# Wind Energy Conversion System Using PMSG Controlled by B-Spline Network

Omar Aguilar Mejía
Ruben Tapia Olvera
Engineering Department
Universidad Politécnica de Tulancingo
Tulancingo, Hidalgo, México
omar.aguilar@upt.edu.mx
rtapia@gdl.cinvestav.mx

Jose M. Sausedo Solorio
CIAII
Universidad Autonoma del Estado de Hidalgo
Pachuca, Hidalgo, México
sausedo@uaeh.edu.mx

***Abstract*—The wind energy boom in the world began in 1980's. This paper presents the modeling and control of a Wind Energy Conversion Systems (WECS) based Permanent Magnet Synchronous Generator (PMSG). The control scheme uses a B-spline artificial neural network for tuning controllers when the system is subjected to disturbances. The currents from VSI's are controlled in a synchronous orthogonal *dq* frame using an adaptive PI control. The B-spline neural network must be able to enhance the system performance and the online parameters updated can be possible. This paper proposes the use a linear control PI to regulate the DC link voltage. Simulation results show the feasibility and robustness of the proposed control schemes for PMSG based wind turbines. Comprehensive models of wind speed, wind turbine, PMSG and power electronic converters along with their control schemes are implemented in MATLAB/SIMULINK environment.**

***Index Terms*--Generation System, Phase Locked Loop, PID Control, Voltage Source Inverter, Wind Energy.**

## INTRODUCTION

Since the petroleum is gradually exhausting and environmental protection is progressively rising, the usage of the clean energy sources such as wind, photovoltaic, and fuel cells has become very important and quite popular in electric power industries. Wind turbine technology has developed rapidly over the past decade into one of the most mature renewable power generation technologies [1]. A WECS is a physical system that has three primary components. The first one is rotor connected to blades. As wind goes through blades, it makes the rotor rotate and therefore creates mechanical power. The second one is a transmission that transfers power from the rotor to generator. The last one is electric generator thatconverts mechanical power to electric power [2]. During the last decades, the development of this technology has had a great advance due mainly to the cost increase, limited reserves and adverse environmental impact of fossil fuels [2]. Now days, there are different configurations of wind turbines, which are different in the type of electric generator, the control to capture maximum wind power and control devices based on power electronics to interface to the grid [3].

Different machine types have been used in WECS through the ages. These include the squirrel cage induction generator (SCIG), doubly fed induction generator (DFIG), and synchronous generator PMSG with power ratings from a few kilowatts to several megawatts. DFIG's are widely used as the generator in a variable speed wind turbine system. But, the DFIG needs a gearbox to match the turbine and rotor speed. The gearbox many times suffers from faults and requires regular maintenance, making the system unreliable [4]. Various control methods and convert technologies of wind energy conversion systems are fast developed in energy conversion application. The PMSG system has been used for wind power generating system due to many advantages such as simpler structure, better reliability, lower maintenance, and higher efficiency. Therefore, the PM synchronous generator generation system stands for a significant trend in progress of wind power applications [5]. The output power behavior of wind turbine is nonlinear. The formatter will need to create these components, incorporating the applicable criteria that follow.

Power electronics, being the technology of efficiently converting electric power, plays an important role in wind power systems. It is an essential element for integrating the variable speed wind power units to achieve high efficiency and high performance in power systems. In particular, VSI units are used to match the characteristics of wind turbines with the requirements of grid connections, including frequency, voltage, control of active and reactive power, harmonics, etc. [6]. The wind systems also have the flexibility to be coupled to the conventional electricity grid, for which is required a system that is able to synchronize the voltage generated by generation system with the network as the phase locked loop (PLL), which allows to get the angle of the grid and with this generate a signal with the same characteristics. PLL applications are Distributed Generation (DG) systems for three-phase and singlephase grids, Flexible AC Transmission

A. M. Omar and T. O. Ruben are with the Engineering Department at Polytechnic University of Tulancingo.

978-1-4799-3656-4/14/$31.00 ©2014 IEEE

Systems (FACTS), Active Power Filters (APF), Active Power Rectifiers (APR) etc. [7]. In this paper we use a PLL to synchronize a WECS with the conventional electricity grid. The wind generation system is composed of a wind turbine, a permanent magnet synchronous generator, an AC-DC rectifier, a DC-DC boost converter, a phase detector and a voltage source inverter, as shown in Fig. 1.

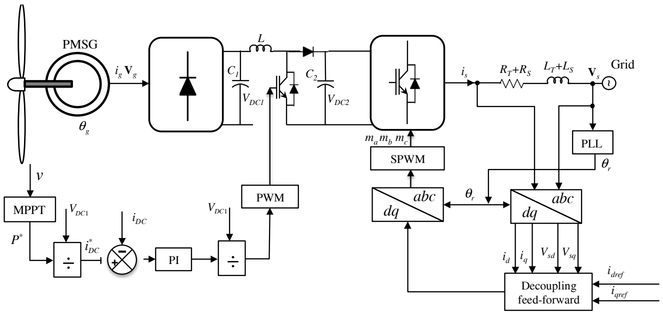


Fig. 1 Wind energy conversion scheme using PMSG.

Major techniques to regulate the VSI output current include either a variable switching frequency, such as the hysteresis control scheme, or fixed switching frequency schemes, such as the ramp comparison, stationary and synchronous frame proportional–integral (PI), optimal, nonlinear, predictive control, and soft computing, neural networks control and on the fusion or hybrid of hard and soft control techniques [8]. However, tuning alternatives are needed for electrical grid complexity. Some author's mixed neural networks and PID techniques to strengthen the linear controller. In [9], [10] a back propagation neural networks was used to adjust coefficients $K_P$, $K_I$, and $K_D$ of PID controllers attaining power regulation of wind turbines. The similar PID tuning strategy using radial basis function (RBF) neural network for pitch angle control systems [11]. In these work we proposed a good adaptive tuning technique based on B-spline neural network (BSNN).

In this paper a B-spline neural network (BSNN) is employed for two main tasks; one for PI simultaneous tuning, taking care of a key feature: the proposed controller must be able to enhance the system performance; the second the online parameters updated can be possible. The strategy is proposed to update conventional PI parameters for currently operating in power converters that were tuned time ago.

## II. WIND-TURBINE CHARACTERISTICS

### A. *Wind Turbine Model*

A wind turbine is a power extracting mechanism. Wind turbine output power Pwt and wind turbine torque $T_{wt}$ are given by the following equations [12]

$$P_{wt} = 0.5\rho\pi v^2 R^3 C_p(\lambda) \tag{1}$$

$$\Gamma_{wt} = \frac{0.5 C_p(\lambda)\rho\pi v^2 R^3}{\lambda} \tag{2}$$

where ρ is the air density, R is the blade length, v is the wind speed and $C_p(\lambda)$ is the turbine performance coefficient, $\lambda = \omega_h R / v$, $\omega_h$ is the angular rotor speed for the wind turbine.

The performance coefficient $C_p$ is a function of the tip-speed-ratio. Therefore, the $C_p(\lambda)$ performance curve gives information about the power. The torque coefficient is derived as

$$C_\Gamma(\lambda) = \frac{C_p(\lambda)}{\lambda} \tag{3}$$

The torque coefficient can be described by a polynomial function of the tip speed ratio as [13]

$$C_\Gamma(\lambda) = a_0\lambda^2 + a_1\lambda + a_2 \tag{4}$$

The output power characteristics of the wind turbine are depicted in Fig. 2. The wind turbine can produce maximum power when the turbine operates at maximum $C_p(\lambda_{opt})$. If the wind speed varies, the rotor speed should be adjusted to follow the change. The objective optimum power from a wind turbine can be written as

$$P_{wt\_opt} = k_{opt}\omega_{h\_opt}^3 \tag{5}$$

Therefore, the objective optimum torque can be given by

$$\Gamma_{wt\_opt} = k_{opt}\omega_{h\_opt}^2 \tag{6}$$

The mechanical power generated by the turbine as a function of the rotor speed for different wind speed is shown in Fig. 2. The optimum power curve ($P_{wt\_opt}$) shows how maximum energy can be captured from random wind. If the controller can properly follow the optimum curve, the wind turbine will produce maximum power at any speed within the allowable range. [12-14].

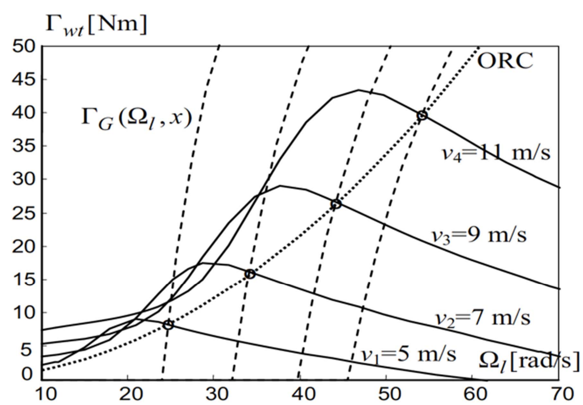


Fig. 2 Output power characteristics of wind turbine.

### B. *Permanent Magnet Synchronous Generator Model*

The PMSG is modeled under the following simplifying assumptions: (a) sinusoidal distribution of stator winding; (b) electric and magnetic symmetry; (c) negligible iron; (d) losses; (e) and unsaturated magnetic circuit. The voltage and electromagnetic torque equations of the PMSM in the *dq* reference frames are given by the following equations [14]:

$$L_d\frac{di_d}{dt} = -R_s i_d + L_q i_q \omega_s - v_d \tag{7}$$

$$L_q \frac{di_q}{dt} = -R_s i_q - \left(L_d i_d + \psi_m\right)\omega_s - v_q \tag{8}$$

where $v_d$, $v_q$, $i_d$ and $i_q$ are the *d-q* axis voltages and currents, respectively; $R_s$ is the stator resistance; $L_d$ and $L_q$ are the *d-q* axis inductances; $\omega_s$ is the generator rotational speed; $\psi_m$ is the permanent magnetic flux. The electromagnetic torque is obtained as

$$T_e = \frac{3}{2} p\left[\psi_m i_q + \left(L_d - L_q\right) i_d i_q\right] \tag{9}$$

where $p$ is the number of pole pairs. When the permanent magnets are mounted on the rotor surface, then $L_d=L_q$, therefore the electromagnetic torque is, $T_e=pi_q\psi_m$. Using generator convention; the rotational speed of the generator and wind turbine driving torque as [12-14]

$$J \frac{d\omega_h}{dt} = P\left(\Gamma_{wt} - T_e - B\omega_h\right) \tag{10}$$

where $\Gamma_{wt}$ is the turbine driving torque referred to the generator ($\Gamma_{wt}=P_{wt}/\omega_l$), $B$ is the active damping coefficient representing turbine rotational losses and $\omega_h= i\omega_l$, where $i$ is the ratio of a rigid drive train.

## III. CONVERTER SYSTEM MODEL.

The objective of the side converter is to regulate the voltage and frequency. The output voltages have to be controlled in terms of amplitude and frequency through a PLL. The output-voltage controller is used to control the output voltage during load transients or wind variation. The dc-link voltage controller is used to stabilize the dc-link voltage. The dc voltage nonlinear controller maintains the dc voltage to the reference value. The PI controllers are used to regulate the currents in the inner control loops.

### A. VSI Dynamic Model

Fig. 1 shows the diagram of a three-phase three-wire VSC connected to the AC system represented by an equivalent Thevenin circuit via the inductance and resistance ($L_T$, $R_T$) of the interface transformer. The converter DC terminal is connected to a shunt capacitance ($C_{dc}$) and resistance ($R_{dc}$) representing the losses of the switching and affiliated components of the VSC. The three-phase AC side voltage balancing equations of the VSC are expressed [15] as:

$$\frac{d\mathbf{I}_{abc}}{dt} = \frac{1}{L_s + L_T}\left[-\left(\mathbf{R}_s + \mathbf{R}_T\right)\mathbf{I}_{abc} + \mathbf{V}_{Sabc} - \mathbf{V}_T\right] \tag{11}$$

where $\mathbf{I_{abc}} =[I_a\ I_b\ I_c]^T$ is the three-phase current vector, $\mathbf{V_{Sabc}} =[V_{Sa}\ V_{Sb}\ V_{Sc}]^T$ is the three-phase AC source voltage vector, $\mathbf{V_T} =[V_{Ta}\ V_{Tb}\ V_{Tc}]^T$ is the voltage source converter AC terminal three-phase voltage vector. The rms amplitude $V_{tm}=m_oV_{dc}$ ($0<m_o<1$, related to the PWM modulation index), the frequency $w$ and phase angle $\phi_T$ are controllable variables of the PWM voltage source converter. When connected to a constant frequency AC systems only $V_{tm}=m_oV_{dc}$ ($0<m_o<1$) and $\phi_T$ need to be used for the control of the VSC operation. Using the orthogonal transformation, the tree-phase vectors in (11) are next converted to the *dqo*-frame. Thus by substituting the system state equations become:

$$\frac{di_{sd}}{dt} = -ai_{sd} + \omega i_{sq} + bV_{sd} - b\mathrm{V}_{Td} \tag{12}$$

$$\frac{di_{sq}}{dt} = -ai_{sq} - \omega i_{sd} + bV_{sq} - b\mathrm{V}_{Tq} \tag{13}$$

where $a=(R_s+R_T)/(L_s+L_T)$, $b=1/(L_s+L_T)$, $\omega$ is grid frequency, $V_{sx}$ are grid voltage and $V_{Tx}$ are terminal voltage grid side converter.

### B. *Instantaneous Complex Power (d-q)*

The *α-β* or Clarke transformation offers advantages in the dimension order reduction. However, for feedback control implementation is highly desirable that the signals to be constant. The inverse Park transform allows, from constant values generating signals in-phase or anti-phase, respect to the reference. That is especially useful for flexible AC transmission systems (FACTS) and power conditioners' control [16]. Instantaneous complex power are expressed by [16]

$$S_s = \frac{3}{2}\left[\left(V_{sd}i_{sd} + V_{sq}i_{sq}\right) + j\left(V_{sq}i_{sd} - V_{sd}i_{sq}\right)\right] \tag{14}$$

Equation (14) suggest that if $V_{Tq}$=0, the active and reactive power components are proportional to $i_d$ and $i_q$, respectively. This property is widely employed in the control of grid-connected three-phase VSC systems [17]. The angle θ of the grid voltage is computed and provided by a phase-locked loop [17]. If the reference frame is as $V_{Tq} = 0$ and $V_{Td}=|V|$, the equation for the power will be

$$S = \frac{3}{2}\left[V_{sd}i_{sd} - jV_{sd}i_{sq}\right] \tag{17}$$

where

$$P_s = \frac{3}{2}V_{sd}i_{sd} = \frac{3}{2}|V|i_{sd} \tag{18}$$

$$Q_s = -\frac{3}{2}V_{sd}i_{sq} = \frac{3}{2}|V|i_{sq} \tag{19}$$

Therefore, controlling the direct and quadrature current components can regulate the active and reactive power, respectively.

### C. *Phase-Locked Loop*

The PLL is a circuit synchronizing an output signal with a reference or input signal in frequency as well as in phase. In the synchronized state the phase error between the output signal and the reference signal is zero, if a phase error builds up, a control mechanism act, in such a way that the phase error is again reduced to a minimum [18]. The PLL takes the voltage of the conventional electricity grid for to get the synchronization angle as shown in the block diagram of Fig. 1. This paper proposes a PID control to the PLL, the purpose of this controller is to keep the angular frequency of the current generated equal to the conventional grid. The angle $\theta_r$ for the Park transformation is detected from the three-phase voltages at the low-voltage side of the grid side transformer by using a phase-locked loop (PLL) [19]. The basic configuration of the PLL system is shown in Fig. 3. The angular position of dq reference frame is controlled by a feedback loop, which regulates the *q* component to zero, where the *d* component depicts the voltage vector amplitude and its phase is determined by the output of the feedback loop [19].

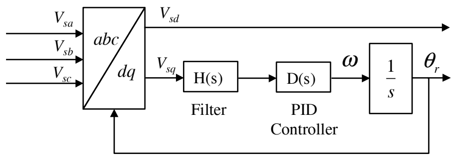


Fig. 3 PLL controller.

## IV. CONTROL WECS-BASED ON PMSG

Figure 1 shows the block diagram of a WECS using a DC/DC boost converter. Similar to the other wind energy systems, three variables need to be tightly controlled: the DC voltage, the generator active power, and the grid reactive power.

### A. Grid Side Converter Control

The control scheme of this strategy is exhibited in Fig. 4. The grid-side converter control aim is to supply a reliable electric power to the consumers, following a specific set of parameters such as voltage, frequency and harmonic levels. The control scheme contains two cascaded loops. The inner loops independently control the grid $i_d$ and $i_q$ currents, the reactive and active power, respectability. The feedback and feed-forward signals are first transformed to the *dq* frame and then processed by compensators to produce the control signals. These control signals are transformed to the *abc* frame and sent to the grid side converter.

Under normal conditions the wind turbine's reactive power output is controlled under the range according to the grid codes. This work proposes the use of adaptive PI controllers to maintain the current and frequency constant. Reactive power flow should be maintained close to zero. Both parameters the proportional and integer gains are updated online to attain a proper performance under different operating conditions, without restructuring the control scheme.

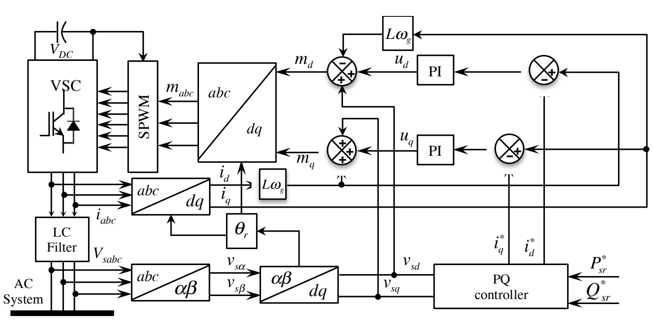


Fig. 4. Block Diagram of grid side converter control.

$$\frac{d\theta_r}{dt} = V_{qs} H(s)\left(\omega_0 t + \theta_0 - \theta_r\right) \tag{20}$$

### B. Control of PLL

In this work, a PID control to keep the voltage $v_q$=0 is implemented. A classical feedback control loop is observed in the equation (20) in which $\omega_0 t+\theta_0$ is the reference input, $\theta_r$ is the output and H(s) is the transfer function of the control.

The function H(s) involves the transfer function of the control and a filter. For the design of the control PID, the system is compensated for a phase margin of approximately 55°. The figure 5 shows the bode diagram of the compensated system and without compensating. One can see that the phase margin in the compensated system is approximately to the value desired.

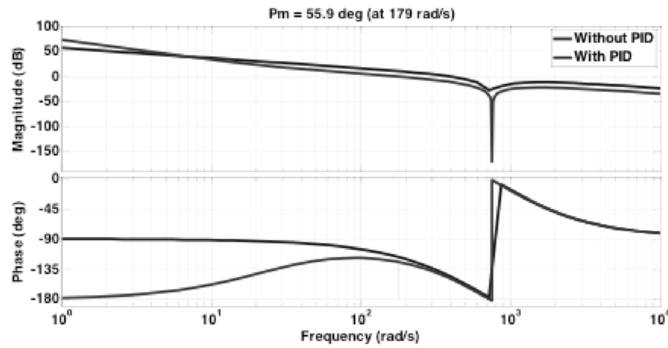


Fig. 5 Bode diagrams from PLL

## IV. SIMULATIONS RESULTS

The models presented in previous sections are implemented in MATLAB/SIMULINK for its simulation; where one can see, the system behavior under different operating conditions. The parameters of the turbine, power converters and PMSG used are given in Table I.

TABLE I. PARAMETERS OF WECS

| Wind turbine | Value |
|---|---|
| Density of air | 1.25 kg/m$^3$ |
| Blade length | 2.5 m |
| Wind speed | 10 m/s |
| Armature resistance | 3.3 Ω |
| Inductances of *d* axis and *q* axis | 41.56 mH |
| Magnetic flux | 0.4382 Wb |
| No. of poles | 3 pairs |
| Equivalent inertia | 0.0552 Kg m$^2$ |
| Boost converter | |
| Inductance | 15.91 mH |
| Capacitor | 4.7 μF |
| Desired output voltage | 650 v |
| Three-phase inverter | |
| Inductance | 25 mH |
| Resistance | 20 Ω |
| Voltage in the grid | 480 VL-L |

The wind speed profile is considered varying smoothly with step rate at different slopes, as see in Fig. 6. The system is subjected to the following sequence of events: until t = 0.05 sec, $P_{ref}$ = 1000 W $Q_{sref} \equiv 0$. At t = 0.1 sec, $P_{ref}$ is subjected to a step change from 1000 to 2000 W. At t = 0.15 s, $P_{ref}$ is subjected to another step change from 2000 to 100 W. Fig. 6 shows the instantaneous load currents when the load changes. The load current is changing with the load variations as expected. From Fig. 6, it is seen that there is no significant rise in the current waveform during load transient.

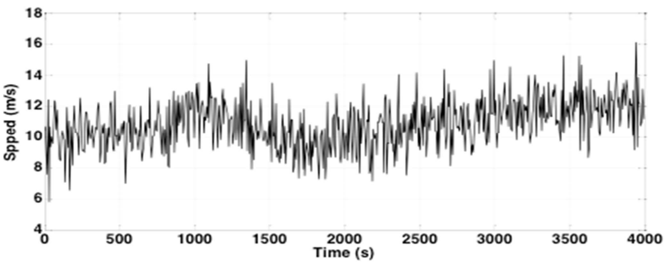


Fig. 5. Approximate wind speed

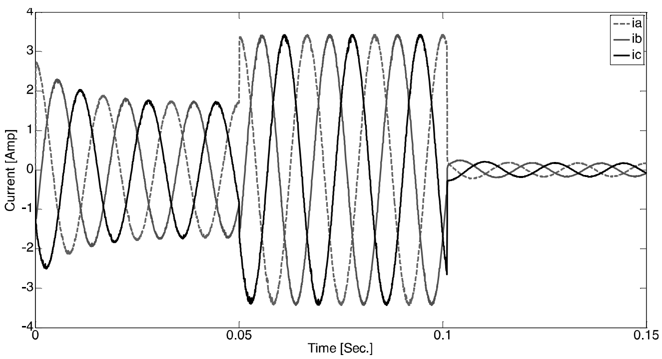


Fig. 6. Instantaneous output current.

Fig. 7 shows the simulation result of DC link voltage with the proposal and considering fixed parameters. Fig. 7 exhibits the dynamic behavior of the reactive power at DC link bus, where the proposed scheme is worked. The transient response is diminished in terms of overshot magnitude without parameters update.

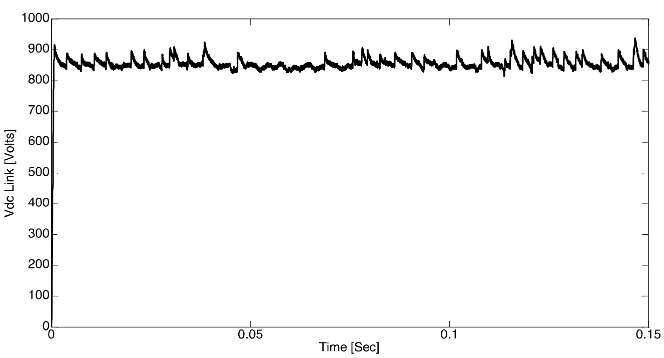


Fig. 7 DC link voltage performance.

## REFERENCES


K. Tan and S. Islam, "Optimum control strategies in energy conversion of PMSG wind turbine system without mechanical sensors," *IEEE Trans. Energy Conversion*, vol. 19, no. 2, pp. 392–399, 2004.

T. Ackermann, *Wind Power in Power Systems, England*, Wiley, 2012.

I. Munteanu, A. I. Bratcu, N. A. Cutululis and E. Ceanga. *Optimal Control of Wind Energy Systems*, London, Springer. 2008.

B. Wu, Y. Lang and S. Kouro, *Power Conversion and Control of Wind Energy Systems,* USA, IEEE Press, 2011.

M. Chinchilla, S. Arnaltes, and J. C. Burgos, "*Control of permanent-magnet generators applied to variable-speed wind energy systems connected to the grid*," IEEE Trans. on Energy Conversion, vol. 21, no. 1, pp. 130–135, 2006.

G. Abad, J. López, M. A. Rodríguez, L. Marroyo and G. Iwanski, *Doubly Fed Induction Machine*, New Jersey: Wiley, 2011, pp. 1-25.

L. R. Limongi, R. Bojoi, C. Pica, F. Profumo and A. Tenconi, Analysis and Comparison of Phase Locked Loop Techniques for Grid Utility Applications, *Proc. IEEE PCC*, Nagoya, pp. 674-681, 2007.

Hoa M., and D. Subbaram N., "Advanced Control Strategies for Wind Energy Systems: An Overview", in Power Systems (PSCE), 2011 International Conference on, Vol. 1, 2011, pp. 1-8.

X. Yao, X. Su, and L. Tian, "Wind turbine control strategy at lower wind velocity based on neural network PID control," in Intelligent Systems and Applications, 2009. ISA 2009. International Workshop on, pp. 1 – 5, May. 2009.

Z. Xing, Q. Li, X. Su, and H. Guo, "Application of BP neural network for wind turbines," in Intelligent Computation Technology and Automation, 2009. ICICTA '09. *Second International Conference on*, vol. 1, pp. 42 –44, Oct. 2009.

X. Yao, X. Su, and L. Tian, "Pitch angle control of variable pitch wind turbines based on neural network PID," in Industrial Electronics and Applications, 2009. ICIEA 2009. *4th IEEE Conference on*, pp. 3235 – 3239, May. 2009.

A. Uehara, A. Pratap, T. Goya, T. Senjyu, A. Yona, N. Urasaki and T. Funabashi, "*A Coordinated Control Method to Smooth Wind Power Fluctuations of a PMSG-Based WECS*", IEEE Trans on Energy Conversion, Vol. 26, No. 2, pp. 550-558, June 2011.

I. Munteanu, A. Iuliana B., N. A. Cutululis, and E. Ceanga, *Optimal control of Wind Energy Systems*, London, Springer, 2008.

E. Haque, M. Negnevitsky, and K. M. Muttaqi, "*A Novel Control Strategy for a Variable-Speed Wind Turbine With a Permanent-Magnet Synchronous Generator*", IEEE Trans. on Industry Applications, Vol. 46, No. 1, pp. 331-339 Jan./Feb. 2010.

J. Arrillaga, Y. Liu, N. Watson and N. Murray, *Self-Commutating Converters for High Power Applications*, United Kingdom: Wiley, 2009.

J. C. Rosas, "Simple Topologies for Power Conditioners and FACT's Controllers," Ph.D. dissertation, Cinvestav, Guadalajara, 2009.

A. Yazdani and R. Iravani, Voltage-Sourced Converters in Power Systems Modeling, Control, and Applications, New Jersey: Wiley, 2010.

R. E. Best, Phase, *Locked Loops. Design, Simulation and Applications, Oberwil*, Switzerland, McGraw-Hill, 2003.

A. Uehara, A. Pratap, T. Goya, T. Senjyu, A, Yona, N. Urasaki A Coordinated Control Method to Smooth Wind Power Fluctuations of a PMSG-based WECS, IEEE Trans. On Energy Conversion, vol. 26, no. 2, June 2011