Pitch Control for Variable Speed Wind Turbines

A. I. Roussos, V. E. Ntampasi and O. I. Kosmidou
Department of Electrical and Computer Engineering, Democritus University of Thrace, GR-67100 Xanthi, Greece

Keywords: Wind Turbine, Power Coefficient, Power Extraction, Pitch Control, PID Control.

Abstract: The main thrust of this paper is to present an efficient method for the pitch control of large scale wind turbines. After an investigation in wind turbine working regions, the “optimum” working levels are determined. A PID controller is designed based on the Ziegler – Nichols method. By appropriately tuning the controller gains, the proposed controller ensures achieving a rapid convergence to the extracted power set point with the minimum of fluctuations even in extreme wind conditions.

1 INTRODUCTION

Wind energy is one of the most promising sources of electrical energy in years to come. Modern wind farms can produce serious amounts of energy without catastrophic climate issues, such as green house gas emissions. Hence, a serious research over the wind turbines is required nowadays more than ever before (Asharif et al., 2011).

However, wind energy has to overcome some technical as well as economical barriers, if it should produce a substantial part of electricity. There are several ways to control a wind turbine system (Munteanu et al., 2008). Pitch, passive stall, active stall and yaw control techniques are some of them.

The pitch control system monitors constantly the extracted power; the controller is designed to regulate the pitch angle such that a desired power amount is obtained from a given level of wind energy. On the other hand, the main characteristic of a passive stall control system is that the wind turbine blades are placed steady on the rotor. Their geometry allows the wind to turn the rotor, provided it remains within a desired range. If not, an amount of friction is developed at the side of the blade opposite to the wind flow and that makes the wind turbine to decelerate (Strazisar and Bright, 2004).

In yaw control systems the rotational speed and power output are regulated by the whole rotor mechanism (Hansen, 2008). This technique is used for small wind turbines of 1kW rated power or less. Large wind turbines with yaw control would be subjected to cyclic stresses that could lead to the failure of the entire structure. Finally, the active stall control systems (Leinhos et al., 2002) differ from the pitch control systems in that their control method uses the gradation of the pitch angle. For low values of the wind the two approaches work in the same way. However, when the generator of a wind turbine with active stall control reaches its set point, the system turns the blades in the opposite direction with respect to the one of the pitch control system. Hence, the control system increases the blades angle of attack in order to decelerate the rotor and thus wasting the excess of wind energy.

In the next sections, PID control schemes are studied for the pitch control of wind turbines. The paper is organized as follows: In Sections 2, 3 the aerodynamic energy conversion as well as the system description are given. The proposed controller design is presented in Section 4 and compared with previous control techniques via simulation in Section 5. Finally Section 6 provides concluding remarks.

2 POWER CAPTURE OF WIND TURBINES

In order to construct an efficient controller, it is necessary to investigate the way the wind turbine converts the wind energy into mechanical energy. Furthermore, a research on the turbine’s working regions is needed in order to achieve the maximum power extraction in every wind scenario.

I. Roussos A., E. Ntampasi V. and I. Kosmidou O..
Pitch Control for Variable Speed Wind Turbines.
DOI: 10.5220/0004391000430049
In *Proceedings of the 10th International Conference on Informatics in Control, Automation and Robotics* (ICINCO-2013), pages 43-49
ISBN: 978-989-8565-70-9

2.1 Power Coefficient

Through the blades of the wind turbine an amount of wind energy is converted to electrical power. The mechanical torque P_m produced by the wind turbine axis is (Zhang et al., 2008)

$$P_m = 0.5 \times \rho \times A \times C_p(\lambda, \beta) \times U_w^3 \qquad (1)$$

The parameters in (1) denote

- ρ: the air density
- A: the area swept by blades
- U_w : the wind speed and
- C_p : the power coefficient with
- λ: the tip speed ratio and
- β: the blade pitch angle.

The tip speed ratio is defined as the ratio between the blade tip speed and the wind speed

$$\lambda = \frac{V_{tip}}{V_w} = \frac{R \times \omega_r}{V_w} \qquad (2)$$

with

- ω_r : the rotor speed and
- R: the radius of the wind turbine blade.

Equation (1) is valid when the airflow is constant, but in practice this is not the case. In fact, the steep alternations of wind produce power deviation from its expected value.

The power coefficient C_p represents the percentage of the kinetic energy that is contained in the wind and rotates the wind turbine blades. The value of C_p depends on the factors λ and β. Its upper theoretical bound, called Betz limit is equal to 0.593. In actual situations the Betz limit varies into the range [0.4, 0.5] and depends on the wind turbine type. The dependence of the power coefficient on λ and β is shown in Fig. 1.

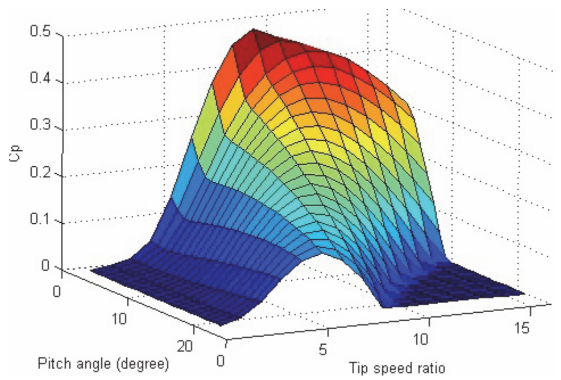

Figure 1: Power coefficient 3D curve.

Several studies (Ackermann, 2005) have shown that in variable speed wind turbines the "optimal" mechanical power is obtained whenever the turbine works with the maximum Cp. Besides, the maximum value of Cp is obtained for a specific value of tip speed ratio λopt. Obviously, the mechanical torque (1) is later converted into electrical torque.

2.2 Maximum Power Extraction

In order to achieve the optimal power extraction operation points for a wind turbine system one has to follow a procedure related to λ: In equation (2) the value of λ is kept constant and then, for each wind speed value, the optimal rotor speed is calculated (Zhang et al., 2008). The mathematical model used is

$$T_m = \frac{P_m}{\omega_r} \qquad (3)$$

and has the internal mechanical torque T_m as input.

In Fig. 2 the T_m waveforms for different wind speeds ω_r are illustrated. The maximum power for each waveform is achieved when the product T_m ω_r is maximized, as well. Relating all points of maximum power one can create the dashed waveform shown in the right bottom of Fig. 2. Obviously, the control action should ensure the wind turbine to work as close as possible to the dashed waveform, in order to achieve the maximum power extraction.

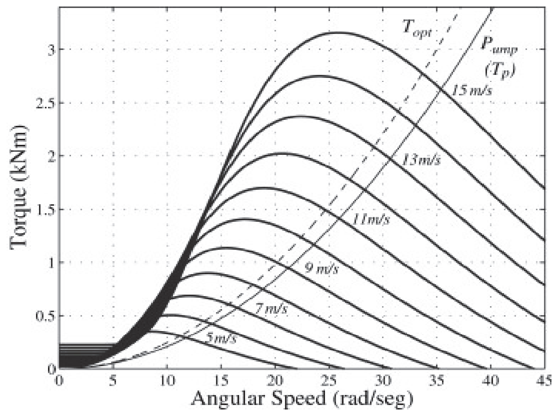

Figure 2: Wind turbine rotor torque - speed waveforms.

In real life cases the dashed waveform is used only for low power values. For upper power values the system should protect itself by limiting the rotor speed under its set points. The proposed operation waveform for the wind turbine under consideration is illustrated in Fig. 3. One can observe that the dashed waveform in Fig. 3 is composed from (i) an initial region with low incline that follows the optimal power extraction (ii) the steep region that limits the rotor speed up to 100 rpm and (iii) the horizontal region where the controller takes action and decelerates the system.

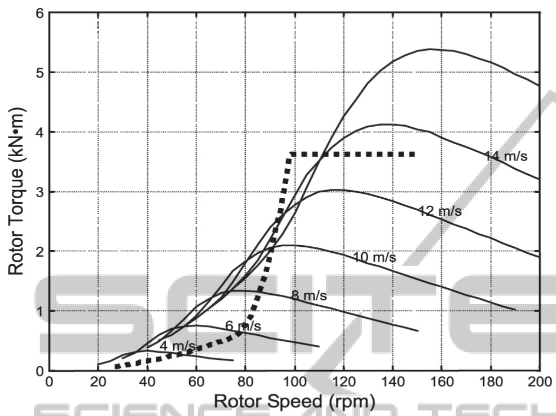

Figure 3: Proposed wind turbine rotor torque - speed waveform.

3 MODEL DESCRIPTION

A variable speed wind turbine is generally composed of several components, namely the wind model, the rotor, the gearbox and the generator that are described in this section.

3.1 Wind Model

Wind speed is calculated as an average of the fixed-point wind speed over the whole rotor; the tower shadow and rotational turbulences are also taken into account. The component of main importance in this model is the normally distributed white noise generator. A problem that occurs when using white noise generators is that different simulation tools use different algorithms and thus different wind time series are obtained. In order to overcome this drawback, a normally distributed white noise generator has been implemented in (Marsaglia and Tsang, 2000); it is based on the Ziggurat Algorithm and uses the so-called ‘C’ S-Function.

The simulation wind model depends on the following parameters:

- Average Wind Speed: 10 m/s
- Length Scale: 600 m
- Wind Turbulence Intensity: 30% or 50%

3.2 Wind Turbine Rotor

The rotor is a component that extracts the energy from the wind and converts it into mechanical energy (Slootweg et al., 2003). The aero-turbine model has two inputs, namely the wind speed and pitch angle. The following parameter values have been used to extract the internal mechanical torque.

- Blade Radius: 22.5 m
- Air Density: 1.25 Kg/m^3
- Cut In Speed: 3 m/sec
- Cut Out Speed: 25 m/sec

Besides, numerical approximations for given values of λ and β (Ackermann, 2002) have been used to calculate the power coefficient C_P. More precisely,

$$C_p\left(\lambda,\beta\right) = 0.73\left(\frac{151}{\lambda_i} - 0.58\beta - 0.002\theta^{2.14} - 13.2\right)e^{-18.4/\lambda_i} \quad (4)$$

with

$$\lambda_i = \frac{1}{\frac{1}{\lambda - 0.002\beta} - \frac{0.003}{\beta^3 + 1}} \quad (5)$$

3.3 Gearbox

At this step the low angular speed produced by the wind turbine rotor is converted into high speed in order to reach the generator nominal values (Iov et al., 2004). The gearbox is a two-mass model as shown in Fig. 4. Let T_{wtr} and T_{gen} be the corresponding rotor and generator torques.

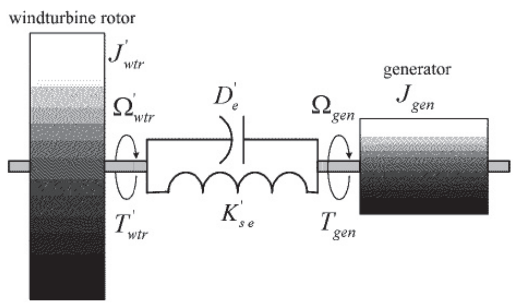

Figure 4: Two-mass gearbox.

The dynamic equations of the drive-train written on the generator side are

$$\dot{T}_{wtr} = \dot{J}_{wtr}\frac{d\dot{\Omega}_{wtr}}{dt} + \dot{D}_e\left(\dot{\Omega}_{wtr} - \Omega_{gen}\right) + \dot{k}_{se}\left(\dot{\theta}_{wtr} - \theta_{gen}\right) \quad (6)$$

$$\frac{d\dot{\theta}_{wtr}}{dt} = \dot{\Omega}_{wtr} \tag{7}$$

$$\begin{aligned} -T_{gen} &= J_{gen} \frac{d\Omega_{gen}}{dt} + \dot{D}_e \left(\Omega_{gen} - \dot{\Omega}_{wtr}\right) + \\ &+ \dot{k}_{se} \left(\theta_{gen} - \dot{\theta}_{wtr}\right) \end{aligned} \tag{8}$$

$$\frac{d\theta_{gen}}{dt} = \Omega_{gen} \tag{9}$$

where the equivalent stiffness is given by

$$\frac{1}{\dot{k}_{se}} = \frac{1}{\frac{k_{wtr}}{k^2_{gear}}} + \frac{1}{k_{gen}} \tag{10}$$

and the equivalent moment of inertia for the rotor is

$$\dot{J}_{wtr} = \frac{1}{k^2_{gear}} J_{wtr} \tag{11}$$

where

- Moment of inertia (Electric Machine Side): J_{gen} = 90 kg*m^2
- Moment of inertia (Turbine Rotor Side): J_{wtr} = 49.5*10^5 kg*m^2
- Shaft Stiffness: k_{se} = 114*10^6 N*m/rad
- Damping Coefficient of Shaft: D_e = 755.658*10^3 N*m*sec/rad
- Gearbox Ratio: 83.531

3.4 Generator

The generator of the wind turbine under consideration is a squirrel cage induction machine with deep bar effect (Boukhezzara et al., 2007). The generator has two inputs, namely the angular velocity from the gearbox Ω_{gen} and an amount of voltage from the electric network required to start working. The nominal value of the generator extracted power is 2 MW.

The parameters of the generator are:

- Rated Voltage per Phase: 960 Volts
- Rated Current per Phase: 1310 A
- Base Frequency: 50 Hz
- Number of Polar pairs: 2
- Starting Current: 8.8 A
- Phase angle at Standstill: 79.5 deg.
- Stator Resistance: 0.005 Ohm
- Stator self-induction: 4.074*10^{-4} H
- Rotor Resistance: 0.0089 Ohm
- Rotor Self-Induction: 2.992*10^{-4} H

4 PID CONTROLLER DESIGN

The controller design of a wind turbine requires determining the physical quantities to be taken into account i.e. wind speed, mechanical torque of the rotor, angular speed of the machine and the amount of extracted power. In our approach the extracted power has to converge to its set point. Besides, the fact that the wind speed is of crucial importance to the wind turbine operation makes the controller construction quite difficult, since wind speed is a non-linear variable transferred into the system. Thus, the controller should take into account the wind speed and continuously adjust the blades such that the stability of the wind turbine system is guaranteed.

PID control is one of the most popular methods in controlling systems as wind turbines. Such controllers are developed either independently or as a combination with other methods (Ebrahim et al., 2010). Recall that the transfer function of the PID controller has the form

$$G_c(s) = K_P + K_D s + \frac{K_I}{s} \tag{12}$$

where K_P, K_D and K_I denote the proportional, derivative and integral gains to be determined during the design procedure.

4.1 PID Controller Tuning

There is no standard algorithm for tuning of the PID controller parameters (Hara et al., 2006). The most popular of the proposed experimental methods is the well known Ziegler – Nichols rule (Ziegler et al., 1942). It is performed by first setting the integral and derivative gains to zero. Then, the proportional gain K_P is increased (starting at zero) until it reaches the ultimate value K_u for which the output of the control loop oscillates with a constant amplitude. The value K_u and the oscillation period T_u are used to set the PID controller gains, for a specific type of controller, according to Tab. 1.

For the wind turbine model described in Section 3 it was found that K_u = 3.33 and T_u = 2.65sec. According to Tab.1, the values of the PID gains are: K_P = 2, K_I = 1.51 and K_D = 0.66. Since the above method is an experimental one, the gain values can be further improved for the system under consideration. Improved gain values should lead to more accurate closed-loop performances and, in some sense, "optimize" the control action. Since in this procedure it is not possible to keep constant two of the gains and adjust the third one, one needs to find a combination of adjustments in order to achieve the "optimal" tuning.

Table 1: Ziegler - Nichols method.

Control Type	K_P	K_I	K_D
P	$K_u/2$	-	-
PI	$K_u/2.2$	$1.2K_p/T_u$	-
Classic PID	$0.6K_u$	$2K_p/T_u$	$K_pT_u/8$
Pessen Integral Rule	$0.7K_u$	$2.5K_p/T_u$	$0.15K_p/8$
Some overshoot	$0.33K_u$	$2K_p/T_u$	$K_pT_u/3$
No Overshoot	$0.2K_u$	$2K_p/T_u$	$K_pT_u/3$

In the light of the above observations, the system's operation has been tested with gain value sets obtained from the "optimal" tuning. More precisely, the gain values have been adjusted by considering that the wind model follows the same wind curve. It has been found that for $K_P = 2$, $K_I = 0.01$ and $K_D = 2$ the power extraction curve was converging tightly to its reference value.

4.2 Controller Description

The block diagram of the closed-loop system is given in Fig. 5. The look-up table and PID controller blocks are created for the control design of the wind turbine.

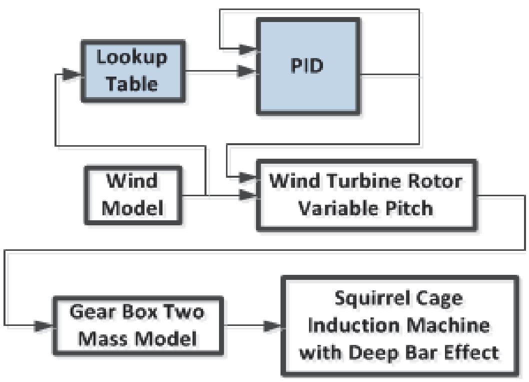

Figure 5: Wind turbine simulation model.

The look-up table block is used to determine the appropriate pitch angles with input the real-time wind value as described in Section 2.2.

The PID controller block contains the blocks necessary to create the controller resulting from the gain value tuning of Section 4.1.

5 SIMULATION RESULTS

The wind turbine under consideration has been simulated in the Matlab® Simulink programming environment using the Wind Turbine Blockset (WTB) Toolbox (Iov et al., 2004). For the simulation purposes, the PID controller design proposed in Section 4.1 has been compared with (i) the PID controller resulting according to the Ziegler – Nichols rules and (ii) the one proposed in the literature and called from here on "initial PID". More precisely, in (Abbas and Abdulsada, 2010) a PID controller has been designed by using the rotational speed to control the wind turbine performance. In order to assess the controller performance, the root mean square error between the actual rotational speed and the desired one indicated the capability of the controller to reject the wind speed fluctuations. The PID controller parameters tuned according this approach were: $K_P = 15$, $K_i = 20$ and $K_d = 0.1$.

5.1 Wind Waveforms

The performance of the three abovementioned controllers has been tested for both, normal and extreme wind conditions. First, a normal wind was considered as in Fig. 6.

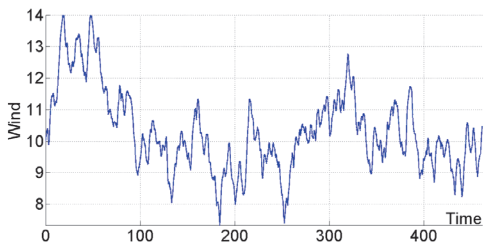

Figure 6: Normal wind waveform.

It was assumed to vary in the range [7m/s – 15m/s]; its turbulence was similar to real-time wind fluctuation values. A second group of simulations were obtained for an extreme wind scenario as shown in Fig. 7.

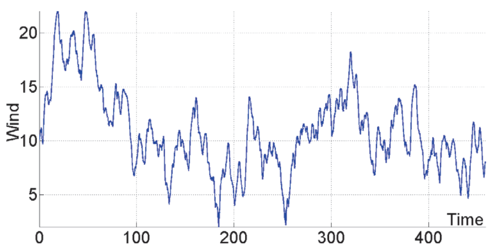

Figure 7: Extreme wind waveform.

Wind speed values vary into the range [2m/s – 22m/s] and are characterized by high turbulence. It should be noted that such a wind waveform is rarely encountered in nature.

5.2 Normal Wind Case

Let us first compare the closed-loop system performances obtained by applying (i) the PID controller resulting from the Ziegler – Nichols rules and (ii) the initial PID controller. Simulations are given in Fig. 8.

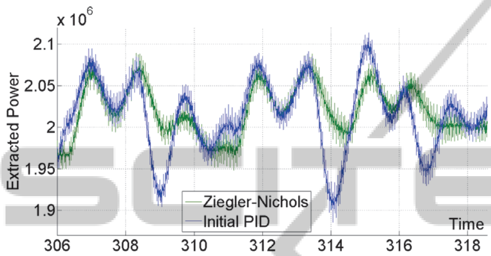

Figure 8: Ziegler - Nichols / Initial PID controller behaviour in normal wind conditions.

It is clear that in this situation the Ziegler – Nichols controller waveform converges more tightly to the set point. It should be noted that small deviations between curves are in fact very important, since the extracted power is measured in MW.

In the sequel, one can see that closed-loop behavior is further improved by the PID controller tuning of the proposed method, Fig. 9.

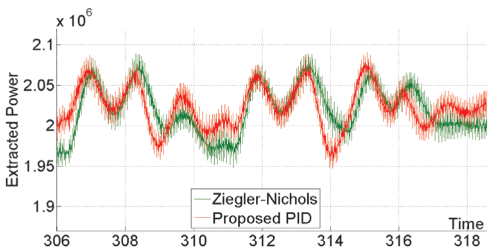

Figure 9: Ziegler - Nichols / Proposed PID controller behaviour in normal wind conditions.

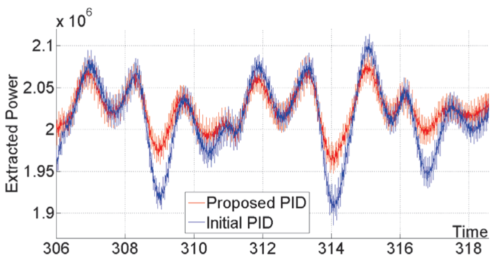

Figure 10: Proposed PID controller / Initial PID controller behaviour in normal wind conditions.

Finally, simulations of the proposed PID controller and the initial one are compared in Fig. 10. An improved convergence is obtained by the proposed method.

5.3 Extreme Wind Case

Analogous performances were obtained in the case of extreme wind conditions. The initial PID vs Ziegler – Nichols controller performances are given in Fig. 11.

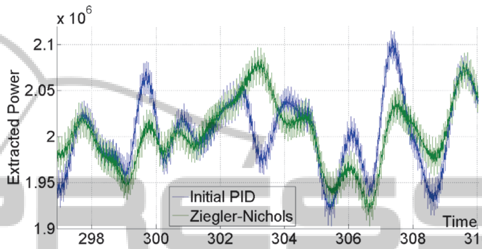

Figure 11: Ziegler - Nichols / Initial PID controller behaviour in extreme wind conditions.

Since in this case the wind turbulence is significantly higher, the distance of the two waveforms is clearly larger. However, it is to be noted that the Ziegler – Nichols PID ensures a better convergence to the set point; moreover, in several time steps like 307sec, 309sec the deviation is almost avoided.

Comparison of Ziegler – Nichols and the proposed PID controller is given in Fig. 12.

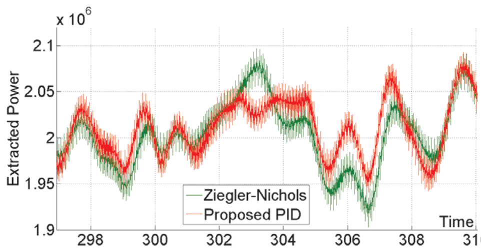

Figure 12: Ziegler - Nichols / Proposed PID controller behaviour in extreme wind conditions.

Even for relatively high turbulence, the proposed method ensures improved performances. Note that the convergence in the time interval 302sec to 308sec remains better.

Finally, comparison of the proposed controller with the initial one is given in Fig. 13. It is noted that unnecessary fluctuations are avoided by using the proposed PID controller. In time steps like 303sec, 304sec minimum fluctuations are produced by using the proposed controller.

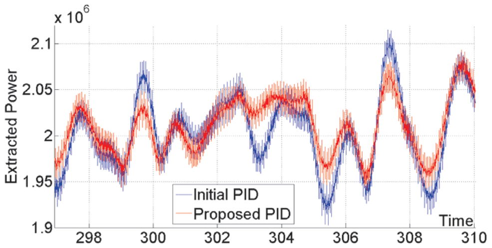

Figure 13: Proposed PID controller / Initial PID controller behaviour in extreme wind conditions.

Furthermore, in waveform regions where fluctuations cannot be avoided, due to the extreme wind's nature, the proposed controller ensures an acceptable performance and convergence to the set point.

6 CONCLUSIONS

In this paper, a design approach for the control of a variable speed wind turbine system is proposed. The extracted power has to achieve a desirable set point of 2MW, despite wind speed fluctuations. By appropriately adjusting the PID controller gains, the proposed control scheme ensures the closed-loop system's stability and an acceptable tracking, even under extreme wind conditions. The output convergence to the set point has been shown to be faster and tighter, as compared with existing PID methods. Different control schemes for the variable speed wind machine are presently under investigation.

REFERENCES

Abbas F. A. R., Abdulsada M. A., 2010. Simulation of Wind-Turbine Speed Control by MATLAB, *International Journal of Computer and Electrical Engineering*, Vol. 2, No. 5.

Ackermann T., 2002. Transmission systems for offshore wind farms, *IEEE Power Engineering Review*.

Ackermann T., 2005. *Wind Power in Power Systems,* John Wiley & Sons, Ltd.

Asharif F., Tamaki S., Nagado T., Nagtata T., Asharif M. R., 2011. *Analysis of Non-linear Adaptive Friction and Pitch Angle Control of Small-Scaled Wind Turbine System*, Springer-Verlag, Berlin Heidelberg.

Boukhezzara B., Lupua L., Siguerdidjanea H., Handb M., 2007. Multivariable control strategy for variable speed, *Renewable Energy*, Vol. 32.

Dunney F., Y. Paoz L. Y., Wrightx A. D., Jonkman B., Neil Kelle N., 2010. Combining standard feedback controllers with feed forward blade pitch control for load mitigation in wind turbines, *Proceedings of the 48th AIAA aerospace sciences meeting*, Orlando.

Ebrahim M. A., Metwally A. E., Bendary F., Mansour W. M., Ramadan H. S., Ortega R. and Romero J., 2010. Optimization of Proportional-Integral-Differential Controller for Wind Power Plant Using Particle Swarm Optimization Technique, *IJETSE International Journal of Emerging Technologies in Sciences and Engineering*, Vol.2, No.2.

Geyler M., Caselitz P., 2007. Individual blade pitch control design for load reduction on large wind turbines, *Proceedings of the European Wind Energy Conference,* Milan, Italy.

Hansen M. O. L., 2008. *Aerodymanics of Wind Turbines,* Second Edition, Earthscan.

Hara S., Iwasaki T., and Shiokata D., 2006. Robust PID Control Using Generalized KYP Synthesis, *IEEE CONTROL SYSTEMS MAGAZINE*.

Iov F., Hansen A. D., Sørensen P., Blaabjerg F., 2004. Wind Turbine Blockset in Matlab/Simulink, General Overview and Description of the Models, *Institute of Energy Technology,* Aalborg University.

Jonkman J. M., 2007. *Dynamics modeling and loads analysis of an offshore floating wind turbine*, Technical report.

Leinhos D. C., Scheidler S. G., Fottner L., 2002. Experiments in Active Stall Control of a Twin-Spool Turbofan Engine, *Proceedings of ASME TURBO EXPO*, Amsterdam, The Netherlands.

Marsaglia G., Tsang W.W., 2000. The ziggurat method for generating random variables, *Journal of Statistical Software*, Vol. 5, No. 8. (5)

Munteanu I., Bractu A. I., Cutululis N. A., Ceanga E., 2008. Optimal Control of Wind Energy Systems, *Towards a Global Approach*, Springer

Slootweg J. G., Haan S. W. H., Polinder H., Kling W. L.,2003. General Model for Representing Variable Speed Wind Turbines in Power System Dynamics Simulations, IEEE TRANSACTIONS ON POWER SYSTEMS, Vol. 18, No. 1.

Strazisar A. J., Bright M. M., 2004. Compressor Stall Control Through Endwall Recirculation, *Proceedings of ASME Turbo Expo Power for Land*, Sea, and Air, Vienna, Austria.

Wilson D. G., Berg D. E., Resor B. R., Barone M. F., Berg J. C., 2009. Combined individual pitch control and active aerodynamic load controller investigation for the 5MW upwind turbine, *AWEA WINDPOWER 2009 Conference and Exhibition*, Chicago.

Ziegler J. G., Nichols N. B., Rochester N. Y., 1942. Optimum Settings for Automatic Controllers, *Transactions of the A.S.M.E.*

Zhang J, Cheng M., Chen Z., Fu X., 2008. Pitch Angle Control for Variable Speed Wind Turbine, *DRPT2008*, Nanjing China.