Torque and pitch angle control for variable speed wind turbines in all operating regimes

Conference Paper · May 2011

DOI: 10.1109/EEEIC.2011.5874598

Adel Merabet
Saint Mary's University

Jogendra Thongam
Ford Motor Company

Jason Gu
Dalhousie University

Torque and Pitch Angle Control for Variable Speed Wind Turbines in All Operating Regimes

Adel Merabet
Division of Engineering
Saint Mary's University
Halifax, NS, Canada

Jogendra Thongam
Department of Renewable Energy Systems
STAS Inc.
Chicoutimi, QC, Canada

Jason Gu
Department of Electrical and Comp. Engineering
Dalhousie University
Halifax, NS, Canada

Abstract—**In this paper, a multivariable control strategy is proposed for variable speed wind turbines operating in the two primary regimes, below-rated and above-rated wind speeds. A torque controller, based on the achievement of zero speed-tracking error, is developed to follow a trajectory that allows the wind turbine to operate with maximum power extraction in below-rated regime. The turbine torque is unknown to the controller, and its effect on it is compensated by estimation. In above-rated wind speed regime, a pitch angle controller is added to maintain a constant rated power, while the torque controller regulates the rotor speed to follow a constant nominal speed. The robustness of the control strategy is guaranteed through the incorporation of the turbine torque estimator. Simulation results demonstrate the effectiveness of the proposed control system for wind turbine operating in all wind speed regimes.**

Keywords– wind turbine; variable speed; maximum power; operating regime; torque estimation; pitch angle

I. INTRODUCTION

In order to improve the profitability and the reliability of wind turbines, accurate control is more than necessary to operate at all wind speed regions. Variable speed wind turbines have many advantages over fixed speed ones such as higher energy yields, lower component stress, and fewer grid connection power peaks. To be fully exploited, variable speed should be controlled in all operating regions for speed-tracking in maximum power extraction, regulation of the electrical power and reducing the loads on the different parts of the wind turbine.

Variable-speed wind turbines operate in two primary regimes, below-rated wind speed and above-rated wind speed. When power production is in below-rated regime, the turbine operates at variable rotor speed to capture the maximum amount of energy available in the wind. Generator torque provides the control input to vary the rotor speed, and the blade pitch angle is held constant. In above-rated wind speed conditions, the primary objective is to maintain a constant power output. This is generally achieved by holding the generator torque constant and varying the blade pitch angle. In both control regimes the turbine response to transient loads must be minimized [1-2].

The objective of multivariable control is to regulate simultaneously both rotor speed and electrical power, especially at above-rated wind speed regime, in order to overcome the drawbacks of using only the pitch angle as a control input while maintaining the generator torque at its rated value [2]. In this work, the control strategy consists of a torque controller for rotor speed tracking and a pitch controller for power tracking. In below-rated wind speed regime, the torque controller allows the wind turbine to operate with maximum power extraction by following a speed trajectory from the wind speed. In above-rated wind speed regime, the pitch controller regulates the electrical power to the rated power, while the torque controller regulates the rotor speed to its nominal value. Furthermore, robustness is guaranteed through the estimation of the turbine torque, which is considered unknown by the torque controller [3].

The paper is organized as follows: the wind turbine model and the two primary operating regimes are described in section II. Then, the torque control law and the estimation of the turbine torque are developed in section III, and the pitch control is given in section IV. Finally, simulation results are presented to verify the performance of the proposed control strategy.

II. WIND TURBINE MODEL

The power captured from the wind by the rotor of the turbine is given by the nonlinear expression

$$P_t = 0.5\,\pi\,\rho\,C_p(\lambda, \beta)\,R^2 v_w^{\,3} \tag{1}$$

where, ρ is the air density, R is the radius of the turbine blade, v_w is the wind speed.

The power coefficient, C_p, of the turbine is a function of the tip-speed ratio λ and the blade pitch angle β (Fig. 1). Its expression depends on the characteristics of the wind turbine. In this work, the following expression has been used

$$C_p(\lambda,\beta) = 0.5\left(\frac{116}{\lambda_1} - 0.4(\beta - 5)\right)e^{\frac{-16.5}{\lambda_1}} \tag{2}$$

where

$$\lambda_1 = \frac{1}{\frac{1}{(\lambda + 0.089)} - \frac{0.035}{(\beta^3 + 1)}}$$

The tip-speed ratio is defined as the ratio between the turbine rotor speed ω_r and the wind speed v_w

$$\lambda = \frac{\omega_r R}{v_w} \quad (3)$$

The power coefficient and hence the power is maximum at a certain value of tip speed ratio called optimum tip speed ratio λ_{opt}. In order to have maximum possible power, the turbine should always operate at λ_{opt}. This is possible by controlling the rotational speed of the turbine so that it always rotates at the optimum speed of rotation [4].

Variable-speed turbine operation can be divided into three regions (Fig. 2). Region 1 describes start-up when wind speeds are below cut-in. Region 2 is between cut-in and rated wind speeds, just before the turbine generates rated power. A main objective of a controller in this region is to capture the maximum amount of energy from the wind. This is achieved by keeping blade pitch approximately constant and using generator torque to vary the rotor speed. With small pitch changes about the optimal angle, a controller can also reduce dynamic loads in the structure. In Region 3, between rated and cut-out wind speeds, wind power must be shed by the rotor to limit output power to the rated value. This is usually accomplished by keeping generator torque constant and commanding blade pitch angles. Structural fatigue loads can also be reduced in Region 3 via pitch commands. The overall goal of the control system is to meet different performance objectives in each operating region and make the transition between Regions 2 and 3 smoothly to avoid load spikes [5].

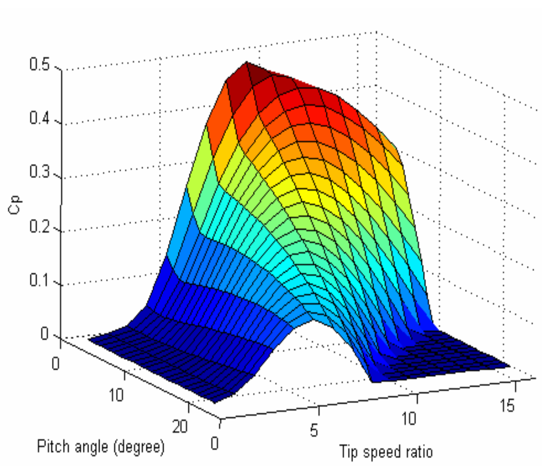

Figure 1. Power coefficient C_p of the wind turbine versus λ and β

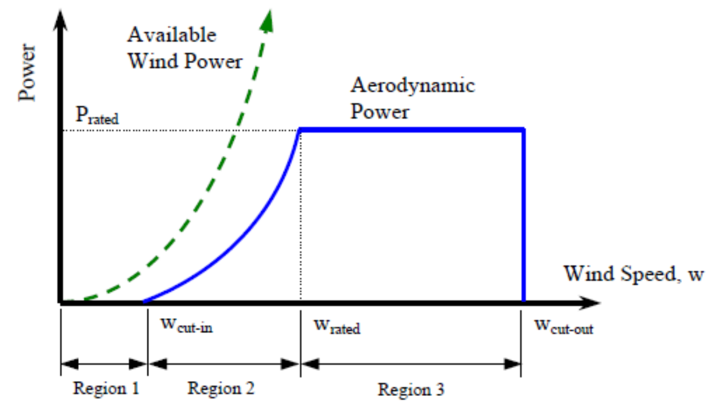

Figure 2. Power operating regions of wind turbines

Using the power equation

$$P_t = \omega_r \, T_t \quad (4)$$

the turbine torque is given by

$$T_t = 0.5\, \pi\, \rho\, C_p(\lambda, \beta)\, R^2\, v_w^{\,3}/\omega_r \quad (5)$$

Assuming a single-mass model of the turbine, the dynamic response of the rotor driven at a speed ω_r by the torque T_t is expressed as

$$J_t \dot{\omega}_r = T_t - K_t \omega_r - T_g \quad (6)$$

where, J_t is the total inertia, K_t is the total damping and T_g is the generator torque.

III. Torque Control Design

The torque control will allow tracking the rotor speed profile, carried out from wind speed and optimum tip speed ratio, in order to achieve maximum power extraction in region 2. Also, it will assist the pitch blade controller to maintain the rotor speed within acceptable limits and to regulate the wind turbine electric power in region 3.

1. *Torque Controller Development*

The controller is designed to allow the k-step ahead speed-tracking error achieving zero.

$$\omega_{\mathrm{ref}}(t+k) - \omega_r(t+k) = 0 \quad (7)$$

The k-step ahead speed-predictor $\omega_r(t+k)$ can be approximated by using Taylor series expansion

$$\omega_r(t+k) = \omega_r(t) + k\dot{\omega}_r(t) \quad (8)$$

The expression of $\dot{\omega}_r$ from (6) is substituted into (8) such that

$$\omega_r(t+k) = \omega_r(t) + \frac{k}{J_t}\left(T_t - K_t \omega_r(t) - T_g\right) \quad (9)$$

then, by substituting equation (9) into equation (7) we obtain

$$\omega_{\text{ref}}(t)+k\dot{\omega}_{\text{ref}}(t)-\omega_r(t)-\frac{k}{J_t}\left(T_t-K_t\omega_r(t)-T_g\right)=0 \quad (10)$$

where, the k-step ahead reference speed-predictor $\omega_{\text{ref}}(t+k)$ is defined similarly as

$$\omega_{\text{ref}}(t+k)=\omega_{\text{ref}}(t)+k\dot{\omega}_{\text{ref}}(t) \quad (11)$$

Finally, form equation (10), the torque controller is given by

$$T_g=-\frac{J_t}{k}\left(\omega_{\text{ref}}(t)-\omega_r(t)\right)-J_t\dot{\omega}_{\text{ref}}(t)-K_t\omega_r(t)+T_t \quad (12)$$

2. *PI-Torque Control based on Turbine Torque Estimation*

The estimation of the turbine torque T_t is derived from the motion equation (6) and the torque control law (17)

From (6), T_t is obtained as

$$\frac{1}{J_t}T_t=\dot{\omega}_r+\frac{K_t}{J_t}\omega_r+\frac{1}{J_t}T_g \quad (13)$$

An estimator based on the torque error is defined as

$$\dot{\hat{T}}_t=p\frac{1}{J_t}(T_t-\hat{T}_t) \quad (14.a)$$

$$\dot{\hat{T}}_t=p\left(\dot{\omega}_r+\frac{K_t}{J_t}\omega_r+\frac{1}{J_t}T_g\right)-p\frac{1}{J_t}\hat{T}_t \quad (14.b)$$

Assuming that $dT_t/dt=0$ and using (14.a), the estimation error has first-order dynamics

$$\dot{e}_T(t)+\frac{p}{J_t}e_T(t)=0 \quad (15)$$

where, $e_T=T_t-\hat{T}_t$, and $p>0$ to guarantee the stability of the estimator.

Now, using the estimated torque $\hat{T}_t$, the control law (12) becomes

$$T_g=-\frac{J_t}{k}\left(\omega_{\text{ref}}(t)-\omega_r(t)\right)-J_t\dot{\omega}_{\text{ref}}(t)-K_t\omega_r(t)+\hat{T}_t \quad (16)$$

Substituting the new control law (16) into (14.b), the torque estimator becomes

$$\dot{\hat{T}}_t=-p(\dot{\omega}_{\text{ref}}-\dot{\omega}_r)-\frac{p}{k}(\omega_{\text{ref}}-\omega_r) \quad (17)$$

Integrating (17), the torque estimator is simplified to

$$\hat{T}_t=-p(\omega_{\text{ref}}-\omega_r)-\frac{p}{k}\int(\omega_{\text{ref}}-\omega_r)dt \quad (18)$$

The torque estimator contains an integral action, which allows the elimination of the steady state error and enhances the robustness of the control scheme with respect to model uncertainties and disturbance rejection.

Compared to [1, 2], where the torque must be measured in order to use it in the control law, the proposed torque estimator will allow avoiding the measurement and its drawback.

Finally, the PI-Torque controller has the following structure

$$T_g=-\frac{J_t}{k}e_\omega(t)-J_t\dot{\omega}_{\text{ref}}(t)-K_t\omega_r(t)-\left(pe_\omega(t)+\frac{p}{k}\int e_\omega(t)dt\right) \quad (19)$$

where, $e_\omega=\omega_{\text{ref}}-\omega_r$ is the speed error.

IV. Pitch Angle Control

Blade pitch control is used to limit the aerodynamic power above rated wind speed in order to keep the turbine shaft torque within its design limits. The blade pitch actuator is modeled as first-order system in closed loop with saturation of the pitch angle and a pitch rate limitation [6, 7].

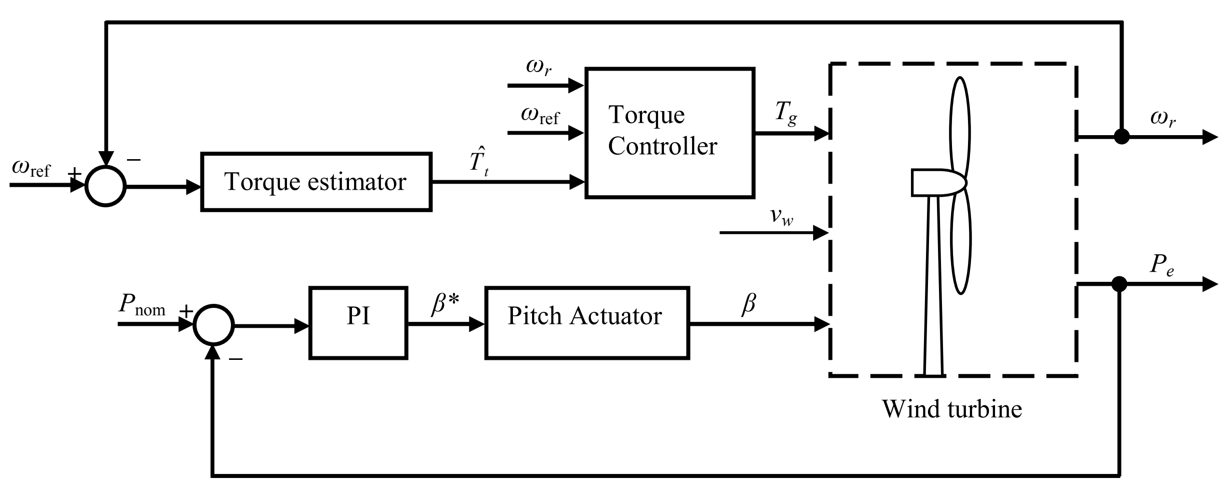

Figure 3. Block diagram of torque and pitch control scheme

In this work, the required pitch angle is generated based on the power error to regulate the power to the rated one, while the torque controller maintains the rotor speed within acceptable limits. A proportional-integral (PI) controller is used to carry out the pitch angle reference

$$\beta^* = K_p e_p(t) + K_i \int e_p(t)dt \tag{20}$$

where, $e_P = P_{nom} - P_e$ is the power tracking error.

V. Simulation and Discussion

Simulation is carried in order to verify the speed tracking performance of the proposed control strategy. The electrical generator used in this work is a permanent magnet synchronous machine and the d-q components of the current are controlled via simple PI controllers. Parameters of the wind turbine system are given in appendix. In region 2, the reference speed is carried out from (3), wherein the tip speed ratio is replaced with optimum tip speed ratio λ_{opt} for maximum power extraction. In region 3, the rotor speed is regulated by the torque controller to follow its rated value, the regulation of the electric power, to follow its rated value, is done by the pitch controller.

In all simulations, the control parameters are: k = 0.01, p = 10, K_p= 100, K_i=0

In below-rated wind speed regime, wind speed profile, rotor speed, reference speed and the speed error are depicted in Fig. 4. It can be seen that the tracking error is good with a zero steady error. This performance is due to the estimated torque given in Fig. 5, which is included in the control law. The performance of the speed tracking is satisfactory with no steady state error and the estimation of the torque quite good. This estimation contributes to the improvement of the speed tracking performance, where the elimination of the steady state error in the speed tracking can be explained by the integral action in the structure of the torque estimator.

In above-rated wind speed regime, wind speed profile and the rotor are given in Fig. 6. The rated wind speed is 18 m/s and the rotor speed is regulated to its nominal value 26 rad/s. Also, the good tracking performance is achieved by the torque estimator, which helps to eliminate the steady error. The regulation of electrical power is shown in Fig. 7, where its mean value is 1120 W. However, the power response is fluctuated and more parameters tuning on the parameters of the proposed control strategy and the control of the electrical generator, not included in this work. The pitch angle control input is given in Fig. 8.

In general, the performance of the controller is satisfactory, and more research work is needed to evaluate the performance of all parts of the wind energy conversion system and the transition between the regions.

In this work, the reference of the rotational speed of the wind turbine (ω_{ref}) is carried out from the measurement of wind speed. However, methods of MPPT such as [8, 9] can be used to define the reference speed without wind speed measurement to avoid inaccuracy of the measurement and its relation to the wind speed as this is perceived by the wind turbine.

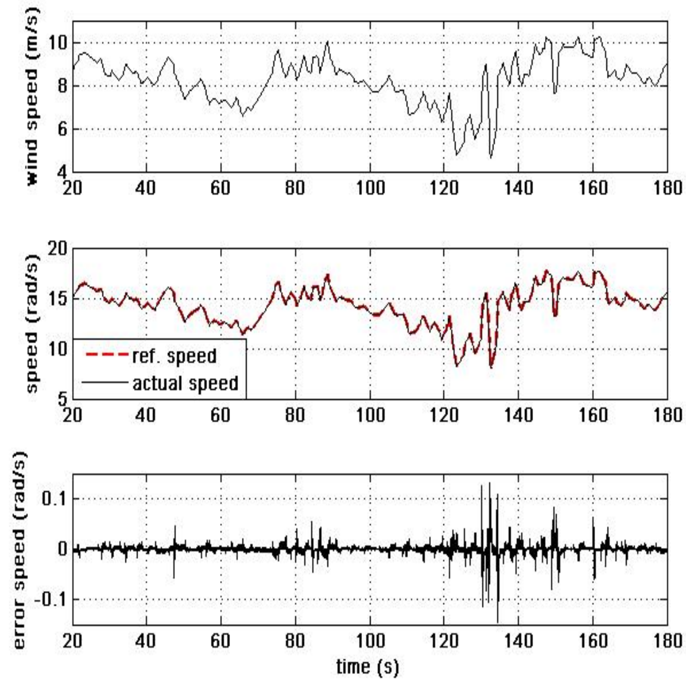

Figure 4 Rotor speed tracking with real wind speed profile in region 2

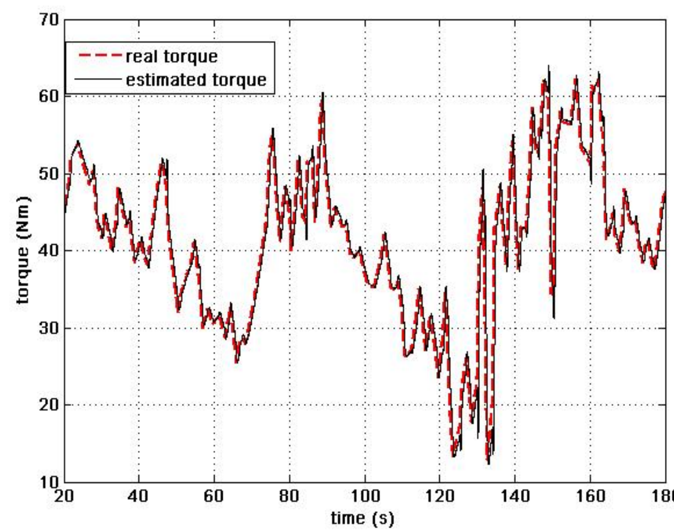

Figure 5. Turbine torque estimation in region 2

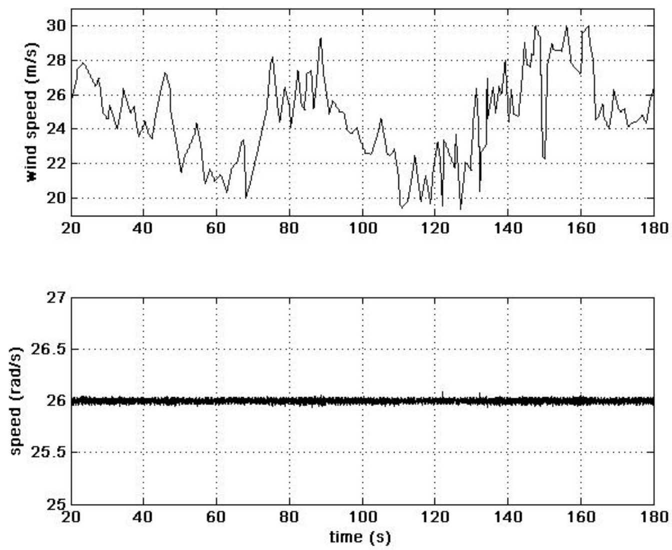

Figure 6. Rotor speed regulation in region 3

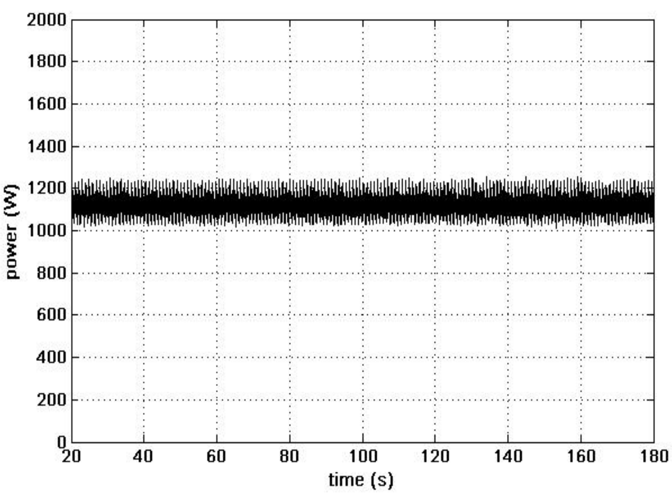

Figure 7. Electric power regulation in region 3

VII. CONCLUSIONS

A multivariable control strategy for variable speed wind, operating in below-rated and above-rated wind speed regimes, has been presented in this work. A torque controller has been developed to follow a speed trajectory that allows the wind turbine to operate with maximum power extraction in below-rated wind speed and to regulate the rated speed in above-rated wind speed. The turbine torque, which is unknown to the controller, has been compensated by estimation to guarantee the robustness. A pitch angle controller has been added to regulate the electric power to its rated value in above-rated wind speed regime.

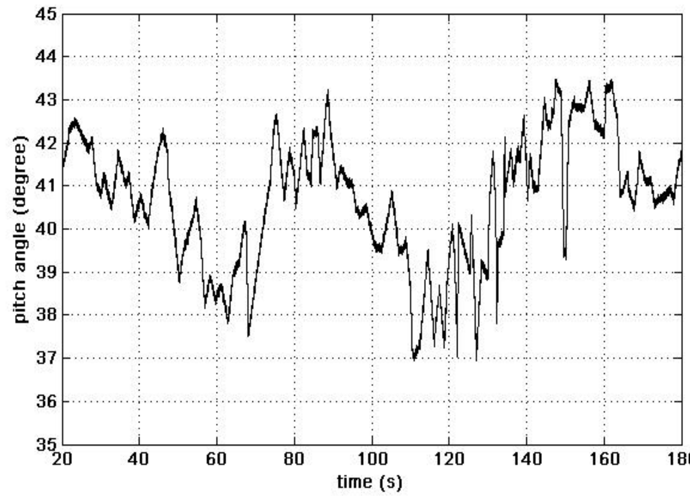

Figure 8. Pitch angle control input in region 3

Simulation results have shown the effectiveness of the proposed control system for wind turbine operating in all wind speed regimes.

APPENDIX

PMSG parameters: P_r=1.12 kW, R= 8.39 Ω, L_d= 0.08483 H, J= 4.12×10^{-3} k·gm^2.

Turbine parameters: P_r=1.32 kW, R=1.26 m, λ_{opt}= 3.8, ρ = 1.14 kg/m^3, J= 1.5 k·gm^2.

REFERENCES

[1] L. Lupu, B. Boukhezzar, and H. Siguerdidjane, "Pitch and Torque Control Strategy for Variable Speed Wind Turbines", European Wind Energy Conference, Athens, Greece, 2006.

[2] B. Boukhezzar, L. Lupu, H. Siguerdidjane, M. Hand, "Multivariable Control Strategy for Variable Speed, Variable Pitch Wind Turbines", Renewable Energy, 32, pp. 1273-1287, 2007.

[3] A. Merabet, H. Arioui, M. Ouhrouche, "Cascaded Predictive Controller Design for Speed Control and Load Torque Rejection of Induction Motor", American Control Conference, Seattle, USA, pp. 1139–1144, 2008.

[4] J. Thongam, P. Bouchard, H. Ezzaidi and M. Ouhrouche, "Wind Speed Sensorless Maximum Power Point Tracking Control of Variable Speed Wind Energy Conversion Systems," IEEE International Electric Machines and Drives Conference, Miami, USA, pp. 2195-2200, 2009.

[5] J. Zhang, M. Cheng, Z. Chen, X. Fu, "Pitch Angle Control for Variable Speed Wind Turbine", DRPT2008, Nanjing China, 6-9 April 2008.

[6] Y. El-Tous, "Pitch Angle Control of Variable Speed Wind Turbine", American Journal of Engineering and Applied Sc. 1(2), pp. 118-120, 2008.

[7] E. Muljadi, "Pitch-Controlled Variable-speed Wind Turbine Generator", IEEE Transactions on Industry Applications Vol. 37, No. 1, 2001.

[8] J. Thongam, P. Bouchard, H. Ezzaidi and M. Ouhrouche, "ANN-based MPPT Control for Variable Speed Wind Energy Conversion Systems", IEEE Conf. Control Applications & Intelligent Control, Russia, p. 1667-1671, 2001.

[9] E. Adzic, Z. Ivanovic, M. Adzic, V. Katic, "Maximum Power Search in Wind Turbine Based on Fuzzy Logic Control", Acta Polytechnica Hungarica, Vol. 6, No. 1, 2009.