The Study of Multimode Power Control System for MW Variable-Speed Wind Turbine

Dingguo Wu, Zhixin Wang
Department of Electrical Engineering
Shanghai JiaoTong University,Shanghai
200240, China
wudingguo@hotmail.com, wangzxin@sjtu.edu.cn

Abstract: Wind energy is a viable option to complement other types of pollution-free generation. In the past constant-speed wind turbine is used for the limitation of the control technology and manufacturing technology. But this kind wind turbine has low efficiency and small operation range.

Recently, more and more people make their focus on studying the MW variable-speed wind turbine for its high efficiency in using wind energy and large operation range. In this paper, base on the study of the model for the variable-speed wind turbine, a multimode power control system is proposed. This control system is consisting of two controllers: the speed controller and the pitch controller. By judging the different power point, the control system use different controller to make the wind turbine run at different mode. Simulation results by using actual detailed parameters for wind turbine show the effectiveness and robustness of this control system.

Key-Words: the shaft system model, feed-forward compensator, multimode power control system, loop-shaping, speed controller, pitch controller, wind turbine

1 Introduction

Because of the environmental pollution problems and the economic benefits of fuel savings, there has been a growing interest in wind energy power systems [1]. Wind energy power systems use wind turbine to convert the wind energy to the electric energy. There are two type of vertical wind turbine in the market: the constant-speed wind turbine (CSWT) and the variable-speed wind turbine (VSWT). In the past years, the constant-speed wind turbine was usually used for the lack of manufacturing technology and control technology. But wind turbine for this kind doesn't have good efficiency and has small operation range. Recently more and more people come to study the variable-speed wind turbine for the lack of the CSWT. The VSWT is consisting of six parts: the rotor, the pitch regulation system, the gear box, the generator, the electronic converter and the control system. The electronic converters are inserted between the generator and the grid or a doubly fed induction controlled by the rotor circuit is used [2-3]. The structure of the VSWT is shown in Fig 1.

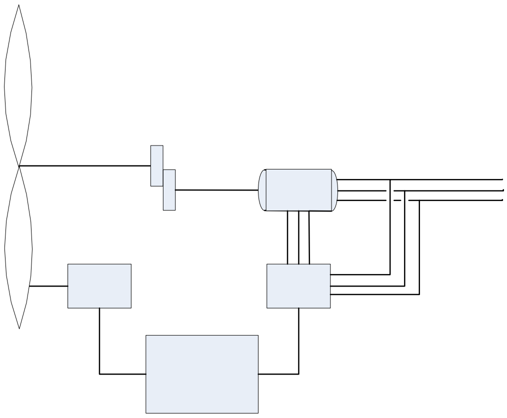

Fig1 the structure of the VSWT

The VSWT has three operation modes: the variable-speed (VS) mode, the constant speed (CS) mode and the zero speed (ZS) mode. In the VS mode,. By controlling the torque of the generator, the rotor speed can vary with the wind speed. Then the VSWT can extract the maximum energy from the wind [2]. In the CS mode, the rotor speed keep constant by change the pitch angle and in the ZS mode, the VSWT stop by use a mechanical brake. As we see, a control system is important to make the VSWT work high effectiveness and safeness. So this several control methods for controlling the VSWT has been reported so far. In [2-9] the authors proposed the back-stepping method, the feed-forward method for the control of the pitch angle in the CS mode. But as we all know, the pitch regulation system has great inertia and can only move the blade to change the pitch angle slowly. A quick control method is not use for the pitch control. In [2] [10] the authors proposed a PI controller for adjust the torque of generator based on feed-forward compensation. This kind controller is used in the VS mode. However the variation in parameters, the effect of wind shear for windmill and the noise on the process of control have not been considered in these methods and in practice it is difficult to use those methods for the controller design in [2-11]. All control schemes above can not make VSWT run in all operating regions neither.

Considering the above, in this paper base modeling the VSWT we propose a power control system. This power control system includes two controllers. One controller is a speed controller which is used to control the torque of generator to make the wind turbine absorb the maximum power from the wind. The feed-forward compensator and loop shaping are used for this controller design. The design of the speed controller is easy and has better robustness than PI controller which is mentioned before. The other is a pitch controller that is used to regulate the pitch angle of the blade. Considering the great mechanical inertia of the blade, we set five given pitch-angles in this controller. This can simplify the design of pitch controller and is easy to implement in practice. These two controllers are switched by judge different power point. The simulation results using actual detailed parameters for wind turbine show the effectiveness and robustness of the proposed control system.

The paper is organized as follows: section 2 provides a mathematics model of the VSWT. Section 3 describes the control objectives and the designs of the control system. In section 4, the effectiveness and robustness of the proposed method is demonstrated by simulation results. Conclusions are drawn in section 5.

2 The Shaft System Model of the VSWT

There are many studies on the modeling of VSWT such as identification modeling, mechanism modeling and etc [13-16]. In this paper, by comparing different modeling methods, the shaft system model is chose to use. In this model, the rotor, the gearbox, the generator and the pitch regulation system are seen as mass. For the converter has fast mill response characteristic compared with other mass, its model is neglected and its signal is equal to the control signal directly. By modeling those masses separation, then link them together. This shaft system model can reflect the dynamic characteristics of the VSWT accurately. The block diagram of the VSWT is shown in Fig.2.

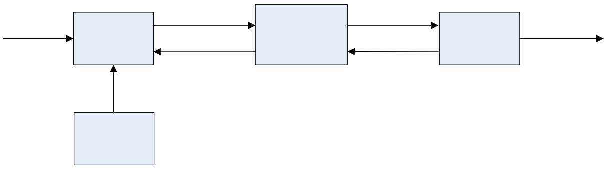

Fig.2. the shaft system model of the VSWT

The model of each mass is described as follows:

2.1 The Rotor

The aerodynamic behavior of the rotor is nonlinear. It is dependent on wind speed and may change due to contamination of blade surface. So its modeling is a complex problem by means of experimental investigation. In this section, by using the data fitting method the rotor output power $\mathrm{P_w}$ is given by the following equation[16-19]:

$$P_{\mathrm{w}} = \frac{1}{2}\rho\pi R^2 C_p(\lambda,\beta)v^3 \tag{1}$$

Where v is wind speed, ρ is air density, R is the radius of rotor：C_p is power coefficient β is pitch angle and λ is tip speed ratio， which is given by $\lambda = \omega_r R / v$.

The power coefficient C_p is a nonlinear expression which use λ and β as its variables. Its graph is shown in Fig.2. It is can be seen that in the steady-state operation, there exist an optimal tip-speed ratios and the largest wind power coefficient for a fixed pitch-angle from the graph.

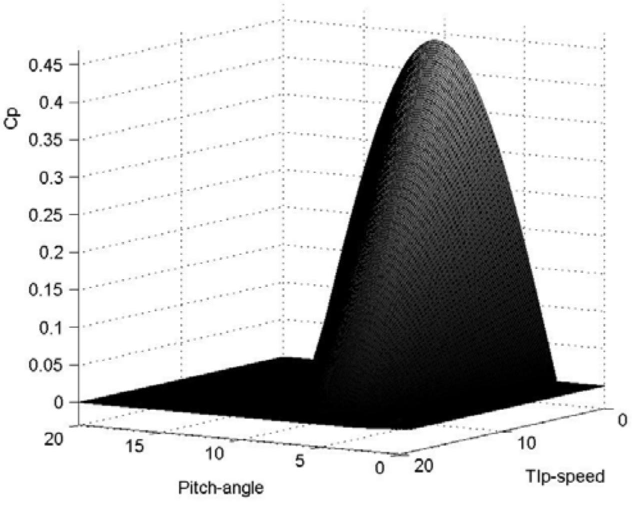

Fig.3. the graph of the power coefficient C_p

2.2 The Generator

There are two kinds generator used in the VSWT in the past: the permanent magnet synchronous generator (PMSG) and the doubly fed induction generator (DFIG). The topological structure diagram of PMSG and the DFIG are shown in Fig 3 and Fig 4. From the Fig3 it can be seen when using the PMSG, a converter is linked between the stator and the grid. So the power grade of converter should equal to or bigger than the power grade of the PMSG.

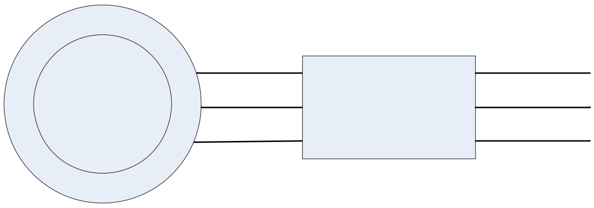

Fig.4. the topological structure diagram of PMSG

But the topological structure of the DFIG is different with the PMSG. The converter is linked between the rotor and the power grid. In this topological structure, the power grade of the converter is only need equal to 1/3 power grade of the DFIG. From the comparison above, it can be seen that using the DFIG is cheaper. For the doubly fed induction generator (DFIG) has great advantage, it is widely used in large capacity wind turbines in recent years [2].

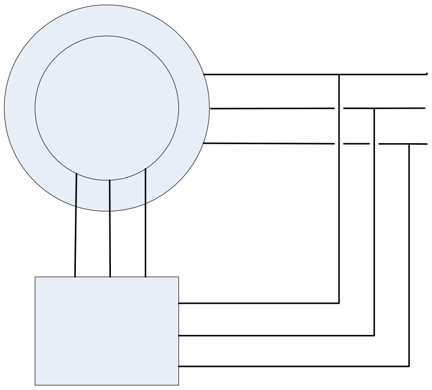

Fig.5. the topological structure diagram of DFIG

According to electromagnetic induction law, the model of the DFIG can be writing as the following equation:

$$\begin{aligned} &U = L\cdot PI + PL\cdot I + RI \\ &U = [U_A, U_B, U_C, U_a, U_b, U_c]^T \\ &I = [I_A, I_B, I_C, I_a, I_b, I_c]^T \\ &R = diag[-R_s, -R_s, -R_s, R_r, R_r, R_r] \end{aligned} \tag{2}$$

Where U is the voltage, I is the current, subscript A,B,C is the expression of the stator' phase, subscript a,b,c is the expression of the rotor' phase r, R is the resistance, subscript s, r is the expression of the stator and rotor.

The expression of the equation (2) is the electromagnetic relation of the DFIG. From the equation (2), if the current of the rotor and the stator is seen as the state variable, it is easy to find the electromagnetic relation of the DFIG is a six-order system and each state variable is coupled. So how study and control this relation is difficult. For convenient use, this model should be reduced order. In this paper, a d-q model is used by motor custom. In the d-q model the electromagnetic relation model can be shown by Fig.6. This model can be used to derive equations that describe the relationship between the voltage and current in d-q frame. The equation (3) (4) (5) below are used to describe the electromagnetic relation again:

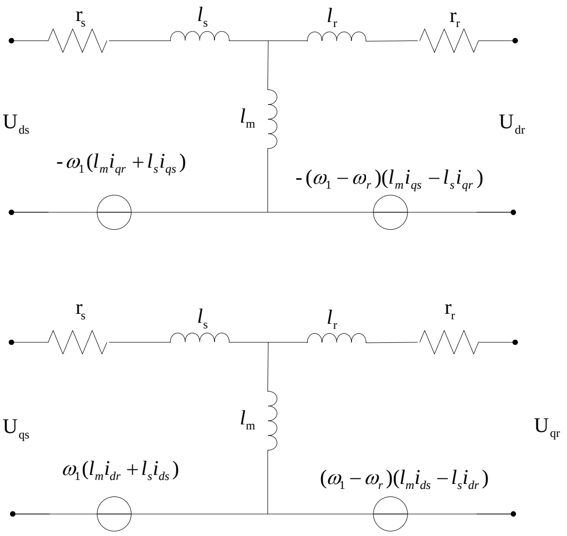

Fig.6. the DFIG equivalent circuit mode

$$\begin{bmatrix} u_{ds} \\ u_{qs} \\ u_{qs} \\ u_{qr} \end{bmatrix} = \begin{bmatrix} pL_s+r_s & -\omega_1 L_s & pL_m & -\omega_1 L_m \\ \omega_1 L_s & pL_s+r_s & \omega_1 L_m & pL_m \\ pL_m & -(\omega_1-\omega_r)L_m & pL_r+r_r & -(\omega_1-\omega_r)L_r \\ (\omega_1-\omega_r)L_m & pL_m & (\omega_1-\omega_r)L_r & pL_r+r_r \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \quad (3)$$

$$T_G = \frac{3}{2}\frac{P}{2} L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \quad (4)$$

$$J_G \frac{p\omega}{pt} = T_s - T_G \quad (5)$$

Where u is the voltage, i is the current, r is the resistance, l is the inductance, ω_1 is the synchronous speed, ω_r is the generator speed, the subscript d, q is the expression of the d-q frame, the subscript s, r is the expression of the stator and the rotor, p is the differential operator

In above we can see the electromagnetic relation of the DFIG is a four-order system. And the DFIG is modeled as a five-order system.

2.3 The Gearbox

The rotor speed of large wind turbine is usually 20-30 rpm. This speed is too low to make the DFIG work normally. So the gearbox is used as a speeder which links the rotor to the generator. The gearbox itself has complicated dynamic characteristics. Choosing different ratio of gearbox may decide the different resonance frequency of the VSWT and the power grade of the DFIG. So it is very important to study it property. But in this paper, our major study is the power control of the wind turbine. The gearbox is only seen as a mass in shaft model. By Mechanical principles the model of gearbox can be written as:

$$\begin{bmatrix} J_{WT} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & J_G \end{bmatrix} \begin{bmatrix} \ddot\theta_{WT} \\ \ddot\theta_{WT}-\ddot\theta_G \\ \ddot\theta_G \end{bmatrix} + \begin{bmatrix} D_{WT} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & D_G \end{bmatrix} \begin{bmatrix} \dot\theta_{WT} \\ \dot\theta_{WT}-\ddot\theta_G \\ \dot\theta_G \end{bmatrix} \quad (6)$$

$$+\begin{bmatrix} 0 & 0 & 0 \\ 0 & K & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \theta_{WT} \\ \theta_{WT}-\theta_G \\ \theta_G \end{bmatrix} = \begin{bmatrix} T_{WT}-T_S \\ T_S \\ T_S+T_G \end{bmatrix}$$

Where J_{WT} and J_G are the rotational inertia of the generator, θ_{WT} is the rotation angle of the rotor, θ_G is the rotation angle of the generator.

2.4 The Pitch Regulation System

The pitch regulation system is a mechanical instrument for changing the pitch angle. Because the pitches have great inertia, the pitch regulation system is composed of hydraulic system. Its model often described as a first-order inertia system [11]:

$$p\beta = \frac{1}{\tau_\beta}\left(\beta_v - \beta\right) \tag{7}$$

Where β is the pitch angle, β_{v} is the given pitch angle, τ_β is the time constant of the pitch regulation system.

3 The control objectives and the designs of the control system

3.1 The Control Objectives

The control system of the VSWT has as the main goals to control the power interchanged between the wind and the power grid. The operation of the VSWT can be divided into different modes by different power point. The operation modes of the VSWT are shown in Fig7. From fig7, the VSWT has three operation modes:

- Mode 1(VS mode): the rotor speed is operating at variable speed/optimum tip-speed ratio when the wind power is between the p_c and the p_r:
- Mode 2(CS mode): the rotor is operating at constant speed when the wind power is between the p_r and the p_f:
- Mode 3(S mode): stop the VSWT when the wind power is less than the p_c or more than p_f

From the request of the operation modes, then the design objective for the VSWT can be defined as following:

- Maximize the power between the p_c and the p_r
- Limit and smooth the power between the p_r and the p_f
- Stop the system at other wind power point

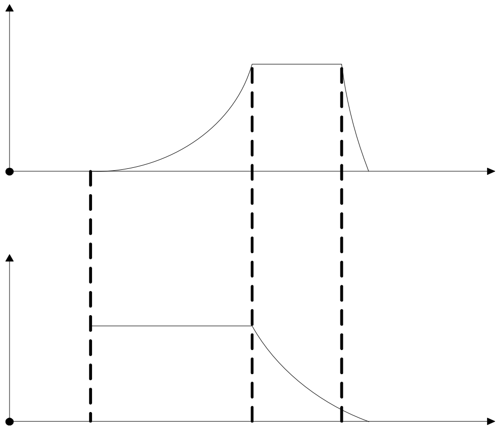

Fig.7.Operation Modes of the VSWT

Where p_c is the cut-in power point, p_r is the rated power point, p_f is the cut-out power point.

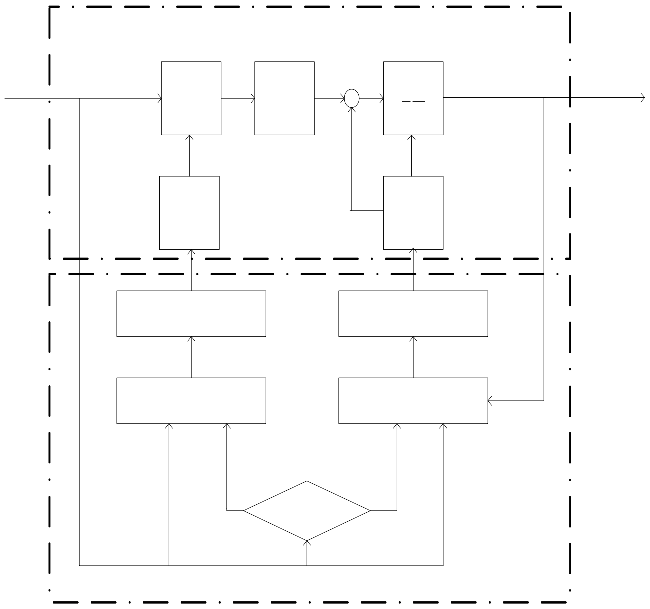

Fig.8 the controls system for the VS wind turbine

3.2 The design of the multimode power control system

For getting the control objective which is described in section 3.1, a multimode power control system is designed. Its diagram is shown in Fig8. This control system is consisting of three parts: the controller for mode selection, the speed controller for the DFIG and the controller for the pitch control. Its control flow is shown in Fig9.

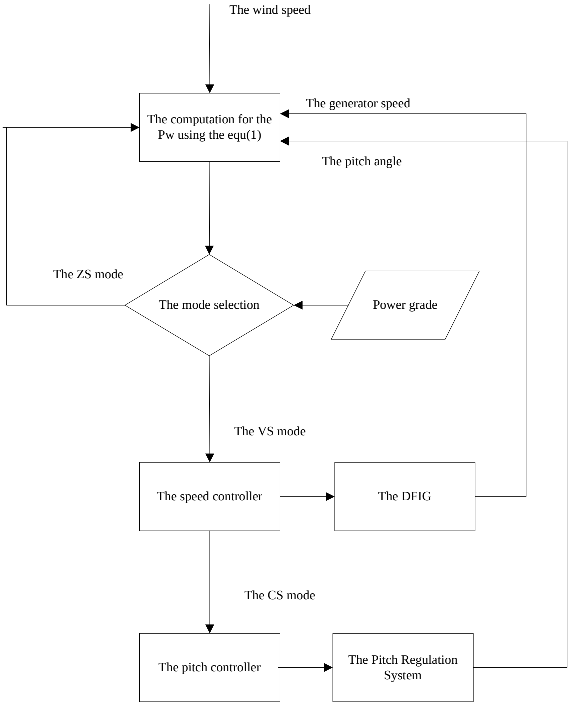

Fig.9.the control flow for the VSWT

When the VSWT is allowed to start, by measure the wind speed and the rotor speed the mode selection's controller choose which controller is used and give some information to the other two controllers. The speed controller for the DFIG is run in mode 1, it make the DFIG get maxim power from the wind and it is consist of two parts: the feed-forward compensator and the robust controller. The pitch controller is run in mode 2, it makes the VSWT run at a constant power grade and it is consisting of two parts: the pitch angle scheduling and the PI controller. Each controller is described as following parts:

3.2.1 The controller for mode selection

The controller for mode selection is very simple. First by using the equation (1), the power that is extracted by the rotor can be calculated. The result is compared to p_c , p_r and p_f , then the mode is choose.(reference for section 3.1)

3.2.2 The Speed Controller for the DFIG

The speed controller is in aim of getting the maximum power form the wind in the VS mode. In this mode, by control the electromagnetic torque, the generator adapt its speed to maintain the optimum C_p (in this time, the pitch angle and the tip speed ratio are a constant). In the mode of the DFIG which is described in section2.2, we can see the variable states is decoupled first and there are some uncertainty in control process. For the complexity of the DFIG and the uncertainty in operation, the design procedure of the speed controller is consists of two steps: the design of the feed-forward compensator and the design of the robust controller

3.2.2.1 The design of the feed-forward compensator

The design of the feed-forward compensator is aimed to decouple the DFIG. From the equation (3) we can see the model of the DFIG has great nonlinear properties and coupling although its model has been simplified. In this section, by using the proper compensation the model of the DFIG can be decoupled. For better simply the model the DFIG, we did two hypothesizes:

- The resistance of the stator is zero

  Because the stator is connected to the power grid and the grid is an infinite net, the stator can be seen equal to zero
- The flux is constant and is only generated from the stator only

  In general, the flux is generated from the stator and the rotor. But the flux generated from the rotor is smallest than the stator. So the flux is generated from the stator only is reasonable.

From the two hypothesizes above, the model of the DFIG can be rewrite as:

$$\psi = \frac{U_1}{\omega_1}$$

$$u_{dr} = (l_r - \frac{l_m^2}{l_s}) p i_{dr} + r_r i_{dr} - (\omega_1 - \omega_r)(l_r - \frac{l_m^2}{l_s}) i_{qr}$$

$$u_{qr} = (l_r - \frac{l_m^2}{l_s}) p i_{qr} + r_r i_{qr} + (\omega_1 - \omega_r)(l_r - \frac{l_m^2}{l_s}) i_{dr} + (\omega_1 - \omega_r)\frac{l_m}{l_s}\psi$$

(7)

Where ψ is the flux of the DFIG, U_1 is the voltage vector of the stator.

In the equation (7), we can observe that coupling terms is:

$$\Delta u_{dr} = -(\omega_1 - \omega_r)(l_r - \frac{l_m^2}{l_s}) i_{qr}$$

$$\Delta u_{qr} = (\omega_1 - \omega_r)(l_r - \frac{l_m^2}{l_s}) i_{dr} + (\omega_1 - \omega_r)\frac{l_m}{l_s}\psi_{ds}$$

The equation (3) can be rewrite:

$$u_{dr} = (l_r - \frac{l_m^2}{l_s}) p i_{dr} + r_r i_{dr} + \Delta u_{qr}$$
$$u_{qr} = (l_r - \frac{l_m^2}{l_s}) p i_{qr} + r_r i_{qr} + \Delta u_{qr} \qquad (7)$$

In equation(9) if we choose Δu_{dr} and Δu_{qr} the feed-forward compensator, then the relationship between the rotor voltage and the rotor current can be decomposed as two independent first-order systems and two compensations. The model of the DFIG can be decoupled.

3.2.2.2 The design of the robust controller

The second step is the design of the robust controller by using loop shaping. Loop shaping is a method which can be described as following:

- Choosing some weight function

  Those weight functions are used to reflect the frequency response of the uncertainties or the noise which exist in the process of controlling.
- Shaping the bode of the system with those weight functions

  Design a controller and make the bode plot of the controller with system can satisfy the frequency response of those weight functions

According to the actual demands, we can see there are two things that make the controller work not normal: the flicker of the wind and the measure noise in control process. So there are two weighting functions in this robust controller's design. The first weighting function is chosen for the wind speed. As we all know, the wind speed change rapidly all the time. Due to the great inertia of the rotor and the generator, the rpm of the rotor can not changed rapidly. So the control signal should not be sensitive for rapid changes of the wind speed. The second weighting function is chosen for the noise in operation. The noise exists in the measurement process and the transmission process. Those kinds of noise often have some special frequency and make controller output wrong control signal. So the controller should inhibit the use of noise in those frequencies.

3.3. The Pitch controller

The pitch angle controller is only active in mode 3. In this mode, the rotor speed can no longer be controlled by increasing the torque of the DFIG for it has already reached its rated power. In this time, the blade pitch angle is changed in order to reduce C_p .Using the expression of C_p , the pitch angle need to limit the power extracted from the wind to the rated power of the VSWT can be calculated for each wind speed theoretically. Furthermore, it should be taken into account that the pitch angle can't change immediately, but only a finite rate for the large rotational inertia of the blade and the desire to save money on the blade drives. In this controller a pitch angle scheduling is used. According to different wind speed point, fixed pitch angle is given. There are two advantages for using this scheduling: first it saves the time and device to calculate the pitch angle for every wind speed, second it gives enough time make the pitch regulation system to reach its destination.

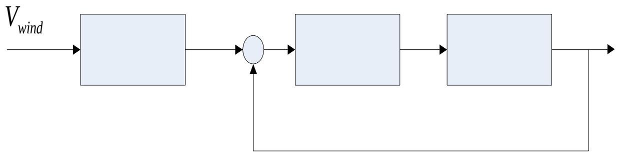

Fig.7. the block diagram of the pitch controller

The block diagram of this controller is shown in Fig7. A PI controller corrects the error between the actual pitch angle and the reference.

4 The simulation results

By using MATLAB/simulink, a VSWT model has been simulated. The parameter values are given in Table 1.

Table 1. the Parameters of the VSWT

parameters	value
R(m)	35.25
Cut-in/(m/s)	4
rated/(m/s)	12.2
Cut-out/(m/s)	25
Drive-train ratio	1: 90
Optimum tip-speed	10
Cp	0.44
Jwt((kg·m^2)	320000
Jg((kg·m^2)	60
The mutual inductance(H)	2.9
The self inductance of the stator(H)	0.171
The self inductance of the rotor(H)	0.156
The resistance of the rotor(Ω)	0.005
The role pair number	3

The wind speed is shown in Fig.8. The initial wind speed is below the rated wind speed. After 15s, a wind speed ramp starts. The average wind speed increase from 4m/s to 25m/s in 50s. The fluctuation frequency of wind speed is 1Hz, 5Hz and 10 Hz. The bode plot of weight function for the wind speed and the noise are shown in Fig.9. and Fig.10. The changes of the pitch angle is shown in Fig.11..

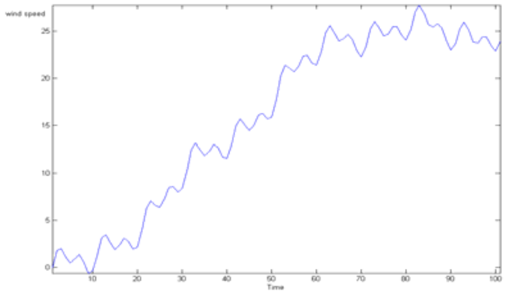

Fig.8. the wind speed

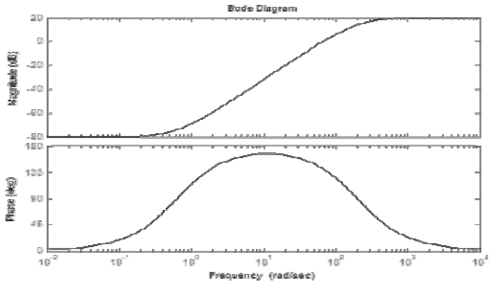

Fig.9.the bode of weight function for the wind speed

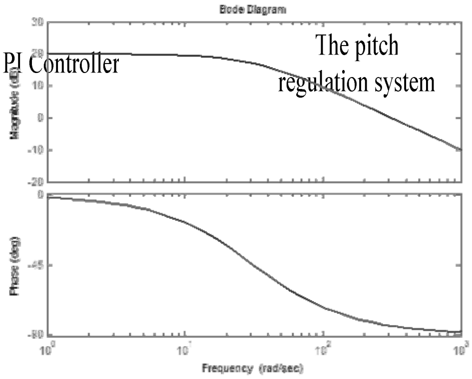

Fig.10. the bode of weight function for the noise

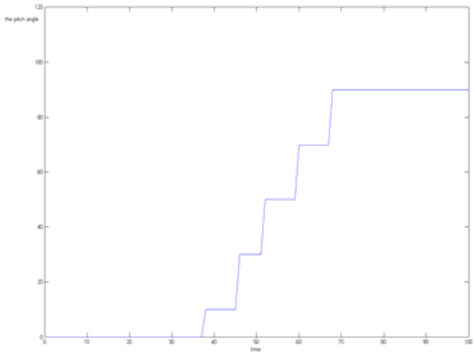

Fig.11. the pitch angle

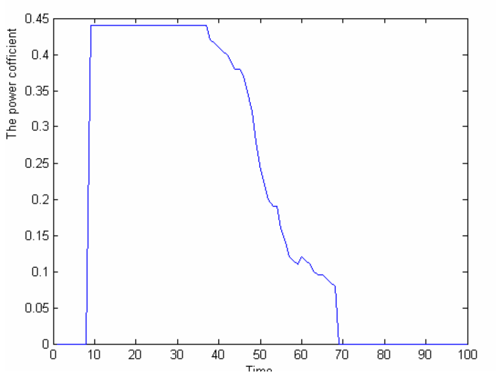

Fig.12. the power coefficient for VSWT

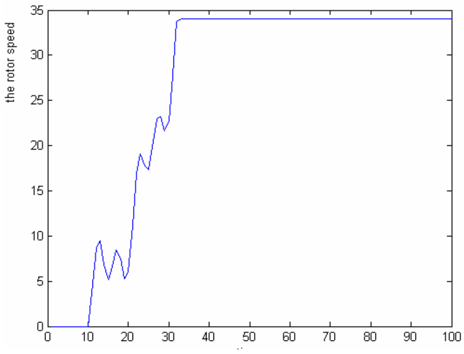

Fig.12 the rotor speed

Five given pitch angle: 15°,30° , 45°,60°,75° correspond to wind speed:13m/s, 13m/s, 16m/s, 19m/s, 22m/s, 25m/s respectively. The power coefficient C_p which changes from 0.44 to 0 is shown in Fig.12. The rotor speed is shown in Fig.13. From these graphs, it can be concluded that the control system performs well.

5 The Conclusion

In this paper, a three mass model for representing VSWT was established. This model can reflect the dynamic characteristics of the VSWT accurately. Based on this model, a control system is designed. The control system contains two parts: the speed controller for generator and the pitch controller for pitch regulation system. By using loop shaping and the feed-forward compensator, the speed controller has great tracking and robust performance. By using five given pitch angle, the design procedure of pitch controller is simplified. The simulation results prove the effectiveness of this control system.

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