ISSN : 0974 - 7451 Volume 7 Issue 4

Trade Science Inc.

Environmental Science

An Indian Journal

Current Research Paper

ESAIJ, 7(4), 2012 [138-146]

Controlling the output of a variable speed wind turbine using pitch controller

Sudipta Dey[1], A.K.Sengupta[2], Riku Chowdhury[1]*, Shuvashis Chakraborty[1], Sanjoy Kumar Nandi[3]

[1]Faculty of Science, Engineering and Technology, University of Science and Technology Chittagong, Chittagong, (BANGLADESH)

[2]Department of Electrical and Electronic Engineering, Chittagong University of Engineering & Technology (CUET), P.O.: CUET, Chittagong-4349, (BANGLADESH)

[3]Department of Physics, University of Chittagong, Chittagong-4331, (BANGLADESH)

E-mail: eeeriku@gmail.com

Received: 2nd February, 2012 ; Accepted: 28th February, 2012

ABSTRACT

Wind energy varies with year, season, and time of day, elevation above ground, and form of terrain. Because of fluctuating nature of the wind speed the variation of the output power occurs. When wind speed exceeds the rated speed of a turbine, the output power also exceeds the rated level. By controlling the pitch angle the output power of the wind turbine can be limited. The purpose of this work is to design a MATLAB\SIMULINK model of a wind turbine using pitch controller where at high wind speed region, the pitch controller will automatically active to maintain the output power at the rated level. From simulation result, it is observed that, at rated wind speed pitch angle is zero i.e. pitch controller remains inactive and above rated wind speed the pitch controller is activated and keep the output power at rated value by changing the value of pitch angle.

INTRODUCTION

The world-wide concern about the environment pollution problems and the economic benefits of fuel savings has led to increasing interest in technologies for generation of electricity from renewable sources is to use wind turbines[1]. The global market for the electrical power produced by the wind turbine generator (WTG) has been increasing steadily, which directly pushes the wind technology into a more competitive era. According to the American Wind Energy Association, the installed capacity of wind grew at an average rate of 29% per year[2]. At the end of 2009, the world wide installed capacity of wind energy was over 159 MW. The prediction capacity for 2010 is over 203 MW[3]. In order to achieve power generation for the utilities sector in the nineties, the wind turbine electric power generator technology was put in place. In their current form, wind driven power stations represent not a replacement for the conventional power station but would exist as a complement, thereby forming a part of the total electric generation mix. In principle, the wind system could replace a part of the existing conventional generation capacity. More realistically, they will cover the envisaged demands of power. This advantage leads to the wind turbine technology undergoing a revolution. Researches are being carried out in different countries to facilitate an improvement generation of power through the use of wind turbine[4]. Wind turbines mainly are of two types: Vertical-Axis (VAWT) and Horizontal-Axis

(HAWT). Vertical-Axis Wind turbines (VAWT) are typically developed only for urban deployment. Changes in wind direction have fewer negative effects on this type of turbine because it does not need to be positioned into the wind direction. However, the overall efficiency of this turbine in producing electricity is lower than Horizontal-Axis Wind turbines (HAWT). And for this reason, the Horizontal- axis wind turbine design in this work falls under this category of wind turbine. There are two types of Horizontal-Axis Wind turbines (HAWT) in the market: the constant-speed wind turbine and the variable-speed wind turbine (VSWT). Nowadays variable-speed wind turbines are becoming more common than constant-speed wind turbines. This is mainly due to its better power quality impact, reduction of stress in the turbine and the reduction of the weight and cost of the main components. The traditional fixed-speed turbines are stall regulated while the new, variable-speed wind turbines (VSWT) are pitch regulated. Pitch-adjusting variable-speed wind turbines have become the dominating type of yearly installed wind turbines in recent years[5-7]. The aerodynamic efficiency $C_p(\lambda,\beta)$ of a wind turbine is a function of tip speed ratio (λ) and pitch angle (β). With a given pitch angle, the efficiency coefficient C_p has a maximum value for a certain tip speed ratio (λ). It is thus obvious that to maximize the efficiency of the turbine, we should able to follow the wind speed. The fluctuating nature of the wind makes the variable speed turbine a nontrivial object to control. But it is required to achieve high efficiency and at the same time have a smooth power output. So, under these conditions for limiting the output power the variables to control are the electro dynamical torque and the pitch angle. This work basically based on two purposes:

(1) Modeling of a wind turbine where pitch angle is a control variable.
(2) At the high wind speed the pitch controller will automatically active to maintain the output power at the rated level.

Here, we used the specifications of VESTAS V52 wind turbine model for design purpose of VSWT model.

STRUCTURE OF A VSWT

A wind turbine must run at a certain speed relative to the current wind speed which is defined by the optimal tip-speed ratio, in order to produce maximum power. For a constant speed concept, it is not possible to get maximum efficiency due to losses which depends on exact design of the turbine and variations of wind speed at the site. An active pitch controller, which adjusts pitch angel instantaneously to the variations of wind speed, is an option to increase the efficiency of that kind of constant speed wind turbine. Unfortunately, it is not possible to utilize this advantage because of the too small bandwidth of that active pitch controller system. By introducing a variable speed operation, it is possible to continuously adapt the rotational speed to the current wind speed, so that ideally, the maximum obtainable power is continuously

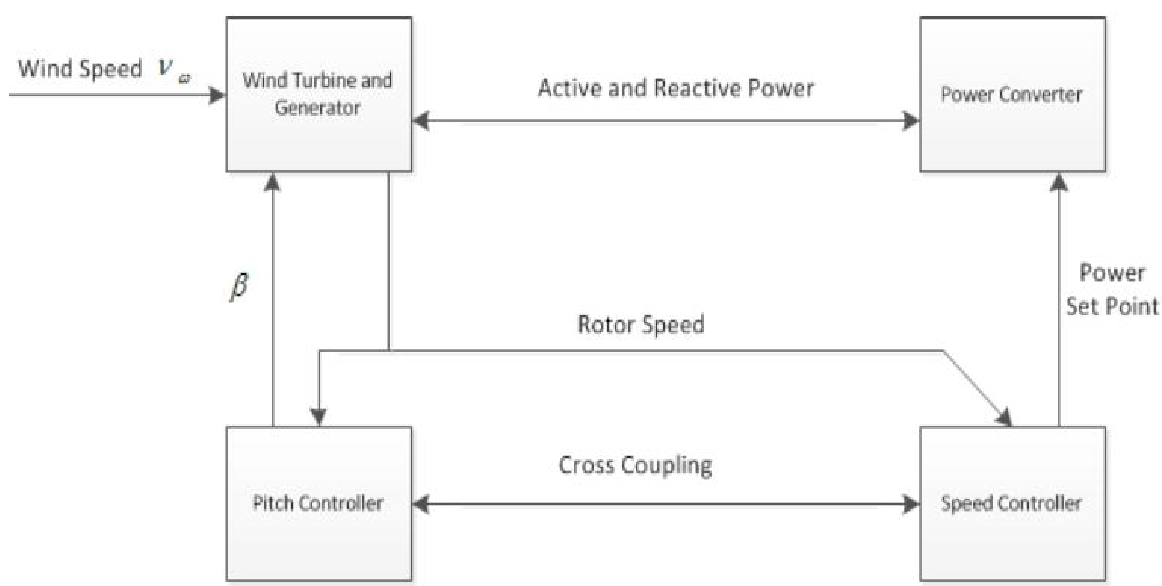

Figure 1 : Structure of a VSWT model

produced by the wind turbine. Because of this, pitch-adjusting variable-speed wind turbines have become the dominating type of yearly installed wind turbines in recent years. There are usually two controllers for the variable-speed wind turbines which are cross-coupled each other, shown as in Figure 1.

When wind speed become low below the rated value, the speed controller can continuously adjust the speed of the rotor to maintain the tip speed ratio constant at the level which gives the maximum power coefficient, and then the efficiency of the turbine will be significantly increased. Pitch angle regulation is required in conditions above the rated wind speed when the rotational speed is kept constant. Small changes in pitch angle can have a dramatic effect on the power output[8-10]. So, the pitch angle control is required to –

- Maintain the maximum output power when wind speed below the rated value by adjusting the pitch angle at its optimum value.
- Providing a very effective means of regulating the aerodynamic power above rated wind speed.
- Minimize the fatigue loads of the turbine mechanical component.

POWER CAPTURE AND CHARACTERISTICS OF VSWT

Wind turbine produces electricity by using the natural power of the wind to drive a generator. The wind is a clean sustainable fuel source, it doesn't create emissions and will never run out as it is constantly replenished by energy from the sun. Although there are many different configurations of wind turbine systems they all work in the same way. The available power originates from the mass flow of the moving air, referred to as the wind speed. The transformation to mechanical torque is done by aero dynamical forces acting on the rotor blades, the actuator disc. The wind turbine shaft then transports the power to the generator which is connected to the electrical grid. Usually there is a gear box between the slowly rotating turbine shaft and the more rapidly rotating generator shaft[11].

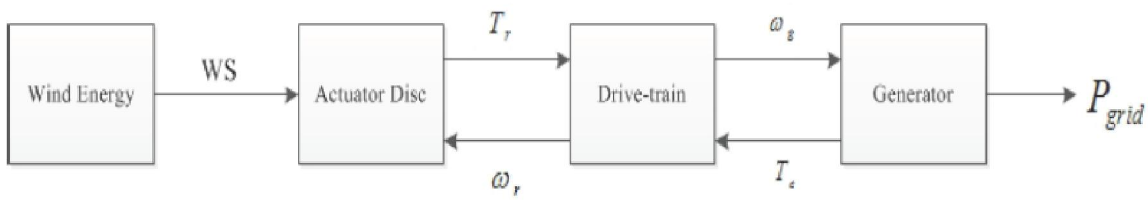

Figure 2 : Power extraction block of a VSWT

From a physical point of view, the static characteristics of a wind turbine rotor can be described by the relationships between the total power in the wind and the mechanical power of the wind turbine. These relationships are readily described starting with the incoming wind in the rotor swept area. It can be shown that the kinetic energy of a cylinder of air of radius R traveling with wind speed V_w corresponds to a total wind power wind P_w within the rotor swept area of the wind turbine. This power in the wind can be expressed as

$$P_w = \frac{\rho}{2}(\pi R^2)C_P(\lambda,\beta)(V_w)^3 \qquad (1)$$

Where, ρ is the density of air; R is the rotor radius; C_p is the Power coefficient; V_W is the wind speed

And the expression for power coefficient is given by,

$$C_P = 0.5\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-21}{\lambda_i}} \qquad (2)$$

Where, $\lambda_i = \frac{1}{\lambda + 0.088} - \frac{0.035}{\beta^3 + 1}$; β is the pitch angle of blade; λ is the tip speed ratio

It is not possible to extract all the kinetic energy of the wind, since this would mean that the air would stand still directly behind the wind turbine. The wind speed is only reduced by the wind turbine, which thus extracts a fraction of the power in the wind. This fraction is determined by the power efficiency co-efficient, C_p, of the wind turbine. The mechanical power, P_{mech}, of the wind turbine is therefore, obtain by the following equation

$$P_{mech} = C_P \times P_w \qquad (3)$$

However, it is theoretically possible to extract approximately 59% of the kinetic energy of the wind. This is known as Beltz's limit. Optimum C_p value lies between 0.52-0.55 for modern three-bladed wind turbines when measured at the hub of the turbine[12].

It is clear from a physical point of view that the power, P_{mech}, that is extracted from the wind will depend on rotational speed, wind speed and blade angle, β. Therefore, P_{mech} and hence also C_p must be expected to be functions of these quantities. That is,

$$P_{mech} = f_{Pmech}(\omega_{urb}, V_w, \beta) \quad (4)$$

From the simple geometric considerations, which ignore the wind turbulence created by the blade tip show that the angle of incidence ϕ is determined by the incoming wind speed V_w and the speed of the blade. The blade tip is moving with speed V_{tip}, equal to ω_{turb} R. This is illustrated in Figure 3.

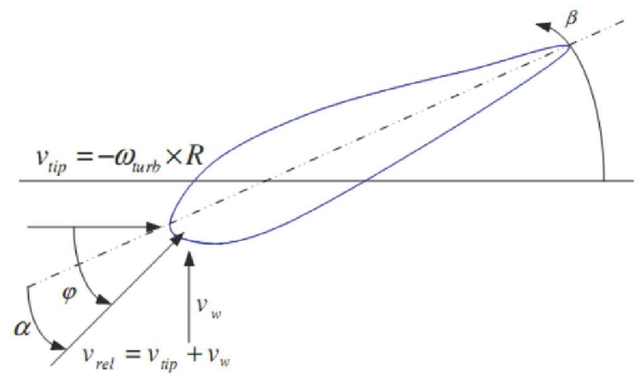

Figure 3 : Blade element velocities at blade cross-section.

Another commonly used term in the aerodynamics of the wind turbines is the tip-speed ratio, λ, which is defined by:

$$\lambda = \frac{\omega_{turb} R}{v_w} \quad (5)$$

The highest values of C_p are typically obtained for λ values in the range around 8-9. This means that the angle between the relative air speed-as seen from the blade tip-and the most rotor plane is rather a sharp angle. Therefore, the angle of incidence φ can be calculated as:

$$\varphi = \tan^{-1}\left(\frac{1}{\lambda}\right) = \tan^{-1}\left(\frac{v_w}{\omega_{turb} R}\right) \quad (6)$$

It is possible to adjust the pitch angle β of the entire blade through a servo mechanism.

If the blade is turned, the angle of attack α between the blade and relative wind V_{rel} will be changed accordingly. So the energy extraction will depend on the angle of attack α between the moving rotor blades and the relative wind speed V_{rel} as seen from the moving blades. It follows that, C_p can be expressed as a function of λ and β.

$$C_P = f_{CP}(\lambda, \beta) \quad (7)$$

C_p is a highly non-linear power function of λ and β. Now, if the λ - C_p curve is Known for a specific wind turbine with a turbine rotor radius R it is easy to construct the curve of Cp against the rotational speed for any wind speed V_w. Therefore, the optimal operational point of the wind turbine at a given wind speed wind V_w is determined by tracking the rotor speed to the point λ_{opt}. Then the optimal turbine rotor speed become

$$\omega_{turb} = \frac{\lambda_{opt} v_w}{R} \quad (8)$$

Thus any change in the rotor speed or the wind speed induces change in the tip speed ratio leading to power coefficient variation. In this way, the generated power is affected. Figure 4 shows a group of typical C_p -λ curves where optimum values of tip speed ratio, λ_{opt}, correspond to the maximum power coefficient, C_{pmax}.

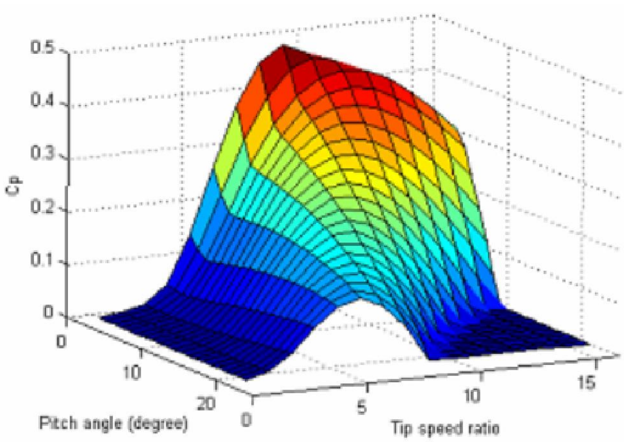

Figure 4 : Power coefficient characteristics curve

The optimal rotational speed for a specific wind speed also depends on the turbine radius, R, which increases with the rated power of the turbine. Therefore, the large rated power of the wind turbine the lower the optimal rotational speed. These basic aerodynamic equations of the wind turbines provide an understanding that fixed-speed wind turbines have to be designed in order for the rotational speed to match the most likely wind speed in the area of installation. In the case of variable-speed wind turbines, the rotational speed of the wind turbine is adjusted over a wide range of wind speeds so that the tip-speed ratio λ is maintained at λ_{opt}. Therefore, C_p reaches its maximum and consequently, the mechanical power output from a variable-speed wind turbine will be higher than that of a similar fixed-speed wind turbine over a wider range of wind speeds. At higher wind speeds, the mechanical power is kept at the rated level of the wind turbine by pitching the turbine blades. There are two possibilities for doing this-either out of the wind or up against the wind:

(1) When the blades are turned out of the wind, the lift on the blades is gradually reduced. This is called pitch control and requires a relatively large change in pitch angle to reduce power significantly.

(2) If the blades are turned up against the wind, the turbine blades will stall and thus automatically reduce the lift on the turbine blades. This effect is obtained with a relatively small change in pitch angle. This is called stall control and requires a more accurate control of the pitch angle because of the high angular sensitivity.

The typical power control regions of wind turbine are shown in Figure 5. The turbine starts operating when the wind speed exceeds cut-in wind speed. The power captured by the turbine increases with the wind speed increasing. At the set point of wind speed, the generating power reaches the rated power of the turbine. If the wind speed continues to rise, the generator output power remains constant at the design limit. Due to safety consideration, the turbine is shut down at speeds exceeding cut-out wind speed.

The typical power control operation of VSWT can be divided into three regions which are shown in Figure 5.

R-1: [V_{cut-in} to V_n] Area where turbine operating at variable speed with an optimal rotor speed giving maximum ratio when wind speed is between the cut-in speed and the rated speed:

R-2: [V_n to V_o] Operating at rated rotor, but below the rated power.

R-3: [V_o to $V_{cut-off}$] Turbine running at full rated power and rated speed. Pitch controller active.

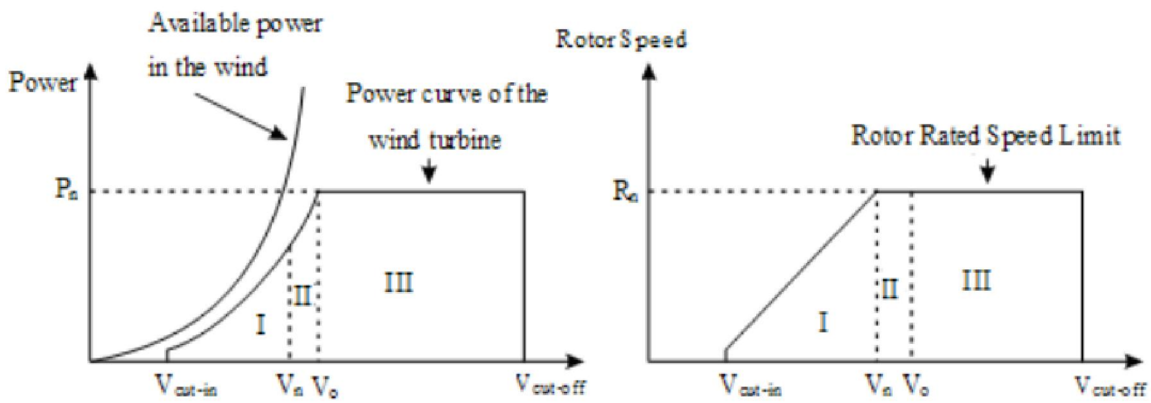

Figure 5 : Operation regions of wind turbine

AERODYNAMIC POWER CONTROL STRATEGY OF VSWT

At high wind speeds it is necessary to limit the input power to the turbine, i.e., aerodynamic power control. There are three major ways of performing the aerodynamic power control, i.e. by stall, pitch or active stall control. Stall control implies that the blades are designed to stall in high wind speeds and no pitch mechanism is thus required.

Pitch control is the most common method of controlling the aerodynamic power generated by a turbine rotor, for newer large wind turbines. In this method, there is a mechanism to physically turn the blades around their longitudinal axes. At low wind speed a control system will use this feature to maximize energy extracted from the wind[13]. In the area of high wind speed, the desired operation is to keep the rotor speed and especially the generated power as close as possible to the nominal. To reduce the surplus energy, we using the blades pitching as a main power control in this area[14]. The pitch angle controller is only active after region 3. when 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[15]. According to different wind speed point, fixed pitch angle is given. There are two advantages for using this scheduling. One of them is saving the time and device to calculate the pitch angle for every wind speed and another one is, gives enough time make the pitch regulation system to reach its destination. The block diagram of this controller is shown in Figure 6. A PI controller corrects the error between the actual pitch angle and the reference.

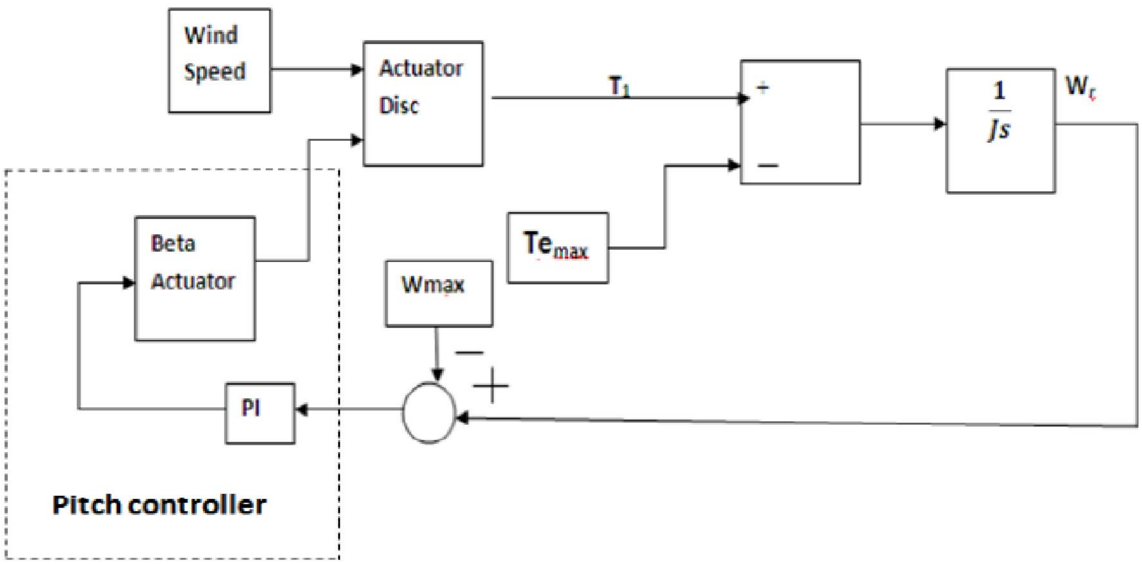

Figure 6 : Pitch control scheme.

MODELING AND SIMULATION RESULT OF VSWT

In this paper, for modeling of VSWT we used the specifications of VESTAS-V52 wind turbine with considering all necessary basic assumptions of wind turbine modeling. The parameter values of VESTAS-V52 model are given in TABLE 1.

TABLE 1 : The specifications of V52 wind turbine[4].

Rotor diameter	52 m
Area swept	2,124m^2
Number of blades	3
Power regulation	Pitch\optimal speed
Air brake	Full blade pitch
Cut-in wind speed	4m\s
Nominal wind speed	16m\s
Cut-out wind speed	25m\s
Nominal output	850kw

By using MATLAB/SIMULINK, a VSWT model has been designed in this paper which is shown in figure 7.

In figure 8, the overall VSWT controlling model by pitch controller has been designed. During the higher wind speed the torque or power can easily be limited to its rated value (W_r) by adjusting the pitch angle β which is controlled by beta actuator. When the power output becomes too high, it requested the blade pitch mechanism to immediately turn the blades slightly out of the wind. When the wind speed is less strong, the blades are turned back into the most effective position.

For VESTAS V52 VSWT model, a flow chart is shown in Figure 9 to draw the C_p Vs λ curve with different value of pitch angle β and the power coefficient surface those are shown in Figure 10 and Figure 11 respectively.

The simulation results obtained from the designed VSWT model are given in TABLE 2 (for various wind speed).

From simulation result, we observed that, at rated wind speed pitch angle (β) is zero i.e. pitch controller remains inactive. But when the VSWT running above rated wind speed, the PI controller sending information to the beta actuator to change the pitch angle. By changing the pitch angle, the power coefficient reduced

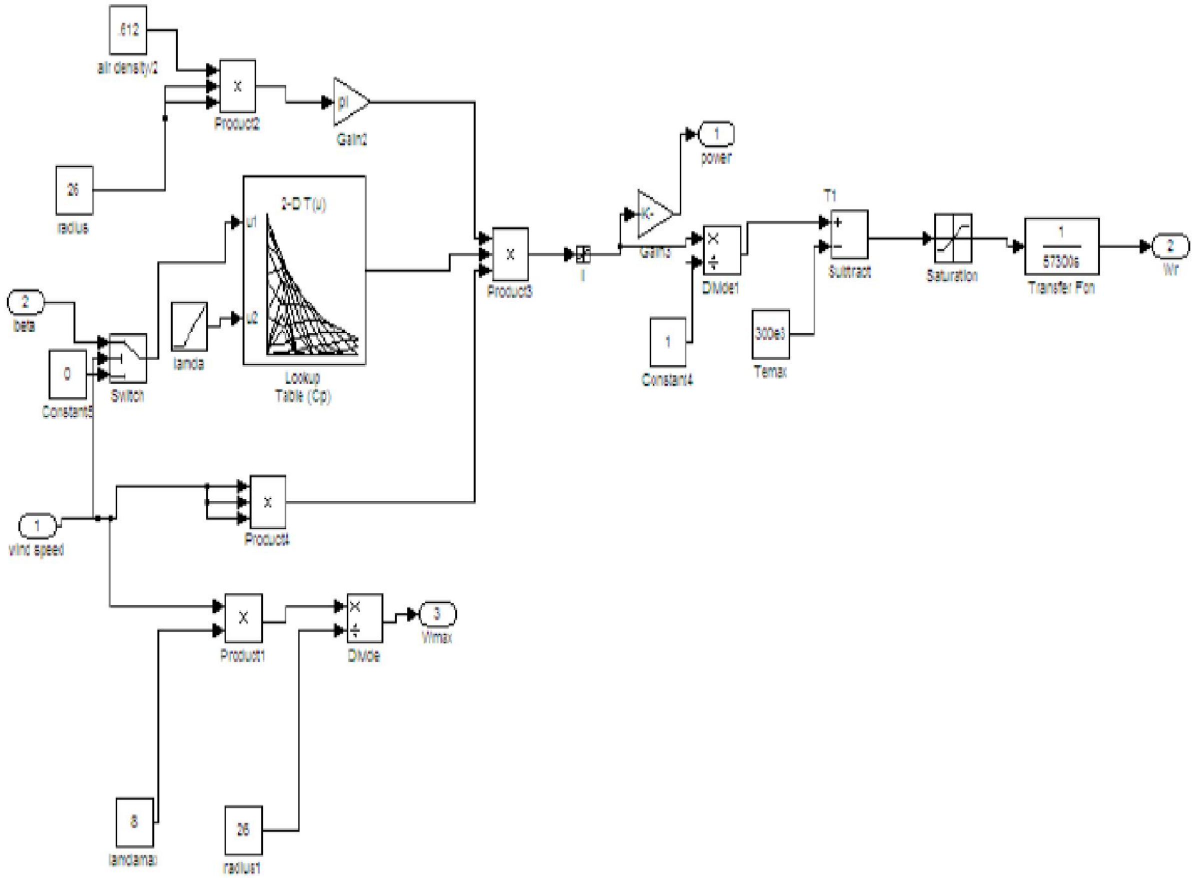

Figure 7 : Wind turbine model

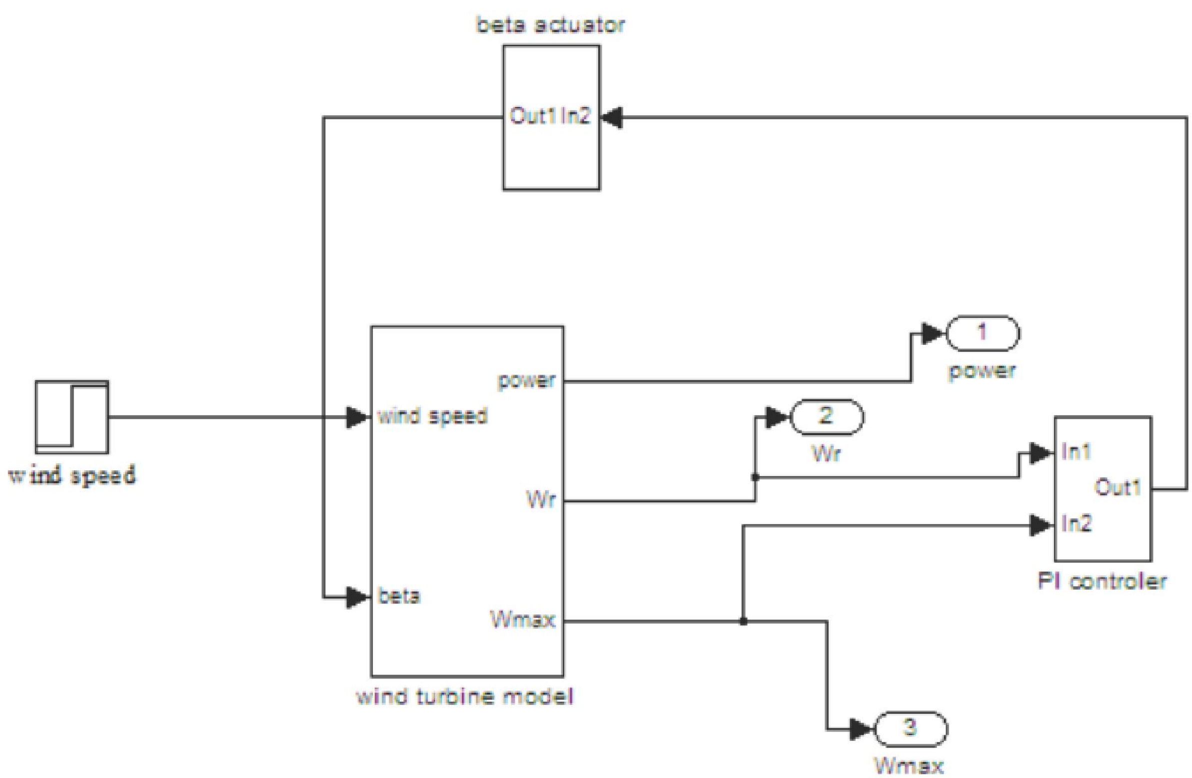

Figure 8 : Wind turbine model with pitch controller

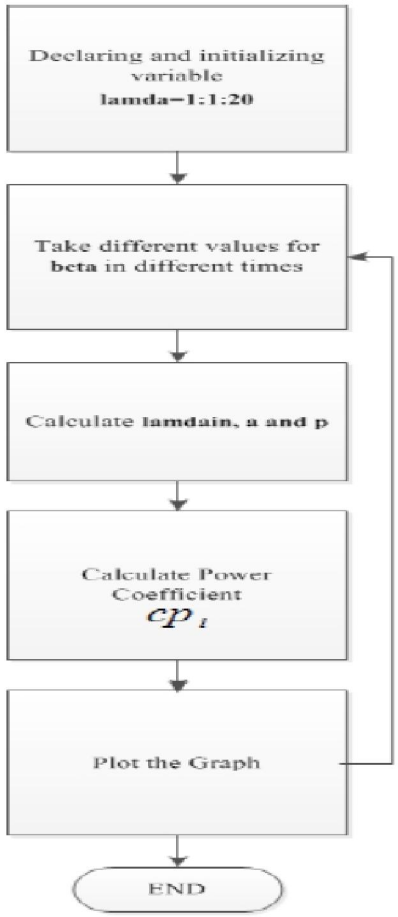

Figure 9 : Flow chart for VESTAS V52 VSWT model simulation

TABLE 2 : Simulation result

Wind speed (m/s)	Pitch angle (degree)	C_p	Power (pu)
16(rated)	0	0.1195	1
17	6.22	0.1138	1
19	12.98	0.11	1

to maintain the output power at rated value which indicates that the designed control system for VSWT performs well.

CONCLUSION

At high wind speed region the fatigue damage of the mechanical parts of the wind turbine can be occurred due to high level of output power. To overcome this problem, a pitch controlling model for VSWT was established in this paper. By using pitch controller the output power has been limited at high wind speed and wind turbine can operate safely. The simulation results has been shown that at the wind speed above the rated speed of the turbine the pitch controller automatically activate and limiting the output power by increasing the pitch angle. In this paper, a step input was used to simulate VSWT model. By using real wind field data for the simulations, a better accuracy for the model will be achieved.

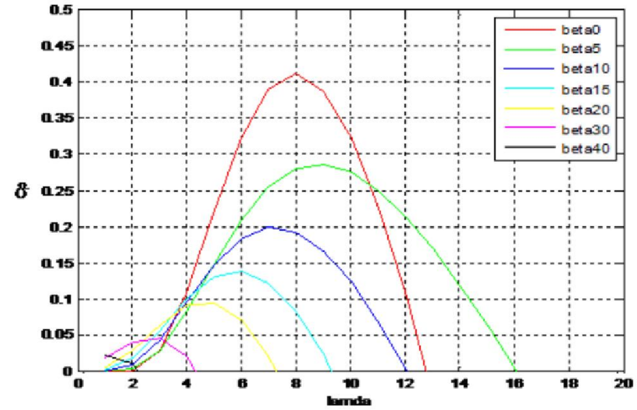

Figure 10 : Cp vs lamda curve with different value of beta

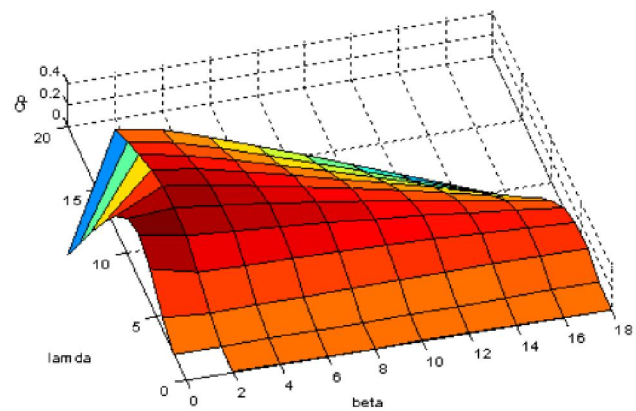

Figure 11 : Power coefficient surface

REFERENCES

[1] O.Kanna, S.Hanba, S.Asato, et al.; Trans.IEE, **117-B(12)**, 1513-1519, Jan., **(1997)** (in Japanese).

[2] L.Y.Pao, K.E.Johnson; A Tutorial on the Dynamics and Control of Wind Turbines and Wind Farms, Proc. Amer.Ctrl.Conf., June **(2009)**.

[3] World Wind Energy Association; World Wind Energy Installed Capacity. Available: http://www.wwindea.org, Accessed 1 April, **(2010)**.

[4] Gary L.Johnson; Wind Energy Systems. Englewood Cliffs, New Jersy: Pretice-Hall Inc., **(1985)**.

[5] E.Muljadi, C.P.Butterfield; IEEE Trans.Ind.Appl., **37(1)**, 240-246 **(2001)**.

[6] J.L.Rodriguez-Amenedo, S.Arnalte, J.C.Burgos; IEEE Trans.Energy Convers., **17(2)**, 279-284 **(2002)**.

[7] A.Miller, E.Muljadi, D.S.Zinger; IEEE Trans. Energy Convers., **12(2)**, 181-186 **(1997)**.

[8] T.Burton, D.Sharpe, N.Jenkins, E.Bossanyi; Wind Energy Handbook, John Wiley & Sons Ltd, Chichester, UK, **(2001)**.

[9] DNV/Risø; Guidelines for Design of Wind Turbines, 2nd Edition, Jydsk Centraltrykkeri, Denmark, **(2002)**.

[10] S.Suryanarayanan, A.Dixit; Control of Large Wind Turbines: Review and Suggested Approach to Multivariable Design, Proc. of the American Control Conference, Portland, USA, 686-690 **(2005)**.

[11] Mika Rasila; Torque and Speed Control of a Pitch-Regulated Wind Turbine, Masters Thesis, Chalmers University of Technology, Göteborg, Sweden, **(2003)**.

[12] T.Ackermann, (Ed); Wind Power in Power Systems. West Sussex: John Wiley and Sons Ltd., **(2005)**.

[13] T.Burton, D.Sharpe, N.Jenkins, E.Bossanyi; Wind Energy Handbook, West Sussex: John Wiley and Sons Ltd., **(2001)**.

[14] W.E.Leithead, S.A.De La Salle, D.Reardon; Int. Journal Control, **55(4)**, 8455876 **(1992)**.

[15] A.J.G.Westlake, J.R.Bumby, E.Spooner; IEE Proc.-Elect.Power Appl., **143(3)**, 269-280, May **(1996)**.