

# Modeling and Design of Control System for Variable Speed Wind Turbine in All Operating Region

Wu Dingguo, Wang Zhixin  
Department of Electrical Engineering  
Shanghai JiaoTong University, Shanghai  
200240, China

[wudingguo@hotmail.com.cn](mailto:wudingguo@hotmail.com.cn), [wangzxin@sjtu.edu.cn](mailto:wangzxin@sjtu.edu.cn)

*Abstract:* In order to get the maximum power from the wind, the variable-speed wind turbine should run at different speed when wind speed changes. In this paper a control system is introduced to get this purpose based on establishing the three-mass model of the wind turbine. The control system consists of two parts: one is a speed controller for generator control; the other is a PI controller for pitch control. Simulation results by using actual detailed parameters for wind turbine show the effectiveness and robustness of this control system.

*Key-Words:* three-mass model, feed-forward compensator, loop-shaping, speed controller, pitch controller, wind turbine, doubly-fed induction generator (DFIG)

## 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]. There are two types of vertical wind turbine in the market: the constant-speed wind turbine and the variable-speed wind turbine. In the past years, the constant-speed wind turbine was usually used for the lack of manufacturing technology and control technology. But this kind of wind turbine is not of good efficiency; and more and more people come to study the variable-speed wind turbine (VSWT) now. In the VS mode, 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 VSWT can change rotor speed with wind speed variation and it is especially useful for all operating region efficiency since the electronic converter can maximize the conversion efficiency by controlling the generator torque [2]. Several control methods for controlling the VSWT has been reported so far. The authors proposed the back-stepping method, the feed-forward method for the control of the pitch angle in above-rated wind speed in [2-9]. The authors proposed a PI controller for controlling the torque of

generator based on feed forward compensation in under-rated wind speed in [2] [10]. 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 these 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 we propose a control system for the VSWT. This control system consists of 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 when wind speed is under rated speed. 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. 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. 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 shown in section 5.

### 2 The Mathematics Model of VSWT

There are many studies on the modeling of VSWT such as identification modeling, mechanism modeling etc [13-16]. In this paper, the three-mass model is used. The rotor, the gearbox and the generator are seen as mass. This model can reflect the dynamic characteristics of the VSWT accurately. The block diagram of the VSWT is shown in Fig.1.

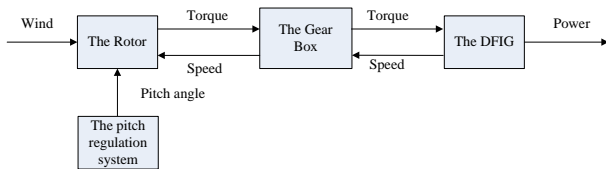


Fig.1 The block diagram of the VS wind turbine  
The model of each mass is described as follows:

#### 2.1 The Rotor

The rotor output power  $P_w$  is given by the following:

$$P_w = \frac{1}{2} \rho \pi R^2 C_p(\lambda, \beta) v^3 \quad (1)$$

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

The power coefficient  $C_p$  is a nonlinear expression which uses  $\lambda$  and  $\beta$  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.

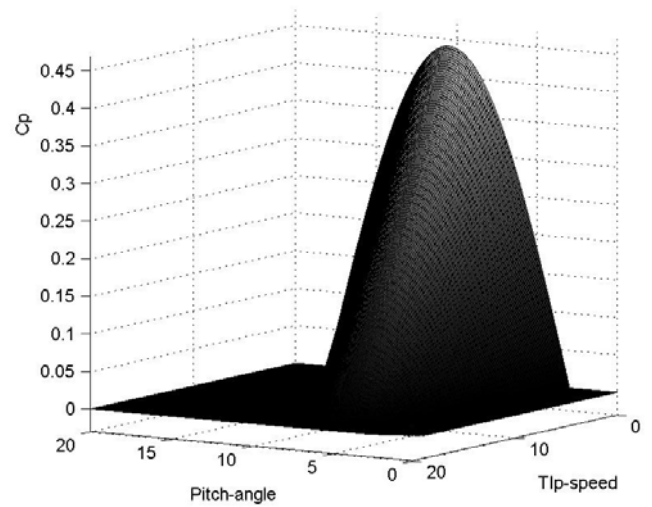


Fig.2. the graph of the power coefficient  $C_p$

#### 2.2 The Gearbox

The rotor speed of large wind turbine is usually 20-30rpm. This speed is too low to make the asynchronous generator work normally. So the gearbox is used as a speeder which links the rotor to the generator. The gearbox itself has complicated dynamic characteristics. In this paper, our major study is the power flows of the wind turbine. The gearbox is seen as a mass. By Mechanical principles the model of gearbox can be written as:

$$\begin{bmatrix} J_{WT} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & J_G \end{bmatrix} \begin{bmatrix} \ddot{\theta}_{WT} \\ \ddot{\theta}_{WT} - \ddot{\theta}_G \\ \ddot{\theta}_G \end{bmatrix} + \begin{bmatrix} D_{WT} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & D_G \end{bmatrix} \begin{bmatrix} \dot{\theta}_{WT} \\ \dot{\theta}_{WT} - \dot{\theta}_G \\ \dot{\theta}_G \end{bmatrix} \quad (2)$$

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

Where  $J_{WT}$  and  $J_G$  are the rotational inertia of the generator,  $\theta_{WT}$  is the rotation angle of the rotor,  $\theta_G$  is the rotation angle of the generator.

#### 2.3 The Generator

DFIG is of great advantage, and is widely used in large capacity wind turbines in recent years [2]. The

topological structure diagram of DFIG is shown in Fig 3.

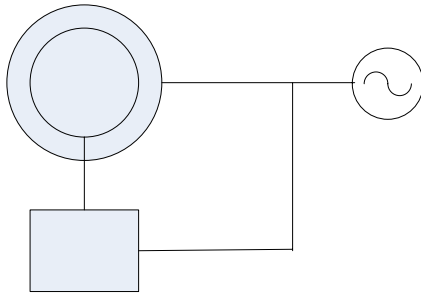


Fig.3. the topological structure diagram of DFIG

The rotor side of generator connects to the grid through the converter and the stator side connects to the grid directly. By controlling the voltage of the rotor side, the generator has a large operation range and the output of stator side can keep stable. The DFIG equivalent circuit model is shown in Fig.4.

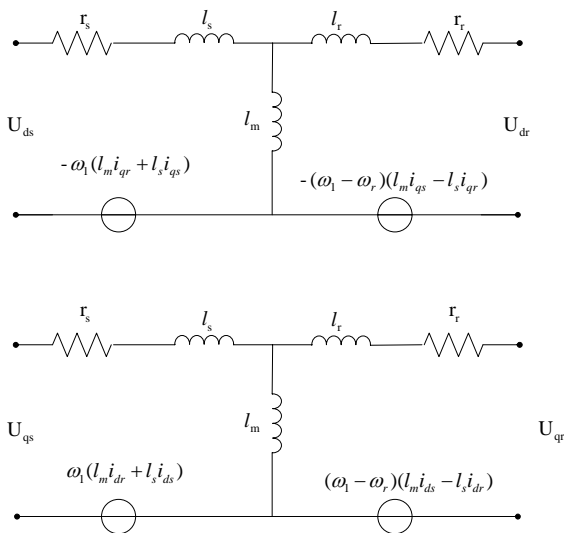


Fig.4. the DFIG equivalent circuit mode

The equivalent circuit model can be used to derive equations that describe the relationship between the voltage and current. The equation (3) (4) (5) below are used to describe the electric and the mechanical relationship of the DFIG:

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

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

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

Where  $u$  is the voltage,  $i$  is the current,  $r$  is the resistance,  $l$  is the inductance,  $\omega_1$  is the synchronous speed,  $\omega_r$  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

### 2.4 The Pitch Regulation System

The pitch regulation system is a mechanical instrument for changing the pitch angle. Its model often described as a first-order inertia system [11]:

$$p\beta = \frac{1}{\tau_\beta} (\beta_v - \beta) \quad (6)$$

### The Stator

Where  $\beta$  is the pitch angle,  $\beta_v$  is the given pitch angle,  $\tau_\beta$  is the time constant of the pitch regulation system.

### The Rotor

## 3 Control object and design of the control system

### 3.1 Control object

The control system of the VSWT is to control the power interchanged between the wind and the grid.

The operation of the VSWT can be divided into three modes which are shown in Fig4

- Mode 1: operating at variable speed/optimum tip-speed ratio when wind speed is between the cut-in speed and the rated speed:
- Mode 2: operating at constant speed when wind speed is between the rated speed and the cut-out speed:
- Mode 3: shut down in other wind speed

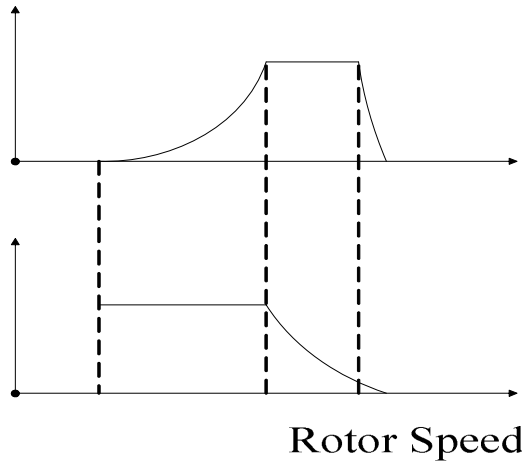


Fig.4. Operation Modes of Wind Turbine

Where  $v_c$  is cut-in wind speed,  $v_r$  is the rate wind speed,  $v_f$  is the cut-out wind speed.

Then control system design object for VSWT can be defined:

- Maximize the power between the cut-in and rate wind speed by using the speed controller to control the torque of the DFIG.
- Limit and smooth the power between the rate and cut-out wind speed by using the pitch angle controller to control the pitch angle of the blade.
- Stop the system at other wind speed area

The diagram of the controls system for the VS wind turbine is shown in Fig.5. The design of the speed controller and the pitch controller is described as following.

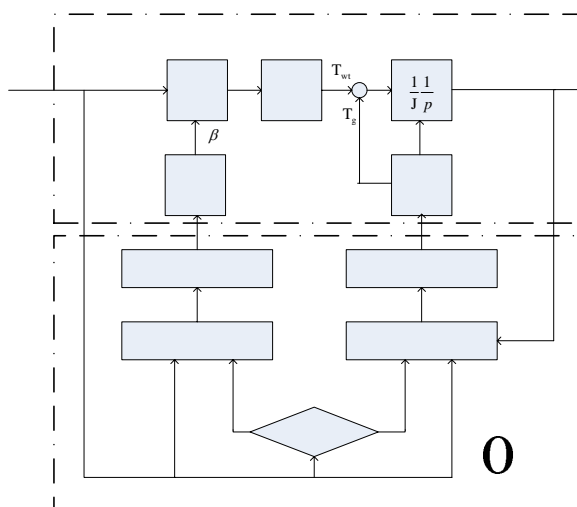


Fig.5 the controls system for the VS wind turbine

### 3.2 DFIG Speed controller

The speed controller is to get the maximum power form the wind in operation mode 2 by making 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). For the complexity of the DFIG and the uncertainty in operation, the design procedure of the speed controller is consists of two steps.

The first step is the design of the feed-forward compensator. From the equation (3) we can see the DFIG has great nonlinear properties and coupling. In this step, by using the proper compensation the model of the DFIG can be decoupled and simplified. The compensation is chosen as:

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

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

The equation (3) can be rewrite:

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

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

From the equation (7), the relationship between the rotor voltage and the rotor current can be decomposed as two independent first-order systems and two compensations. So if these two compensations are added in the controller, the model of the DFIG can be decoupled.

The second step is the design of the robust controller by using loop shaping (Through choosing some weighting functions, the bode plot of the given system's transfer function is adjusted to the desired shape). According to the actual demands, two weighting functions are chosen in this speed controller 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 VSWT 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 noise in those frequencies.

**3.3. 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.

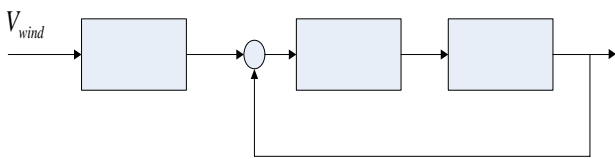


Fig.7. the block diagram of the pitch controller

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 Simulation Results**

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

Table I.

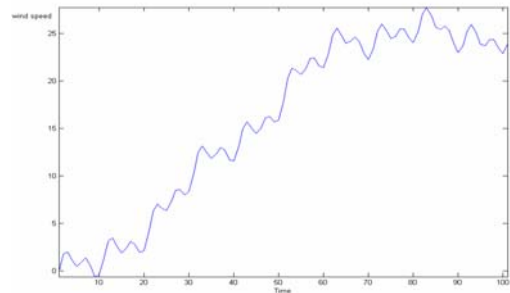


Fig.8. the wind speed

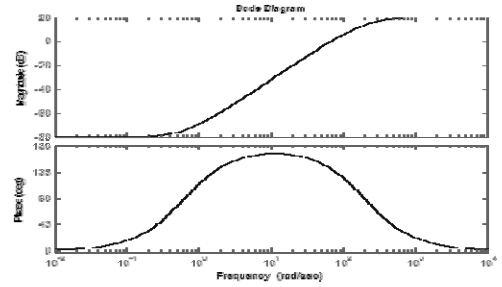


Fig.9.the bode of weight function for the wind speed

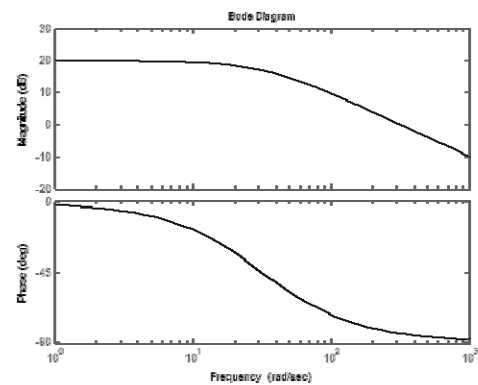


Fig.10. the bode of weight function for the noise

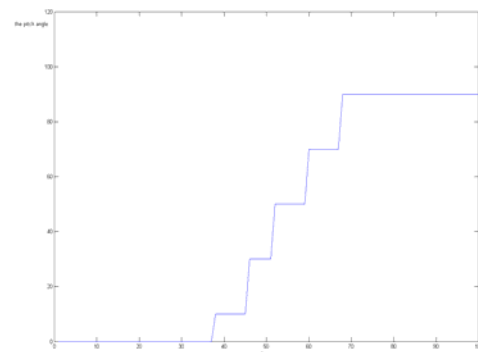


Fig.11. the pitch angle

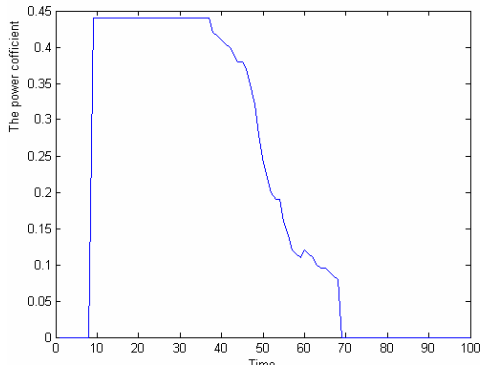


Fig.12. the power coefficient for VSWT

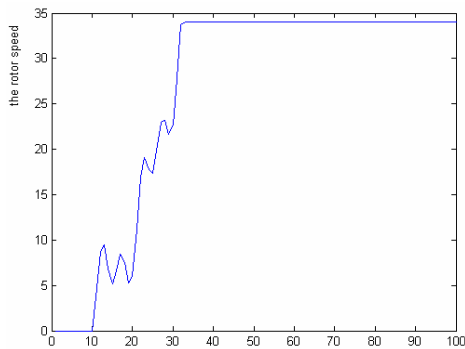


Fig.12 the rotor speed

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 bodes 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.. 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 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.

Table. 1. the Parameters of the wind turbine

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
$C_p$	0.44
$J_{wt}$ ( kg·m <sup>2</sup> )	320000
$J_g$ ( kg·m <sup>2</sup> )	60

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