Journal of Engineering Science and Technology
Vol. 8, No. 4 (2013) 493 - 507

WIND ENERGY CONVERSION SYSTEMS - A TECHNICAL REVIEW

N. RAMESH BABU[1], P. ARULMOZHIVARMAN[2,*]

[1]School of Electrical Engineering, VIT University, Vellore, India
[2]School of Electronics Engineering, VIT University, Vellore, India
*Corresponding Author: parulmozhivarman@vit.ac.in

Abstract

Wind power production has been under the main focus for the past decade in power production and tremendous amount of research work is going on renewable energy, specifically on wind power extraction. Wind power provides an eco-friendly power generation and helps to meet the national energy demand when there is a diminishing trend in terms of non-renewable resources. This paper reviews the modeling of Wind Energy Conversion Systems (WECS), control strategies of controllers and various Maximum Power Point Tracking (MPPT) technologies that are being proposed for efficient production of wind energy from the available resource.

Keywords: Wind energy, Conversion systems, Maximum power, Induction generator, Permanent magnet, Wind turbine.

1. Introduction

The wind energy conversion system (WECS) includes wind turbines, generators, control system, interconnection apparatus. Wind Turbines are mainly classified into horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). Modern wind turbines use HAWT with two or three blades and operate either downwind or upwind configuration. This HAWT can be designed for a constant speed application or for the variable speed operation. Among these two types variable speed wind turbine [1] has high efficiency with reduced mechanical stress and less noise. Variable speed turbines produce more power than constant speed type, comparatively, but it needs sophisticated power converters [2, 3], control equipments to provide fixed frequency and constant power factor [4].

Abbreviations

DFIG	Fed induction generator
DTC	Direct torque control
FOC	Field oriented control
HAWT	Horizontal axis wind turbines
MPPT	Maximum power point tracking
PMSG	Permanent magnet synchronous generator
VAWT	Vertical axis wind turbines
WECS	Wind energy conversion system

The generators used for the wind energy conversion system mostly of either doubly fed induction generator (DFIG) or permanent magnet synchronous generator (PMSG) type. DFIG have windings on both stationary and rotating parts, where both windings transfer significant power between shaft and grid. In DFIG the converters have to process only about 25-30 percent of total generated power (rotor power connected to grid through converter) and the rest being fed to grid directly from stator. Whereas, converter used in PMSG has to process 100 percent power generated, where 100 percent refers to the standard WECS equipment with three stage gear box in DFIG. Majority of wind turbine manufacturers utilize DFIG for their WECS due to the advantage in terms of cost, weight and size. But the reliability associated with gearbox, the slip rings and brushes in DFIG is unsuitable for certain applications. PMSG does not need a gear box and hence, it has high efficiency with less maintenance [3, 5-9]. The PMSG drives achieve very high torque at low speeds with less noise and require no external excitation. In the present trend WECS with multibrid [10, 11] concept is interesting and offers the same advantage for large systems in future. Multibrid is a technology where generator, gearbox, main shaft and shaft bearing are all integrated within a common housing. This concept allows reduce in weight and size of generators combined with the gear box technology. The generators with multibrid concept become cheaper and more reliable than that of the standard one, but it loses its efficiency.

To achieve high efficient energy conversion on these drives different control strategies can be implemented like direct torque control (DTC) [12], field oriented control (FOC) [13]. The FOC using PI controller has linear regulation and the tuning becomes easier. The wind turbine electrical and mechanical parts are mostly linear and modeling will be easier. The blade aerodynamics of the wind turbine is a nonlinear one and hence the overall system model will become nonlinear. The wind energy conversion system which will be modeled as shown in Fig. 1 may not be optimal for extracting maximum energy from the resource and hence various optimization techniques are used to achieve the goal.

2. WECS modeling

The basic device in the wind energy conversion system is the wind turbine which transfers the kinetic energy into a mechanical energy. The wind turbine is connected to the electrical generator through a coupling device gear train. The output of the generator is given to the electrical grid by employing a proper controller to avoid the disturbances and to protect the system or network. Figure 1 shows the overall block diagram of the wind energy conversion system (WECS). Here, V_ω represents wind speed, P_ω, P_m and P_e represent wind power, mechanical power and electrical power respectively.

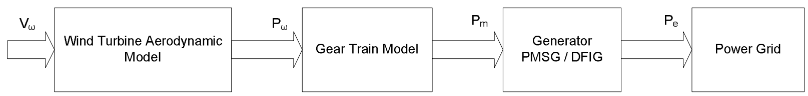

Fig. 1. WECS Block Diagram.

2.1. Wind turbine

Wind energy is transformed into mechanical power through wind turbine and hence it is converted into electrical power. The mechanical power is calculated by using the following equation [13],

$$P_m = 0.5\rho A C_p(\lambda,\beta) v_{wind} \tag{1}$$

where, ρ is the air density which normally takes the value in the range 1.22-1.3 kg/m^3, A is the area swept out by turbine blades (m^2), v_{wind} is the wind speed (m/s), $C_p(\lambda,\beta)$ is the power coefficient [14-17] which depends on two factors: β, the blade pitch angle and the tip speed ratio and, λ, which is defined as:

$$\lambda = \Omega . R / v_{wind} \tag{2}$$

where, Ω is the angular speed (m/s) and R is the blade radius (m).

The power coefficient, C_p is defined as

$$C_p(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)\exp\left(\frac{-C_5}{\lambda_i}\right) + C_6\lambda \tag{3}$$

where

$$\frac{1}{\lambda_i} = \left(\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}\right)$$

and coefficients $C_1 = 0.5176$, $C_2 = 116$, $C_3 = 0.4$, $C_4 = 5$, $C_5 = 21$, and $C_6 = 0.0068$.

The power coefficient is nonlinear, and it depends upon turbine blade aerodynamics and it can be represented as a function of tip speed ratio, λ. The optimum value of λ corresponds to maximum of C_p from the power coefficient-tip speed ratio curve.

Figure 2 shows the power coefficient with respect to tip speed ratio. It is observed that the maximum power coefficient value $C_{p\_max}(\lambda,\beta) = 0.48$ for $\lambda = 12$ and for $\beta = 0^0$. This particular value of λ_{opt} results in optimal efficiency point where maximum power is captured from wind by the turbine.

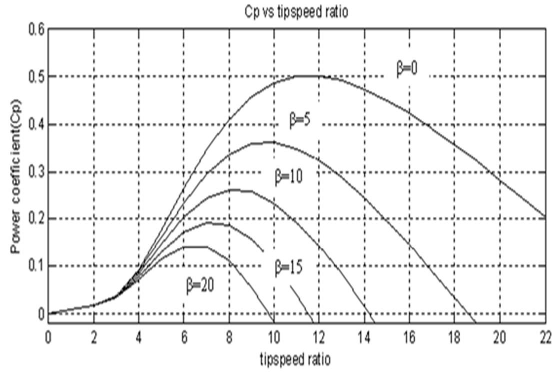

Fig. 2. Power Coefficient of the Wind Turbine Model [13].

As the power transmitted is assumed to be the product of rotational speed with mechanical torque, the rotational torque is obtained as:

$$T_m = P_m / \Omega \tag{4}$$

Thus the optimal angular speed is achieved through the relation,

$$\Omega_{opt} = \lambda_{opt}\, v_{wind} / R \tag{5}$$

and the maximum mechanical power is,

$$P_{m\_max} = 0.5 \rho A C_{pmax} v^3{}_{wind} \tag{6}$$

Figure 3 shows the wind turbine power characteristics obtained for various values of the wind tangential speed [18]. Here it can be observed that maximum power (active) is achieved through optimal wind speeds and not at high wind velocity. The wind turbine does not operate when the wind speed is less than the minimum speed because the captured wind energy is not enough to compensate the losses and operation cost.

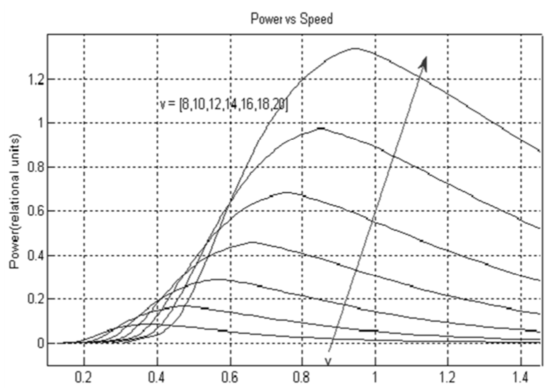

Fig. 3. Wind Turbine Power Characteristics [18].

2.2. Drive train modeling

The gear box enables to convert the slow speed of the turbine blades to high speed required by the electrical machine through the gear box ratio, g_r. This element converts the mechanical torque and the machine speed as follows [19]:

$$T_{aero} = g_r \,.\, T_m \tag{7}$$

$$\Omega_m = g_r \,.\, \Omega \tag{8}$$

where, T_{aero} is the aerodynamic torque and Ω_m is the machine speed. The drive train is modeled by the simplified motion equation as follows:

$$J\frac{d\Omega_m}{dt} = T_m - T_e f\,\Omega_m \tag{9}$$

where J is the mechanical inertia of the wind turbine and generator, T_e is the electromagnetic torque, and f is the friction coefficient.

2.3. PMSG modeling

The modeling of PMSG type electrical equipment is made through the following equations, represented by d-q reference frame [19]:

$$V_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \tag{10}$$

$$V_q = R_s i_q + L_q \frac{di_q}{dt} - \omega_e L_d i_d + \omega_e \varphi_m \tag{11}$$

where V_d and V_q are d and q components of stator voltages (V), i_d and i_q are d and q components of stator currents (A), R_s is stator resistance (ohms), L_d and L_q are machine inductances (H), ω_e is the electrical speed (rad/s) and φ_m is the magnetic flux (wb). The electrical torque is obtained through the following equation:

$$T_e = \frac{3}{2} p \left\{ \varphi_m i_q + \left(L_d - L_q\right) i_d i_q \right\} \tag{12}$$

where p is the pair of poles. The rotor dynamics of the machine is given by

$$T_m - T_e = B\,\omega_r + J\frac{d\omega_r}{dt} \tag{13}$$

where B is the rotor friction (kgm^2/s), J is the rotor inertia (kgm^2), ω_r is rotor speed (rad/s) and T_m is the mechanical torque produced by wind (Nm). The machine dynamics can be simplified by assuming ($L_d = L_q = 0$) and the d-reference current is zero ($i_d^* = 0$) and hence the product term $(L_d - L_q)i_d i_q$ is negligible. More information about the PMSG modeling is presented in [20-22].

2.4. DFIG modeling

The commonly used model for induction generator is the Park model [20]. To obtain its state model we neglect stator resistance, and then we have:

$\Phi_{sq} = 0$, $\frac{d\Phi_{sd}}{dt} = 0$, $V_{sd} = 0$ and $V_{sq} = - V_s$

where V_s is the stator voltage. The reduced state model [23] is obtained as follows:

$$V_{rd} = \sigma L_r \frac{di_{rd}}{dt} + r_r\, i_{rd} - (\omega_s - \Omega)\, \sigma L_r\, i_{rq} \tag{14}$$

$$V_{rd} = \sigma L_r \frac{di_{rq}}{dt} + r_r i_{rq} + (\omega_s - \Omega)\, \sigma L_r\, i_{rd} + \frac{M}{L_s} \Phi_{sd}(\omega_s - \Omega) \tag{15}$$

where V_{rd} and V_{rq} are the d and q components of rotor voltage (V), V_{sd} and V_{sq} are the d and q components of stator voltage (V), i_{rd} and i_{rq} are the d and q components of rotor current (A), Φ_{sd} and Φ_{sq} are the d and q components of stator flux (wb), ω_s is the synchronous pulsation, Ω is the generator speed, r_r is the rotor resistance, L_s and L_r are the stator and rotor inductances (H), M is the mutual inductance (H) and σ is the leakage parameter given as, $\sigma = 1 - (M^2/L_sL_r)$. More information about stand-alone and/or grid connected operation of DFIG is presented in papers [24-27].

DFIG is one of the most important generators and are widely used for variable speed WECS. Nowadays, this type of DFIG-WECS has a part of wind energy market, which is close to 50%. Major wind turbine producers manufacture wind energy conversion system based on DFIG's but the difficulties associated in complying with grid side ride-through requirement may limit its use in future [28, 29]. To overcome the above stated difficulty, PMSG technology looks most promising in WECS, which shares nearly 45% in wind energy market. Multi-pole PMSG's with full power back-to-back converters appears to be the configuration to be adapted by most of the wind turbine manufacturers in near future, gradually replacing DFIG in wind energy market. Wind energy conversion systems with the range of 1.5 MW to 3 MW are manufactured by 44 companies in 163 models. Among these 60 models uses DFIG, 66 models uses PMSG, 18 models uses cage type IG and 19 models uses synchronous generator with external excitation [5].

3. Control Strategies

3.1. DFIG-WECS control

Controller is designed to adjust the turbine speed to extract the maximum power from wind source. Usually PI controller is designed for this purpose according to the estimated parameters either offline or online and the observed disturbance torque is feed forward to increase system robustness. But this type of classical controller is not enough to serve the purpose efficiently. Hence various improvements are made for the controller to achieve the requirement as stated below.

The general structure of control block diagram in the DFIG-WECS having two levels of control is shown in Fig. 4. The highest level is WECS optimization which is explained in section IV. The lower level control being the electrical control system, i.e. torque and reactive power control. The rotor side controller (RSC) and grid side controller (GSC) are employed to serve the electrical control system. To compromise the dynamics of variable speed WECS Poitiers et al. [30] has implemented a two degree freedom Regulation-Solution-Tracking (R-S-T) controller, which is a widely preferred digital controller and Linear Quadratic

Gaussian (LQG) controller with state feedback. For the ease of implementation of controller tuning the LQG controller is preferred than R-S-T controller.

To reduce the output power fluctuations of DFIG with a flywheel energy storage system (FESS) Jerbi et al. [31-33] has proposed a fuzzy supervisor using sugeno fuzzy model based on two parameters flywheel speed and wind power accessibility so as to ensure a smooth reactive power to the load supplied by the wind generator [19]. This ensures to reduce the voltage fluctuations. For the variable speed WECS [34] has proposed a method which will combine fuzzy neural network and sliding mode speed observer. This technique allows faster convergence to a simple linear dynamic behavior, even in presence of parameter changes and uncertainties which are the major problems expected from variable speed drive control. As most of the controllers depends on torque control M. Pucci [15] proposes a method based on speed control of the machine. This is achieved through total least squares (TLS) EXIN full order observer [35] which turns as an intelligent sensor less technique for wind generation control

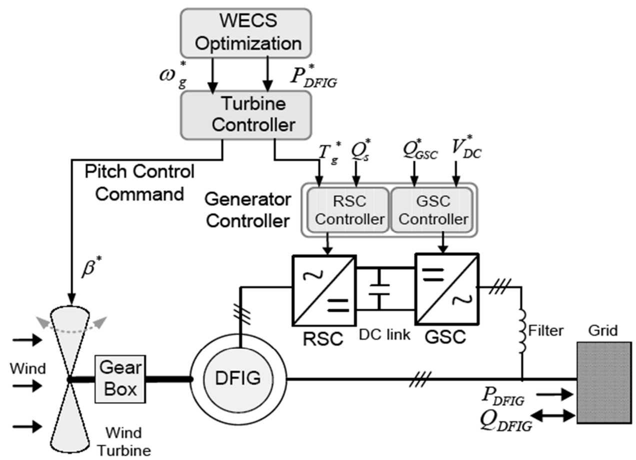

Fig. 4. Control Block Diagram of DFIG Based WECS [30].

There are other types of controllers using PID for controlling the WECS with optimal power output. Muhando et.al proposes a self-tuning regulator [17] by incorporating recursive least square algorithm to predict the process parameters and update the states. This regulator gives more efficient compared to classical PID controller. To achieve optimal power, adaptive fuzzy PID control strategies are proposed [36] and proved the performance is improved than that of conventional one.

Many research papers discuss the intelligent controllers with sensor less [37] wind energy control. Whei-Min Lin et al. [38] proposed a technique where design is made online through recurrent fuzzy neural controller (RFNN) with high performance model reference adaptive system (MRAS) observer which replaces the use of sensors to measure the parameters. Lin et.al suggested that to increase the learning ability of back propagation network of RFNN modified particle swarm optimization is used (mPSO). This provides fast and accurate velocity information to avoid anemometers and rotor position is estimated from flux linkages.

Behra and Rao [39] investigated novel grid side controller, modeled in synchronously rotating reference frame to improve the dynamic response on various load conditions. Liu and Hsu [40] discuss the stator resistance effect on the excitation voltage, which gives the maximum output power and minimal loss for the DFIG. The DFIG-WECS model can be validated through various simulation tools. To improve the real time simulation time FPGA's can be incorporated using Runge-Kutta numerical integration algorithm [41] in compared to PC based simulation.

3.2. PMSG-WECS control

Figure 5 shows the block diagram of PMSG based WECS with two stages as optimization and electrical controllers. The various techniques are discussed as below.

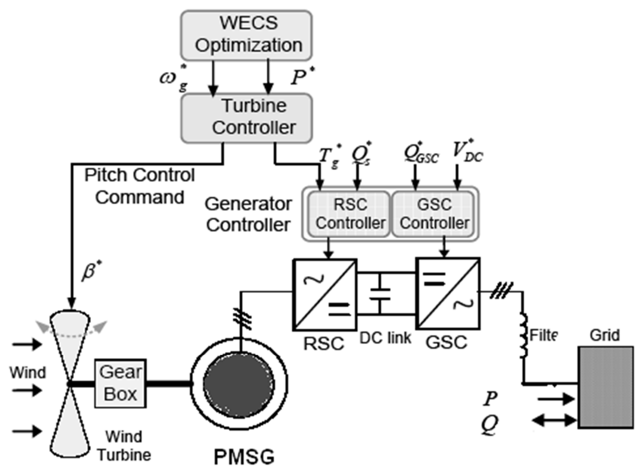

Fig. 5. Control Block Diagram of PMSG Based WECS [13].

Jordi Zaragoza et al. [13] discusses the control of PMSG based WECS using field oriented control (FOC) for controlling speed regulation and generating current. A PI controller is used for this purpose and the tuning parameters are determined through zero-pole cancellation (ZPC) strategy. Jemaa Brahmi et.al [42] compares three control methods for PMSG based WECS. In the first model MRAS observer is used to estimate the parameters of the controller by comparing output of reference model and adaptive model. Secondly artificial neural network (ANN) based observer were trained to produce desired output correction to the estimated speed. And lastly, sliding mode observer (SMO) based control is discussed. Among these three techniques SMO and ANN observer gives good results when static resistance varies and chattering phenomenon is observed with SMO. The static resistance causes a static error in case of MRAS observer. The SMO is more robust than the other two methods.

Kelvin Tan and Syed Islam [43] proposed a sensor less optimal control strategy using fuzzy power mapping technique. Using the result of power mapping loop and alternator frequency derivative loop, the controller allows the bus voltage to vary to maximum power operating point. Bao et al. [44] proposes an adaptive control strategy [45] for variable speed wind turbine using neural based identifier [46] and inverse model controller which has good learning capability and high performance than nonlinear controller. Wang et.al proposes indirect matrix converter of PID [47] type which has more degree of freedom and can be implemented in an easy way for the PMSG based WECS. This shows excellent dynamic performances with lower mechanical stress [48] and robust in control.

There are other techniques for controlling the WECS [49]. Wind prediction control scheme is the one where the control parameters are obtained through forecasting the wind using autoregressive statistical models. This method will avoid the mechanical sensors used to get the actual parameter tracking.

4. Optimization of WECS

The next challenging task in WECS is to operate the system at the optimal point so as to increase the output. The optimization block is shown in Figs. 4 and for DFIG and PMSG based WECS. Among the various techniques followed for this, maximum power point tracking (MPPT) [50] plays a vital role.

Kesraoui et al. [51] proposed the MPPT algorithm using step and search method to extract the maximum power from the wind turbine from cut-in to rated wind velocity by sensing the dc link power. Iulian Munteanu et al. [52] used wind turbulence as a search for MPPT instead of sinusoidal search. Here high speed shaft's average speed is slowly adjusted using FFT of measures from system as an estimate to the optimal point. This method is effective when the wind turbulence level is high. The same author also proposes sliding mode control [53], optimal regime tracking [54, 55], and frequency separation principle [56] for optimizing the WECS based on PMSG type. Syed Muhammad et.al [57] proposes a novel method of MPPT along with Hill Climb Search (HCS) algorithm [58]. This method performs self-tuning to cope with the non-constant efficiency of the generator- converter systems. This paper ensures high control efficiency and faster tracking under rapid wind change without requiring any prior knowledge of system characteristics.

Adaptive neuro fuzzy inference system (ANFIS) based MPPT is discussed in Meharrar et al. [59]. Here variation of wind speed is used as input for ANFIS to predict optimal speed rotation and back propagation learning algorithm is used for training this network. This method shows better response than compared to FLC. Other type of fuzzy controller was proposed by Calderaro et al. [60] using Takagi-Sugeno-Kang (TSK) model to maximize energy extraction which avoids sensors in MPPT. To estimate the optimum value for generator support vector regression (SVR) algorithm is used by Lee et al. [61]. It is proved that the generator losses are reduced up to 40% and also excellent in accuracy. Kazmi et al. [15] proposes growing neural gas (GNG) based MPPT which is having FOC integrated with TLS EXIN observer without sensors to optimize the system.

A new method of MPPT which uses gradient approximation algorithm is proposed by Ying-Yi Hong et al. [62]. This method does not require anemometer, tachometer and information of wind turbine generator system characteristics. As the gradient approximation converges very fast and the implementation is easy, this method is efficient for an optimization problem. Kongnam and Nuchprayoon [63] propose to apply PSO to solve for optimum rotor speed in fixed and variable speed operation of WECS. In this power and energy are more dependent of mean wind speed than weibull distribution of speed.

Pitch angle control of wind turbine turns out to be another optimization problem in WECS [64, 65]. Yilmaz and Zafer [66] discusses radial basis function based neural network controller which tracks the reference signal based on training to achieve better controller. Boukhezzar et al. [67] propose control strategy by combining torque control and pitch control which leads to good performance in rotor speed regulation and electrical power regulation with acceptable control loads compared to classical PID and LQG controllers.

5. Conclusions

An attempt has been made in this paper to discuss the most-recent research trends in the field of wind energy conversion systems. From the study, it can be concluded that in case of generators and converters, most system adopts DFIG with back-to-back converter due to their less weight and cost. However, for the large capacity wind turbines where efficiency and reliability plays a major role has been utilizing PMSG's even though it has more weight and increased installation cost. Moreover, WECS based on the multibrid concept, will become more attractive alternative technology in the future.

Regarding the controllers for the WECS, is still the most important and challenging topic of research as there are various controllers had been proposed by various researchers has been discussed in this paper. As there are lot of ongoing developments takes place at various stages of WECS, it is noted that the most suitable (optimized) solutions to extract maximum power of the installed system is ad-hoc, rather than generalized solution.

The overview of this information highlights the current research progress in the field of wind energy conversion system and this will be helpful for the new researchers to focus on the above area.

References

1. Herbert, G.M.J.; Iniyan, S.; Sreevalsan, E.; and Rajapandian, S. (2007). A review of wind energy technologies. *Renewable and Sustainable Energy Reviews*, 11(6), 1117-1145.
2. Melicio, R.; Mendes, V.M.F.; and Catalao, J.P.S. (2010). Power converter topologies for wind energy conversion system: Integrated modeling, control strategy, performance simulation. *Renewable Energy*, 35(10), 2165-2174.
3. Baroudi, J.A.; Dinavahi, V.; Knight, A.M. (2007). A review of power converter topologies for wind generators. *Renewable Energy*, 32(14), 2369-2385.
4. Hau, E. (2006). *Wind Turbine: Fundamentals, Technologies, Application and Economics*, Springer, Berlin, Germany.

5. Liserre, M.; Cardenas, R.; Molinas, M.; and Rodriguez, J. (2011). Overview of multi-MW wind turbines and wind parks. *IEEE Transactions on Industrial Electronics*, 58(4), 1081-1095.
6. Liserre, M.; Sauter, T.; and Hung, J.Y. (2010). Future Energy Systems: Integrating Renewable Energy Sources into the Smart Power Grid through Industrial Electronics. *IEEE Industrial Electronics Magazine*, 4(1), 18-37.
7. Blaabjerg, F.; Teodorescu, R.; Liserre, M.; and Timbus, A.V. (2006). Overview of control and grid synchronization for distributed power generation systems. *IEEE Transactions on Industrial Electronics*, 53(5), 1398-1409.
8. Hansen, L.H.; Helle, L.; Blaabjerg, E.; Ritchie, S.; Nielson, M.; Bindner, H.; Sorenson, P.; and Bak-Jensen, B. (2001). Conceptual survey of generators and power electronics for wind turbines. *Risø National Lab., Roskilde, Denmark, Technical Report*, Riso-R-1205 (EN), 1-99.
9. Li, H.; and Chen, Z. (2008). Overview of different wind generator systems and their comparisons. *IET Renewable Power Generation*, 2(2), 123-138.
10. Wind Turbines and Wind Farms Database. Accessed on Oct. 2010. [Online]. Available: *http://www.thewindpower.net/turbines_list.php.*
11. Li, H.; Chen, Z.; and Polinder, H. (2009). Optimization of multibrid permanent magnet wind generation systems. *IEEE Transactions on Energy Conversion*, 24(1), 82-92.
12. Kowalski. C.; Lis, J.; and Kowalska, O.T. (2007). FPGA implementation of DTC control method for induction motor drive. *Proceedings of The International Conference on Computer as a Tool*, *EUROCON*, Warsaw, 1916-1921.
13. Zaragoza, J.; Pou, J.; Arias, A.; Spiteri, C.; Robles, E.; and Ceballos, S. (2011). Study and experimental verification of control tuning strategies in a variable speed wind energy conversion system. *Renewable Energy*, 36(5), 1421-1430.
14. Mansour, M.; Mansouri, M.N.; and Mmimouni, M.F. (2011). Study and control of a variable-speed wind-energy system connected to the grid. *International Journal of Renewable Energy Research*, 1(2), 96-104.
15. Cirrincione, M. Pucci, M.; and Vitale, G. (2011). Neural MPPT of variable speed wind generators with induction machines in a wide speed range. *Proceedings in IEEE Conference on Energy Conversion Congress and Exposition*, 857-864.
16. Heir. S. (1998). *Grid integration of wind energy conversion systems*. Newyork: John Wiley and Sons Inc.
17. Muhando, B.; Senjyu, T.; Kinjo, H.; and Funabashi, T. (2009). Extending the modeling framework for wind generation systems: RLS-based paradigm for performance under high turbulence inflow. *IEEE Transactions on Energy Conversion*, 24(1), 211-221.
18. Mishra, S.; Mishra, Y.; Li, F.; and Dong, Z.Y. (2009). TS-fuzzy controlled DFIG based wind energy conversion system. *Proceedings of IEEE Power and Energy Society General Meeting*, Canada, 1-7.

19. Krichen, L.; Francois, B.; and Ouali, A. (2008). A fuzzy logic supervisor for active and reactive power control of a fixed speed wind energy conversion system. *Electrical Power System Research*, 78(3), 418-424.
20. Nicolas, C.; and Poul, S. (2007). Proceedings of Nordic Wind Power Conference. *Risø National Lab., Roskilde, Denmark, Technical Report,* Riso-R-1624 (EN), 1-271.
21. Zhang, J.; Chen, Z.; and Cheng, M. (2007). Design and comparison of a novel stator interior permanent magnet generator for direct-drive wind turbines. *IET Renewable Power Generation*, 1(4), 203-210.
22. Chinchilla, M.; Arnaltes, S.; and Burgos, J.C. (2006). Control of permanent magnet generators applied to variable-speed wind-energy systems connected to the grid. *IEEE Transactions on Energy Conversion*, 21(1), 130-135.
23. Mayurappriyan, P.S.; Jerome, J.; Ramkumar, M.; and Rajambal, K. (2009). Dynamic modeling and analysis of wind turbine driven doubly fed induction generator. *International Journal of Recent Trends in Engineering*, 2(5), 367-372.
24. Abad, G.; Rodriguez, M.A.; Iwanski,G.; and Poza, J. (2010). Direct power control of doubly-fed-induction-generator-based wind turbines under unbalanced grid voltage. *IEEE Transactions on Power Electronics*, 25(2), 442-452.
25. Pena, R.; Clare, J.C.; and Asher, G.M. (1996). Doubly-fed induction generators using back-to-back PWM converters and its applications to variable-speed wind-energy generation. *Proceedings of IEE Electrical Power Applications*, 143(3), 231-241.
26. Cardenas, R.; Pena, R.; Clare, J.; Asher, G.; and Proboste, J. (2008). MRAS observers for sensorless control of doubly-fed induction generators. *IEEE Transactions on Power Electronics*, 23(3), 1075-1084.
27. Peña, R.; Cardenas, R.; Proboste, J.; Asher, G.; and Clare, J. (2008). Sensorless control of doubly-fed induction generators using a rotor current based MRAS observer. *IEEE Transactions on Industrial Electronics*, 55(1), 330–339.
28. Iov, F.; Teodorescu, R.; Blaabjerg, F.; Andersen, B.; Birk, J.; and Miranda, J. (2006). Grid code compliance of grid-side converter in wind turbine systems. *Proceedings of 37th IEEE Power Electronics Specialists Conference*, 1-7.
29. *Grid Code. High and Extra High Voltage*, E.ON Netz, Bayreuth, *Germany*. [Online]. Available: www.eon-netz.com.
30. Poitiers, F.; Bouaouiche, T.; and Machmoum, M. (2009). Advanced control of a doubly-fed induction generator for wind energy conversion. *Electrical Power System Research*, 79(7), 1085-1096.
31. Jerbi, L.; Krichen, L.; and Ouali, A. (2009). A fuzzy logic supervisor for active and reactive power control of a variable speed wind energy conversion system associated to a flywheel storage system. *Electrical Power System Research*, 79(6), 919-925.
32. Kairous, D.; Wamkeue, R.; and Belmadani, B. (2010). Sliding mode control of DFIG based variable speed WECS with flywheel energy storage. *Proceedings of XIX International Conference on Electrical Machines*, *ICEM (IEEE)*, 1-6.

33. Ghedamsi, K.; and Aouzellag, D. (2010). Improvement of the performances of Wind energy conversion systems. *International Journal of Electrical Power and Energy System*, 32(9), 936-945.
34. Lin,W.M.; Hong, C.M.; and Cheng, F.S. (2010). Fuzzy neural network output maximization control for sensorless wind energy conversion system. *Energy*, 35(2), 592-601.
35. Cirrincione, M.; Pucci, M.; Cirrincione, G.; and Capolino, G.-A. (2011). Sensorless control of induction motor by a new neural algorithm: The TLS EXIN neuron. *IEEE Transactions on Industrial Electronics*, 54(1), 127-149.
36. Wu, D.; and Wang, Z. (2008). The study of Optimal Power Control system of MW variable speed wind turbine. *WSEAS Transactions on Systems*, 7(10), 890-899.
37. Wei, Q.; Wei, Z.; Aller, J.M.; and Harley, R.J. (2008). Wind speed estimation based sensorless output maximization control for a wind turbine driving a DFIG. *IEEE Transactions on Power Electronics*, 23(3), 1156-1169.
38. Whei-Min, L.; Chih-Ming, H.; and Fu-Sheng, C. (2011). Design of intelligent controllers for wind generation system with sensorless maximum wind energy control. *Energy Conversion and Management*, 52(2), 1086-1096.
39. Behera, R.K.; and Gao, W. (2010). A novel controller for grid-side converter of doubly fed induction generator for wind power interface: An experimental investigation. *Electrical Power and Components and Systems*, 38(14), 1531-1545.
40. Liu, C.H.; and Hsu, Y. (2011). Effect of rotor excitation voltage on steady state stability and maximum output power of a doubly fed induction generator. *IEEE Transactions on Industrial Electronics*, 58(4), 1096-1109.
41. Chen, H.; Sun, S.; Aliprantis, D.C.; and Zambrano, J. (2010). Dynamic simulation of DFIG wind turbines on FPGA boards. *Proceedings of Power and Energy Conference, PECI,* 39-44.
42. Brahmi, J.; Krichen, L.; and Ouali, A. (2009). A comparative study between three sensorless control strategies for PMSG in wind energy conversion system. *Applied Energy*, 86(9), 1565-1573.
43. Tan, K.; and Islam, S. (2004). Optimum control strategies in energy conversion of PMSG wind turbine system without mechanical sensors. *IEEE Transactions on Energy Conversion*, 19(2), 392-399.
44. Bao, Y.; Wang, H.; and Zhang, J. (2010). Adaptive inverse control of variable speed wind turbine. *Nonlinear Dyn*amics. *Springer*, 61(4), 819-827.
45. Pahlevaninezhad, M.; Safaee, A.; Eren, S.; Bakshai, A.; and Jain, P. (2009). Adaptive nonlinear maximum power point tracker for a WECS based on permanent magnet synchronous generator fed by a matrix converter. *Proceedings of Energy Conversion Congress Exposition, ECCE (IEEE)*, 2578-2583.
46. Sheeja, V.; Jayaprakash, P.; Singh, B.; and Uma, R. (2010). Neural network theory based voltage and frequency controller for standalone wind energy conversion system. *Proceedings of International Conference on Power Electronics*, *Drives and Energy Systems*, 1-6.
47. Sedighizadeh, M.; and Rezazadeh, A. (2008). Adaptive PID control of wind energy conversion system using RASP1 mother wavelet basis function

networks. *Proceedings of World Academy of Science: Engineering Technology*, 39, 269-273.

48. Gonzalez, L.G.; Figueres, E.; Garceres, G.; and Carranza, O. (2010). Maximum-power-point tracking with reduced mechanical stress applied to wind-energy-conversion-system. *Applied Energy,* 87(7), 2304-2312.
49. Ahshan, R.; Iqbal, I.T.; Mann; and George, K.I. (2008). Controller for a small induction-generator based wind-turbine. *Applied Energy*, 85(4), 218-227.
50. Rao, S.S.; and Murthy, B.K. (2009). A new control strategy for tracking peak power in a wind or wave energy system. *Renewable Energy*, 34(6), 1560-1566.
51. Kesraoui, M.; Korichi, N.; and Belkadi, A. (2011). Maximum power point tracker of wind energy conversion system. *Renewable Energy*, 36(10), 2655-2662.
52. Munteanu, I.; Bratcu, A.I.; and Ceanga, E. (2009). Wind turbulence used as searching signal for MPPT in variable-speed wind energy conversion systems. *Renewable Energy*, 34(1), 322-327.
53. Muntaneau, I.; Bacha, S.; Bratcu, A.I.; Guiraud, J.; and Roye, D. (2008). Energy-reliability optimization of wind energy system by sliding mode control. *IEEE Transactions on Energy Conversion*, 23(3), 975-985.
54. Vlad, C.; Munteanu, I.; Bratcu, A.I.; and Ceanga, E. (2008). Optimal control in energy conversion of small wind power systems with Permanent magnet synchronous generator. *WSEAS Transactions on System and Control*, 3(7), 644-653.
55. Vlad, C.; Munteanu, I.; Bratcu, A.I.; and Ceanga, E. (2010). Output power maximization of low-power wind energy conversion systems revisited: possible control solutions. *Energy Conversion and Management*, 51(2), 305-310.
56. Bratcu, A.I.; Muntaneau, I.; and Ceanga, E. (2008). Optimal control of wind energy conversion system: From energy optimization to multipurpose criteria- A short survey. *Proceedings of 16th Mediterranean Conference on Control and automation*, 759-766.
57. Kazmi, S.M.R.; Goto, H.; Guo, H.J.; and Ichinokura, O. (2011). A Novel algorithm for fast and efficient speed-sensorless maximum power point tracking in wind energy conversion systems. *IEEE Transactions on Industrial Electronics*, 58(1), 29-36.
58. Wang, Y.; Chen, R.; Tan, J.; and Su, M. (2009). An optimal PID control of wind generator based on matrix converter. *Proceedings of 6th International Conference on Power Electronics and Motion Control,* 1104-1109.
59. Meharrar, A.; Tioursi, M.; Hatti, M.; and Stambouli, B.A. (2011). A variable speed wind generator maximum power tracking based on adaptive neuro-fuzzy inference system. *Expert System and Applications*, 38(6), 7659-7664.
60. Calderaro, V.; Galdi, V.; Piccolo, A.; and Siano, P. (2008). A fuzzy controller for maximum extraction from variable speed wind power generation systems. *Electrical Power System Research*, 78(6), 1109-1118.
61. Lee, D.C.; and Abo-khalil, A.G. (2008). Optimal efficient control of induction generator in wind energy conversion system using support vector regression. *Journal of Power Electronics*, 8(4), 345-353.

62. Hong, Y.-Y.; Lu, S.-D.; and Chiou, C.-S. (2009). MPPT for PM wind generator using gradient approximation. *Energy Conversion and Management*, 50(1), 82-89.
63. Kongnam, C.; and Nuchprayoon, S. (2010). A particle swarm optimization for wind energy control problem. *Renewable Energy*, 35(11), 2431-2438.
64. El-Tous, Yosif (2008). Pitch Angle Control of Variable Speed Wind Turbine. *American Journal of Engineering and Applied Sciences*, 1(2), 118-120.
65. Jauch, C.; Islam, S.M.; Sorensen, P.; and Bak Jensen, B. (2007). Design of a wind turbine pitch angle controller for power system stabilization. *Renewable Energy*, 32(14), 2334-2349.
66. Yilmaz, A.S.; and Özer, Z. (2009). Pitch angle control in wind turbines above the rated wind speed by multi-layer perceptron and radial basis function neural networks. *Expert Systems and Applications*, 36(6), 9767-9775.
67. Boukhezzar, B.; Lupu, L.; Siguerdidjane, H.; and Hand, M. (2007). Multivariable control strategy for variable pitch wind turbines. *Renewable Energy*, 32(8), 1273-1287.