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.

II. 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.

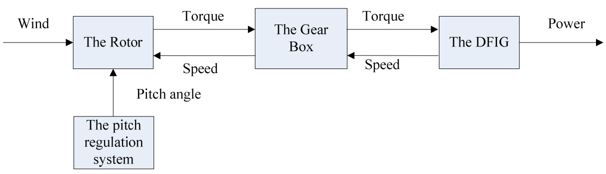

Fig.1 The block diagram of the VS wind turbine

The model of each mass is described as follows:

A. 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, 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 uses 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.

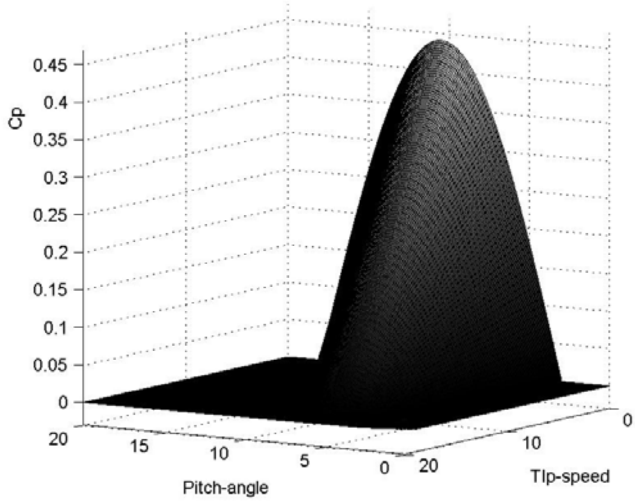

Fig.2. the graph of the power coefficient C_p

B. 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, θ_{WT} is the rotation angle of the rotor, θ_G is the rotation angle of the generator.

C. 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.

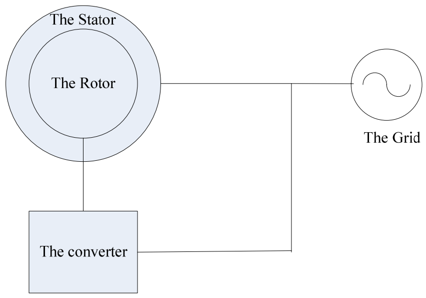

Fig.3. the topological structure diagram of DFIG

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.

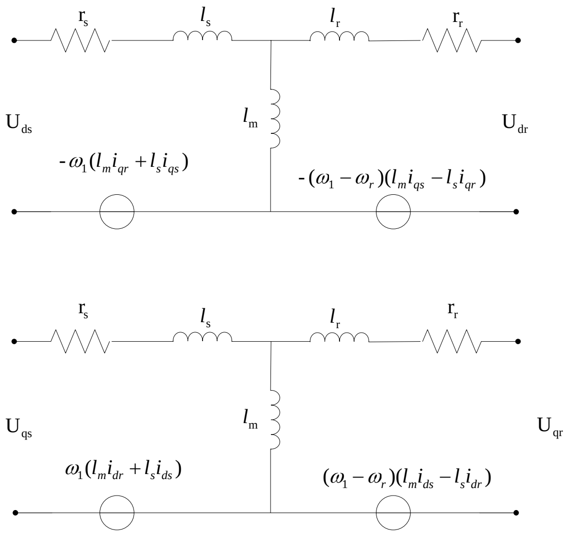

Fig.4. the DFIG equivalent circuit mode

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:

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

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

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

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

D. 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]:

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

Where β is the pitch angle, β_v is the given pitch angle, τ_β is the time constant of the pitch regulation system.

III. CONTROL OBJECT AND DESIGN OF THE CONTROL SYSTEM

A. 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

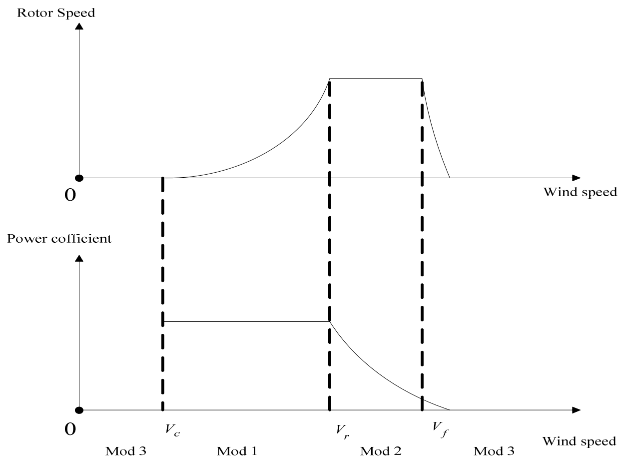

Fig.4.Operation Modes of Wind Turbine

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.

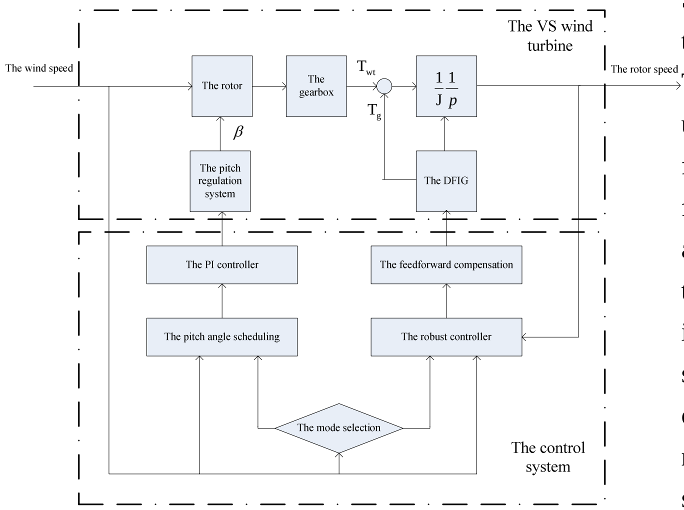

Fig.5 the controls system for the VS wind turbine

B. 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:

$$\begin{aligned} u_{dr} &= (l_r - \frac{l_m^2}{l_s})pi_{dr} + r_r i_{dr} + \Delta u_{qr} \\ u_{qr} &= (l_r - \frac{l_m^2}{l_s})pi_{qr} + r_r i_{qr} + \Delta u_{qr} \end{aligned} \quad (7)$$

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.

C. 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.

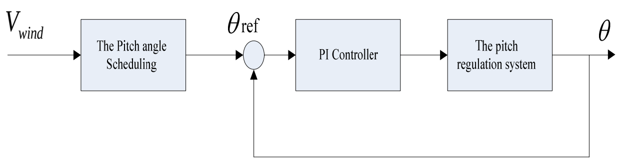

Fig.7. the block diagram of the pitch controller

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

IV. SIMULATION RESULTS

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

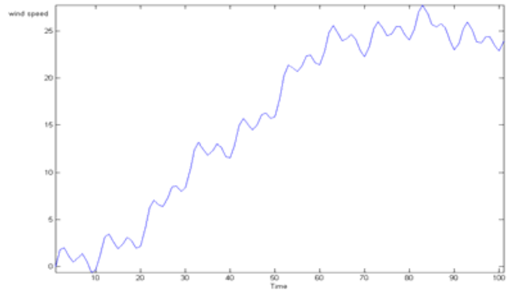

Fig.8. the wind speed

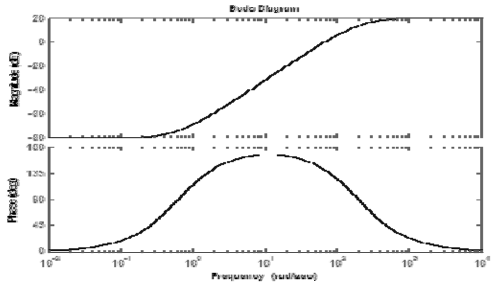

Fig.9.the bode of weight function for the wind speed

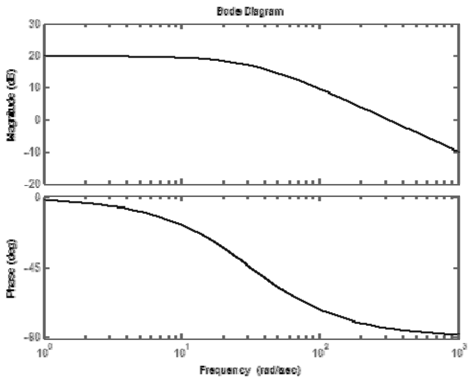

Fig.10. the bode of weight function for the noise

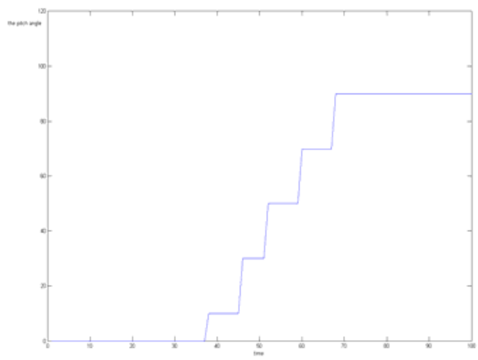

Fig.11. the pitch angle

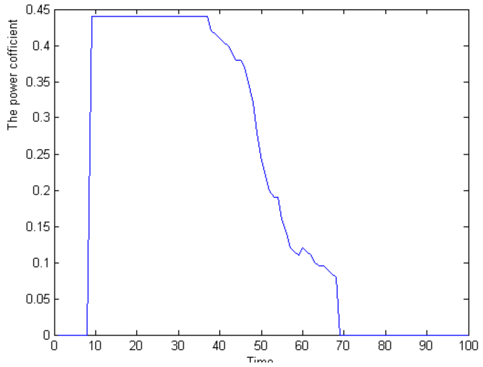

Fig.12. the power coefficient for VSWT

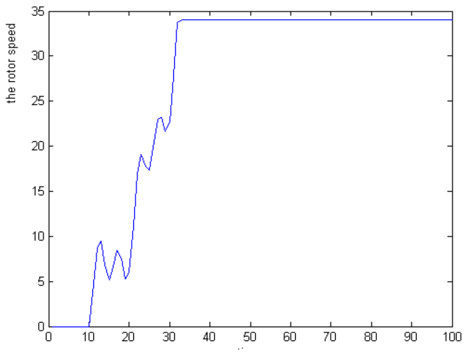

Fig.12 the rotor speed

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: $15^{\bullet}$,$30^{\bullet}$, $45^{\bullet}$,$60^{\bullet}$,$75^{\bullet}$ 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.

V. 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
Cp	0.44
Jwt((kg·m^2)	320000
Jg((kg·m^2)	60

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