global installed capacity exceeds 50,000 MW, with a growth of 10,000 MW/year.
- Cost-of-Energy :approximately $0.04/kW-Hr.
- Fastest-growing renewable energy source in the world



GE Wind Energy's 3.6 megawatt wind turbine is one of the largest prototypes ever erected.

Wind Turbine Basics



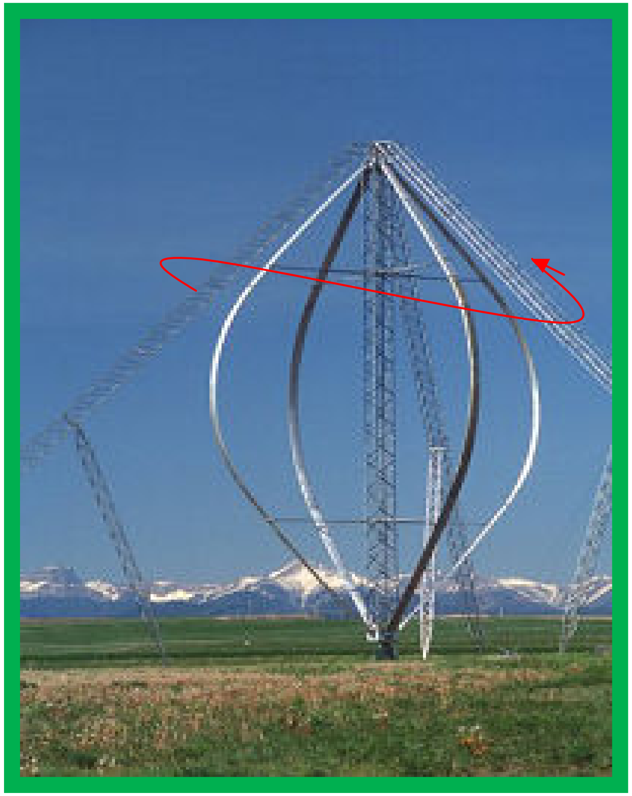
The purpose of a wind turbine is to extract kinetic energy from the wind and convert to mechanical energy and then to electrical energy.

- Large wind turbines are more efficient and cost effective.
- Typically have 70 to 120 meter blade spans, 60 to 120 meter tower heights, and power ratings in the 1 to 5 MW range.

Larger turbines are grouped together into wind farms to provide bulk power to the electrical grid.

Two Types of Wind Turbines

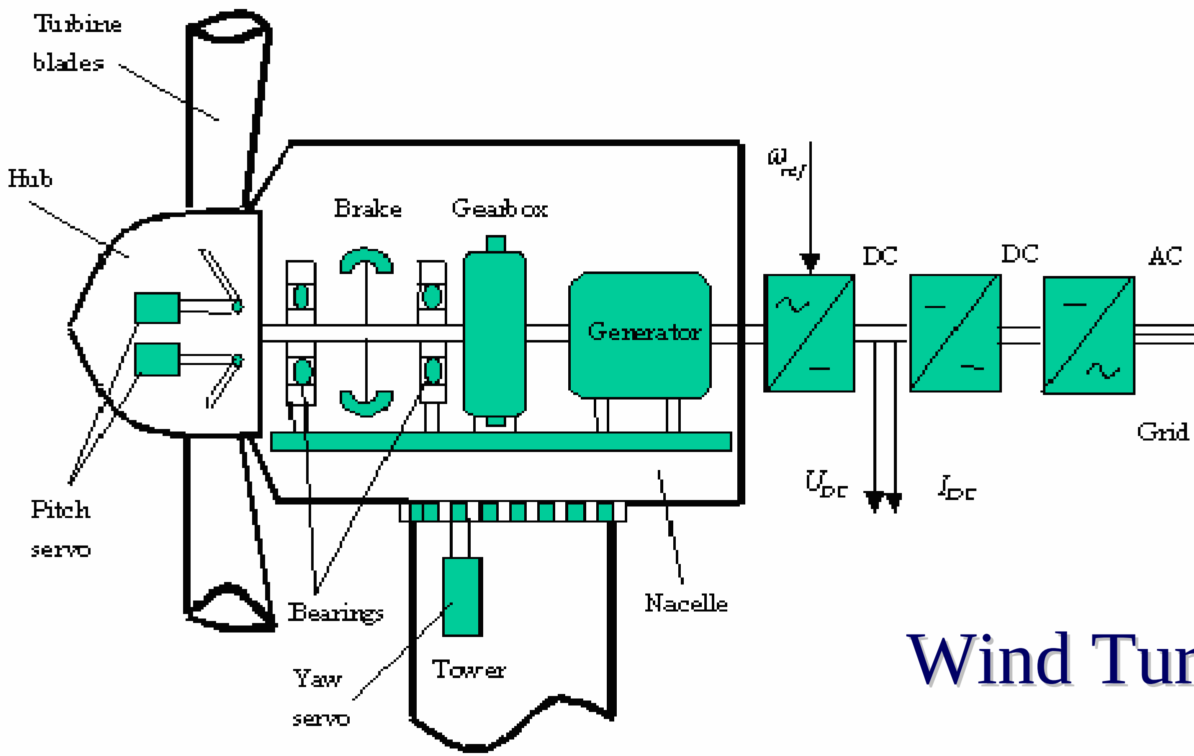
Horizontal Axis Wind Turbine



Vertical Axis Wind Turbine

Components and Modeling

- Yaw control – steer the machine to align with wind direction
- Pitch control –optimizes power generation
- Generator/Converter System control –High quality electricity



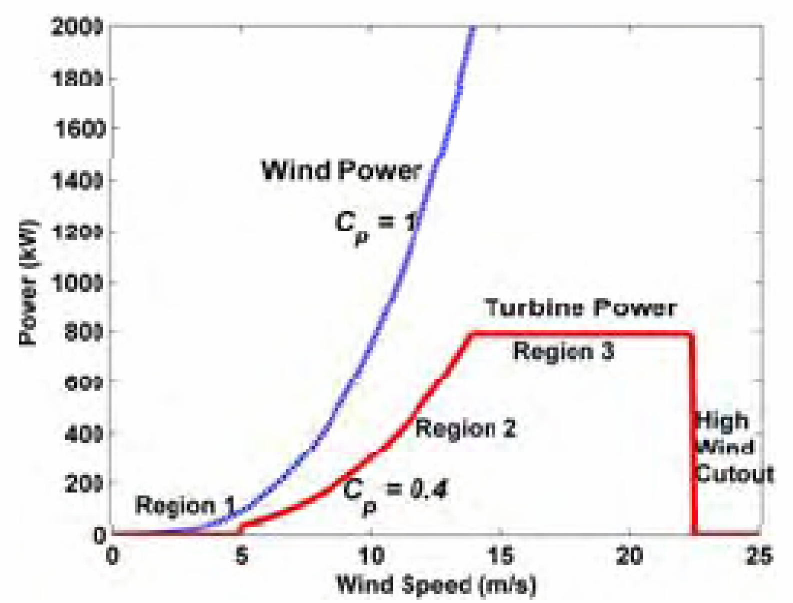
Wind Turbine System

Turbine Aerodynamics

Power Coefficient $C_p = \frac{\text{Turbine Power}}{\text{Wind Power}}$

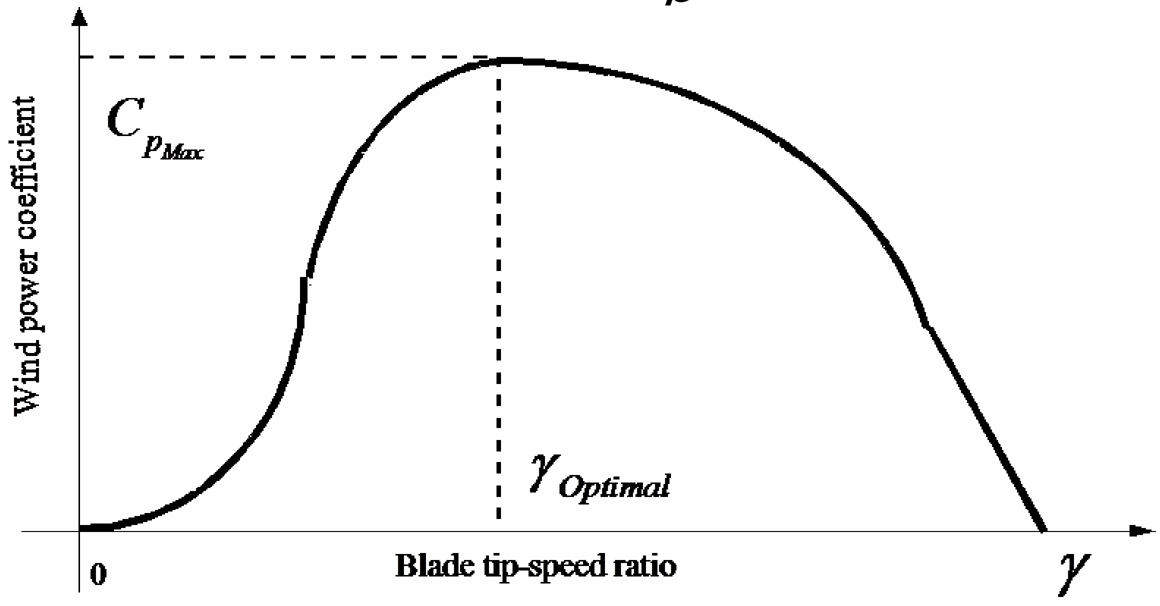
Tip-speed Ratio : $\gamma = \frac{\omega R}{V_w}$

Turbine power: $P = \frac{1}{2}\rho \cdot \pi R^2 \cdot C_p \cdot \mathrm{V_w}^3$



Wind Power Coefficient

C_p is a function of blade pitch β and tip-speed ratio γ



Power coefficient versus tip-speed ratio

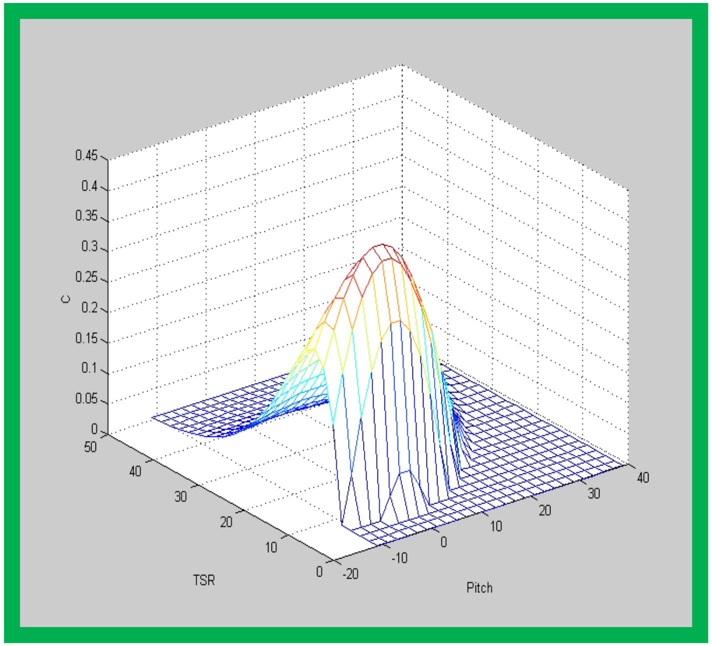
Note:

If the rotor speed is kept constant, any change in wind speed leads to a change in tip-speed ratio , causing C_p deviates from the “optimal value” .

Our Scheme: Nonlinear Pitch Control Based Variable Speed Operation

Compare with other control method:

- Variable speed control
- Include the pitch servo dynamics into the wind turbine model.
- Nonlinear model instead of the commonly used linear or linear plus perturbation model



Power coefficient versus tip speed ratio and pitch angle

System Dynamics

- Turbine Rotor dynamics

$$J\dot{\omega} = \tau_r - \tau_e$$

$$\tau_r = K_\omega C_p(\beta, \gamma)\phi(\omega)$$

J : rotor moment inertia

ω : rotor speed

τ_e :generator torque

τ_r :aerodynamic torque

Define: $e = \omega - \omega^*$

Error dynamics: $\dot{e} = f(.) + g(.)C(\beta, \gamma) - \dot{\omega}^*$ (1)

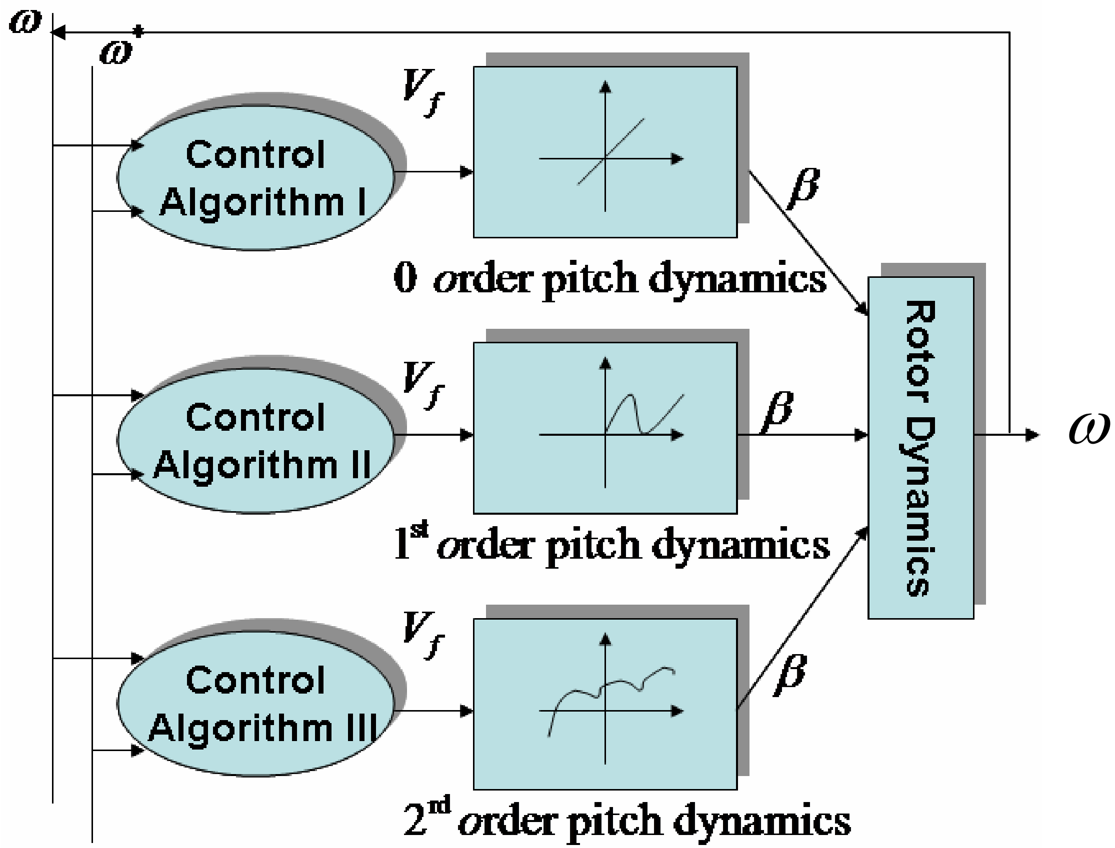
- Pitch Servo Actuator dynamics

Case I : 0order pitch dynamics $\beta = \eta V_f$ (2)

Case II : 1order pitch dynamics $\dot{\beta} + a\beta = \eta V_f$ (3)

Case III : 2order pitch dynamics $\ddot{\beta} + a\dot{\beta} + b\beta = \eta V_f$ (4)

Control Algorithms



Schematic diagram of nonlinear pitch control

Control Algorithms

Observation

Consider the error dynamic system $\dot{e} = -k_0 e + r$

with positive constant k_0

If $r \to 0$ as $t \to \infty$, then $e \to 0$ as $t \to \infty$.

Note:

The aim is to guarantee $r \to 0$ as $t \to \infty$,instead of $e \to 0$ as $t \to \infty$.
This method cascades the pitch servo dynamics to the turbine dynamics easily and thus we develop a series of algorithms for pitch servo voltage to adjust the pitch angle in order that the wind turbine speed tracks its desired value asymptotically .

Algorithm for Case I

Let: $\dot{e} = f + gC(\beta,\gamma) - \dot{\omega}^* = -k_0 e + r$

Then: $r = k_0 e + f + gC(\beta,\gamma) - \dot{\omega}^*$

Take derivative: $\dot{r} = (k_0 + f_\omega + g_\omega C)\dot{\omega} + gC_\beta \dot{\beta} + gC_\gamma \dot{\gamma} - k_0 \dot{\omega} - \ddot{\omega}^*$ (5)

Where: $f_\omega = \frac{\partial f}{\partial \omega},\ g_\omega = \frac{\partial g}{\partial \omega},\ C_\beta = \frac{\partial C}{\partial \beta}$ and $C_\gamma = \frac{\partial C}{\partial \gamma}$

Combine with: $\dot{\beta} = \eta \dot{V}_f$ and $\dot{\gamma} = \frac{\dot{\omega} R}{V_W} - \frac{\dot{V}_W \omega R}{V_W^2}$

Gives: $\dot{r} = A + B\dot{V}_f$ (6)

Where: $A = -k_0 \dot{\omega}^* - \ddot{\omega}^* - gC_\gamma \frac{\dot{V}_W \omega R}{V_W^2} + (k_0 + f_\omega + g_\omega C + gC_\gamma \frac{R}{V_W})(f + gC)$

$B = g\eta C_\beta$

Algorithm for Case I

Design V_f so that

$$V_f = -\int_0^t \{(k_1 r + A)/B\} d\tau$$

where $k1>0$ is a designed constant, we obtain

$$\dot{r} = -k_1 r$$

It implies that $r \to 0$ as $t \to \infty$.

Based on the observation, the rotor speed ω tracks the desired speed ω^* asymptotically

Algorithm for Case II

Combine system error equation (5) with: $\dot{\beta} + a\beta = \eta V_f$

We have: $$\dot{r} = BV_f + A - Ba\beta \qquad (8)$$

Design V_f as: $$V_f = (-k_1 r - A + Ba\beta)/B \qquad (9)$$

where $k1>0$ is a design constant.

Apparently, such a controller leads to: $\dot{r} = -k_1 r$

It implies that : $r \to 0$ as $t \to \infty$.

Thus, the rotor speed ω tracks the desired speed ω^* asymptotically

Algorithm for Case III

Noted that the actuator involves the second order derivative of β, we take the second order derivative

$$\ddot{r} = \sum_{j=1}^{4} \zeta_j + gC_\beta \ddot{\beta} \qquad (10)$$

Where:

$$\zeta_1 = (f_{\omega\omega} + g_{\omega\omega}C)(f + gC)^2 + (f_\omega + g_\omega C)^2 (f + gC) + gC_\gamma \ddot{\gamma}$$

$$\zeta_2 = k_0 (f_\omega + g_\omega C)(f + gC) + (k_0 + f_\omega + g_\omega C) g (C_\beta \dot{\beta} + C_\gamma \dot{\gamma})$$

$$\zeta_3 = 2g_\omega (C_\beta \dot{\beta} + C_\gamma \dot{\gamma})(f + gC) + g(2C_{\beta\gamma} \dot{\beta}\dot{\gamma} + C_{\beta\beta} \dot{\beta}^2 + C_{\gamma\gamma} \dot{\gamma}^2)$$

$$\zeta_4 = -k_0 \ddot{\omega}^* - \dddot{\omega}^*$$

$$\left(f_{\omega\omega} = \frac{\partial f_\omega}{\partial \omega},\ g_{\omega\omega} = \frac{\partial g_\omega}{\partial \omega},\ C_{\beta\beta} = \frac{\partial^2 C}{\partial \beta^2},\ C_{\gamma\gamma} = \frac{\partial^2 C}{\partial \gamma^2},\ C_{\beta\gamma} = \frac{\partial^2 C}{\partial \beta \partial \gamma} \right)$$

Combine with: $\ddot{\beta} + a\dot{\beta} + b\beta = \eta V_f$

Obtain:

$$\ddot{r} = \sum_{j=1}^{4} \zeta_j + gC_\beta (-a\dot{\beta} - b\beta) + BV_f \qquad (11)$$

Algorithm for Case III

Design:

$$V_f = (-\sum_{j=1}^{4}\zeta_j - (k_1+k_2)\dot{r} - k_1k_2r)\frac{1}{B} + \frac{a\dot{\beta}+b\beta}{\eta} \qquad (12)$$

where $k1$ and $k2$ are positive constants.

Substitute V_f into (11), leads to: $\ddot{r} = -(k_1+k_2)\dot{r} - k_1k_2r$

Consequently, we have the augmented system:

$$\frac{d}{dt}\begin{bmatrix} e \\ r \\ \dot{r} \end{bmatrix} = \begin{bmatrix} -k_0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -k_1k_2 & -(k_1+k_2) \end{bmatrix}\begin{bmatrix} e \\ r \\ \dot{r} \end{bmatrix}$$

Algorithm for Case III

It is easily verified that this augmented system has the following characteristic equation:

$$Q(\lambda) = (\lambda + k_0)(\lambda + k_1)(\lambda + k_2)$$

which bears the eigenvalues of k_0, k_1 and k_2.

Therefore, we have $e \to 0$, $r \to 0$ and $\dot{r} \to 0$ as $t \to \infty$.

Simulation Results

The simulation studies were performed to verify the effectiveness of the proposed control strategy. We test the controller designed in three situations.

System parameters :

$$J = 16Kgm^2, R_f = 0.02\Omega$$

Torque coefficient:

$$C_p(\beta,\gamma) = 0.5*(\gamma - 0.022*\beta^2 - 5.6)*e^{-0.17*\gamma}$$

Desired rotor speed trajectory :

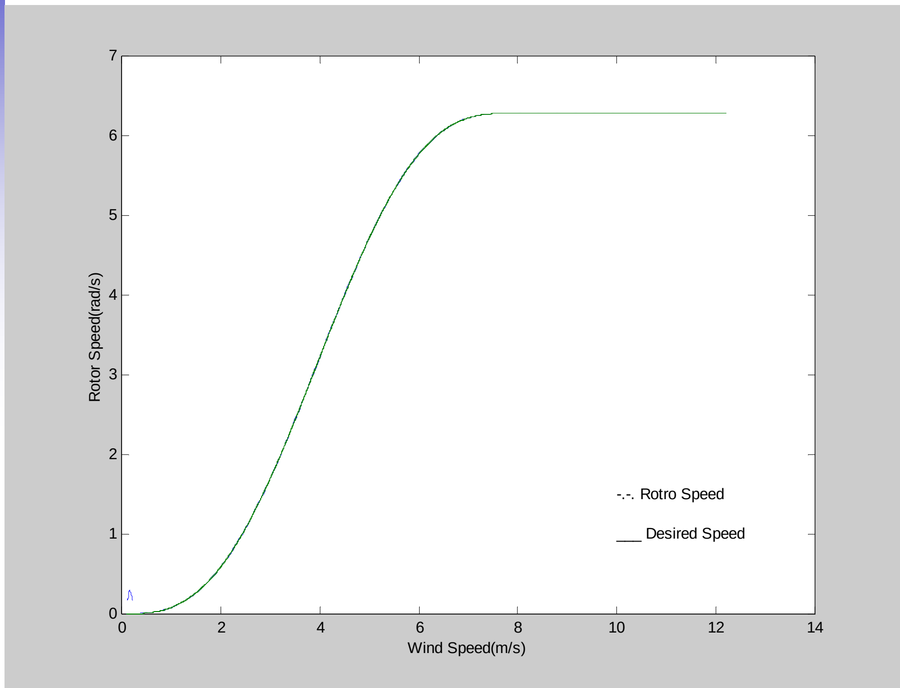
$$\omega^* = \frac{Xm}{1+\exp[-\frac{1}{2}(V_w(t) - \frac{3}{8}t_f)]}$$

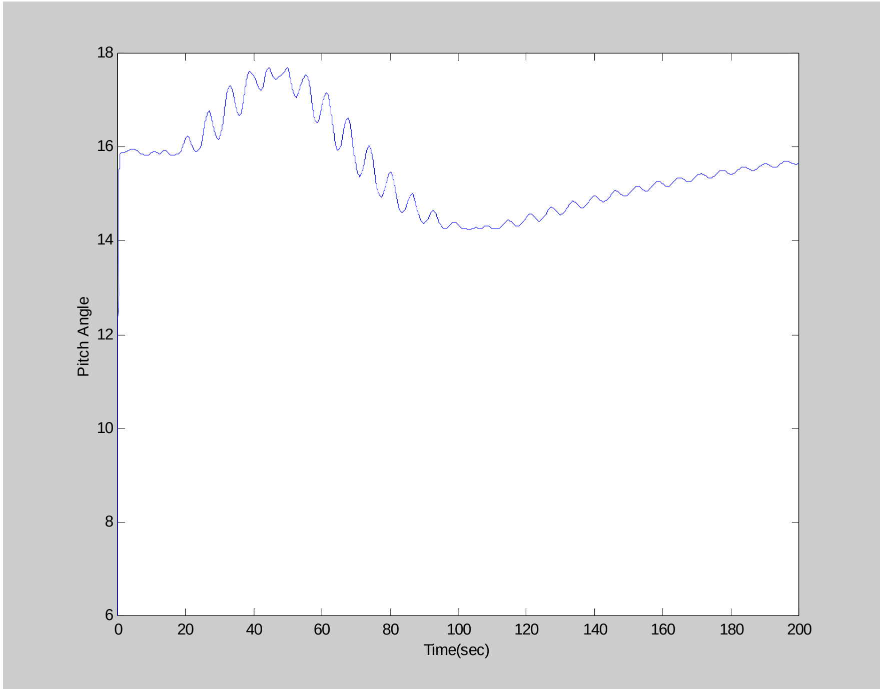
(*Xm* is the rotor speed under average wind speed, *tf* is a constant)

Control Parameter:

$$k_0 = 10,\ k_1 = 1,\ k_2 = 7.9$$

Simulation- Case I

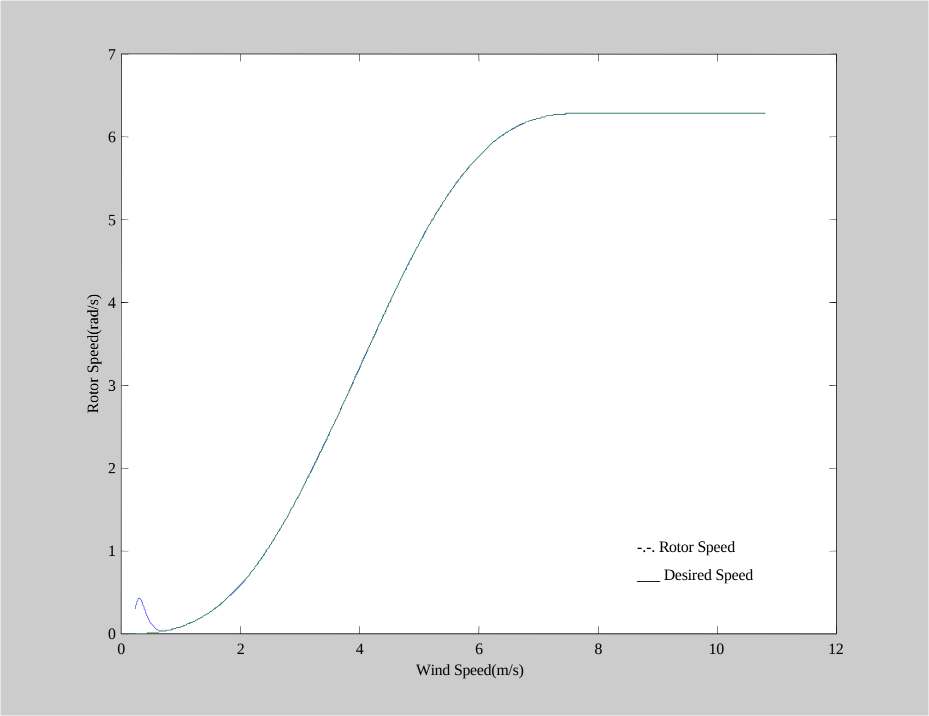


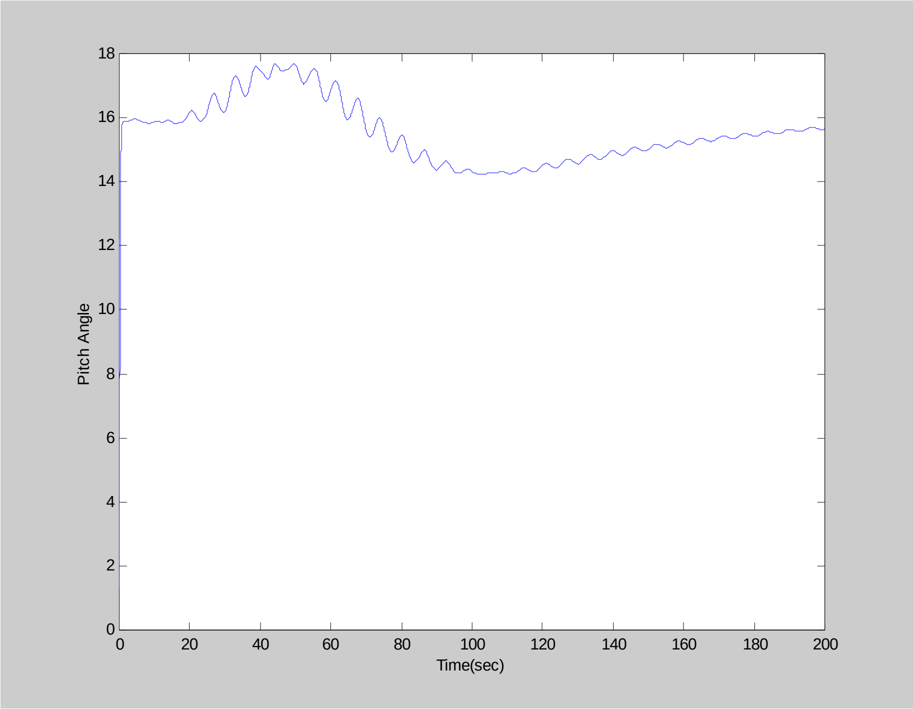


Case I-Rotor speed tracking

Case I-Pitch angle

Simulation- Case II

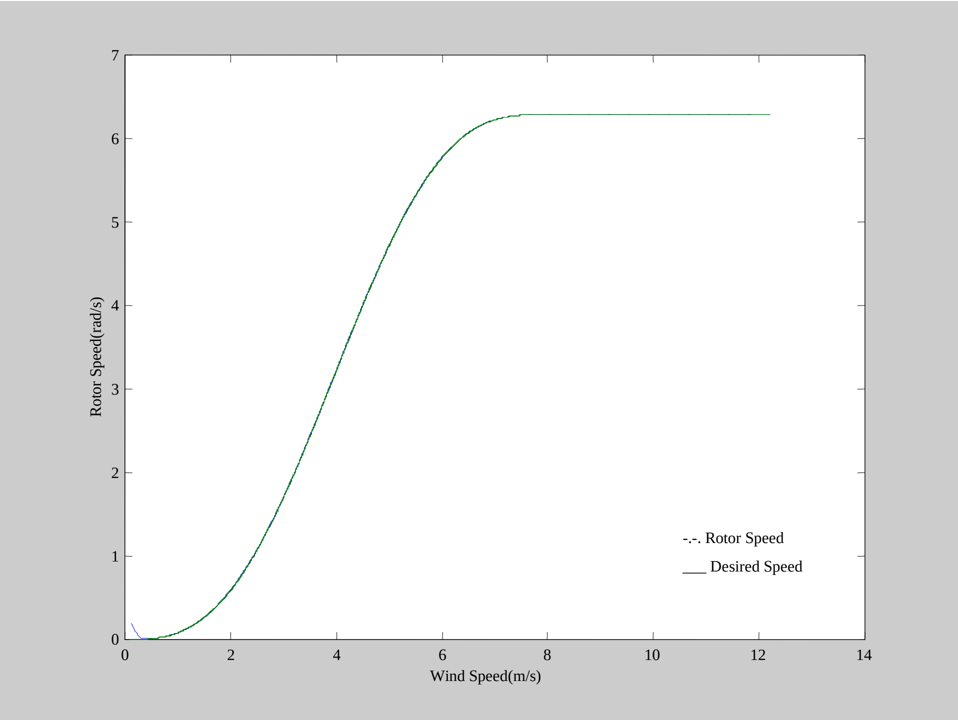




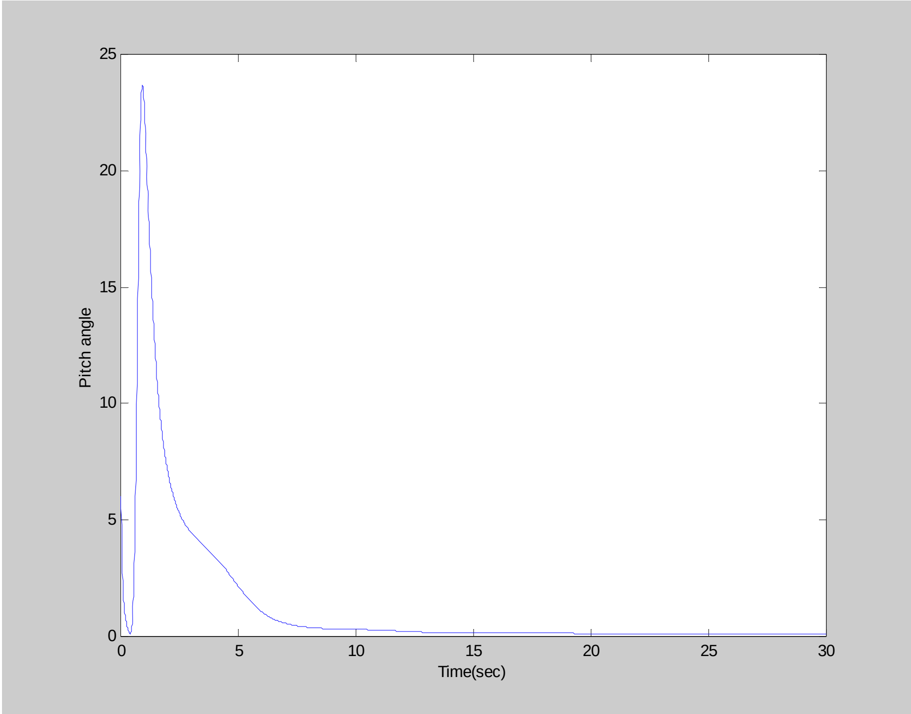
Case II-Rotor speed tracking

Case II -Pitch angle

Simulation - Case III



Case III-Rotor speed tracking



Case III -Pitch angle

Conclusion

1. Develops a method of achieving variable speed operation of wind turbines via a pitch servo-mechanism.

2. Three types of pitch actuator dynamics are considered and integrated into control design.

3. The pitch control algorithms are derived using back-stepping method and applied to a numerical example for verification.

4. Both analytical and simulation studies confirm that the developed pitch control schemes ensure smooth and asymptotic rotor speed tracking .

Conclusion

Advantages:

1. The proposed pitch control algorithms are based on the nonlinear model instead of the commonly used linear or linear plus perturbation model.

2. Since the actuator dynamics are considered in our design, , the developed pitch control algorithms are less sensitive to operating points and more practical and suitable for real-time implementation