

A Stand-Alone Wind Energy Conversion System (WECS) Based on a Self-Excited Squirrel-Cage Induction Machine in Renewable Energy System

Dr. S.Ramalinga Reddy¹ & G.Vijayakumar²

¹M.Tech., Ph.D., M.I.S.T.E, M.I.E.

Professor, Department of Mechanical Engineering, Aditya college of Engineering,
Madanapalle, A.P., India

²M.E, IEEE MEMBER

Assistant Professor, Department of EEE, Aditya college of Engineering, Madanapalle, A.P.,
India.

Abstract: Induction generators are increasingly being used in nonconventional energy systems. The advantages of using an induction generator instead of a synchronous generator are well known. Some of them are reduced unit cost and size, ruggedness, brushless (in squirrel cage construction), ease of maintenance, self-protection against severe overloads and short circuits, etc. In isolated systems, squirrel cage induction generators with capacitor excitation, known as self-excited induction generators (SEIGs), are very popular. This paper discusses the regulation of the voltage and frequency of a stand-alone wind energy conversion system (WECS) based on a self-excited squirrel-cage induction machine. The proposed new closed loop PWM controller (AC-DC-AC) is used to maintain constant voltage and constant frequency at the output of the generator against varying rotor speed, changing load conditions and as well as to generate optimum power from the induction generator. The feasibility of the proposed system is simulated by using MATLAB/Simulink.

Keywords: Self-excited Induction Generator (SEIG), frequency control, voltage control, PWM converter, wind power generation.

1. INTRODUCTION

Stand-alone wind energy conversion systems (WECSs) are useful for powering small villages located far from the utility grid. The squirrel-cage induction machine [1] is very attractive for small and medium power generation systems because of its low cost, robustness, and high-power density (W/kg). However, the magnitude and frequency of the generated voltage depends upon the rotor speed, the amount of excitation, and the load (magnitude and power factor).

It is well known that the total power available in the wind is proportional to the cube of wind speed and the fraction of this which a wind Turbine can

utilise depends upon the velocities of wind and rotor as shown in Fig. 1. To have some level of control on the wind generation unit, various forms of systems can be used. A number of lower cost schemes with a single power electronic converter have been proposed in the literature. In [2], a series connected pulse width modulated (PWM) VSI with a battery bank is used to regulate voltage and frequency. However, this scheme presents low-frequency harmonic distortion for low values of rotor speeds. Terminal impedance concept was proposed in [3] where a shunt connected thyristor rectifier followed by a PWM switched resistor is controlled to pick up the active and reactive power not used by a variable load. The thyristor rectifier can only absorb active and reactive power, the excitation capacitor bank is relatively large and the efficiency of the system is low. Alternatively, one can use a shunt connected VSI with a capacitor and a switched resistor in the dc bus, as proposed in [4]. The converter automatically absorbs or generates reactive power to regulate the terminal voltage. However, it can only absorb active power as the terminal impedance controller in [3] does.

In addition to the above schemes, squirrel cage generators with shunt passive or active VAR (volt ampere reactive) generators [5], [6] have been proposed which generate constant voltage constant frequency power through a diode rectifier and line-commutated thyristor inverter. Using this arrangement, only the terminal voltage can be controlled. Also, despite its being economical and reliable, a VAR compensating system severely limits the energy capture of the wind generating system [7].

The voltage rise problem has been addressed in [8] and some suggestions to overcome this problem are made. The effect of pitch control of the wind turbine of power quality has been addressed in [9] and sliding mode control strategy has been used in [10] for efficiency and torsional dynamics.

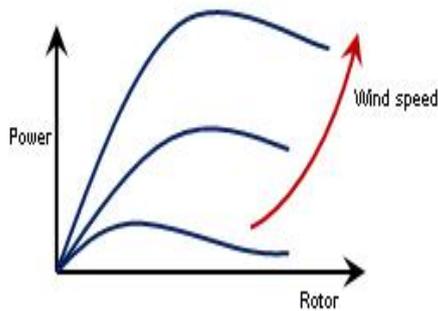


Fig.1. Wind turbine power

A variable-speed generator system is described in this paper which uses a 3-phase cage rotor induction machine with self excitation capacitors and a double-sided PWM converter. A control strategy is developed in which all three control objectives, i.e. voltage rise, output power and efficiency, are taken into account, using only the rectifier and inverter control signals.

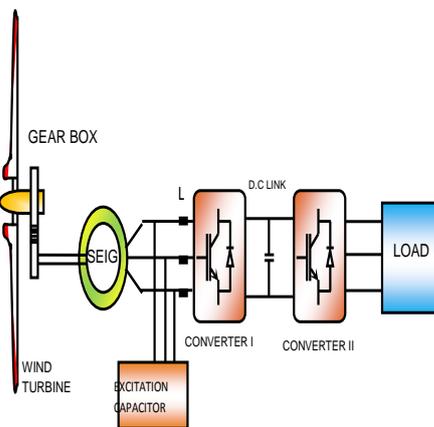


Fig.2. Proposed wind turbine topology

I. TEST SYSTEM AND EQUIVALENT CIRCUIT

A.C. commutator motor was used as the variable-speed drive for a 6-pole/3-phase 415V/50Hz 11 kW squirrel-cage induction machine. In order to operate the machine as an induction generator, the necessary self-excitation was provided by 3-phase capacitor banks shunt connected at the stator terminals.

A simplified equivalent circuit of the electrical system is illustrated in Fig. 3. The generator is represented by a leakage reactance X and a winding resistance R , $R'2$ is the rotor winding resistance referred to the stator, Xo the magnetising reactance and Ro the magnetising losses of the generator. All

resistance and reactance values were obtained from conventional tests.

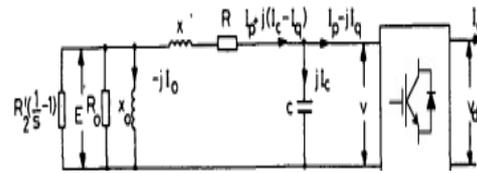


Fig.3. Self-excited induction generator / controlled rectifier unit

A similar model was used earlier [11] to predict constant speed characteristics, with a 2-pole wound-rotor machine instead of the present 6-pole squirrel-cage induction motor. In such cases the capacitive current Ic reduced by the convertor reactive current I_Q taken as the excitation current I_o and the active component of convertor current I_p was assumed to have negligible regulating effect. Hence at any given frequency and voltage level the values of Ic and Iq could easily be obtained from the excitation curve and the capacitor load line.

Such direct calculation of Iq is inaccurate in the present case due to the significant winding impedance of the 6-pole motor, and the voltage drop due to active current flow must now be taken into account.

II. EXCITATION CHARACTERISTICS WITH VARIABLE SPEED

The magnetisation characteristic of Fig. 4 was obtained by exciting the induction motor from a 50 Hz variable-voltage supply while running at synchronous speed. The results are equally valid for a self-excited induction machine.

As a self-excited induction generator the no-load operating voltage is determined by the intersection of the magnetisation characteristic with the capacitor load line (Fig. 5). Obviously at the higher speeds the no-load voltage can be dangerously high. However, when load is applied there is a considerable fall in voltage level and the current rating of the apparatus may then be the limiting factor. The useful speed range is thus limited by the minimum excitation speed at the lower end, and by the voltage and current ratings of the individual components at higher speeds. Two sets of capacitor banks were used of 32 μ F and 52 μ F per phase, respectively, the corresponding minimum open-circuit self excitation speeds being 1070rev/min and 830rev/min, and at these speeds self excitation was consistently attained. With the two capacitors combined to give 84 μ F the open-circuit self-excitation speed is 670rev/min.

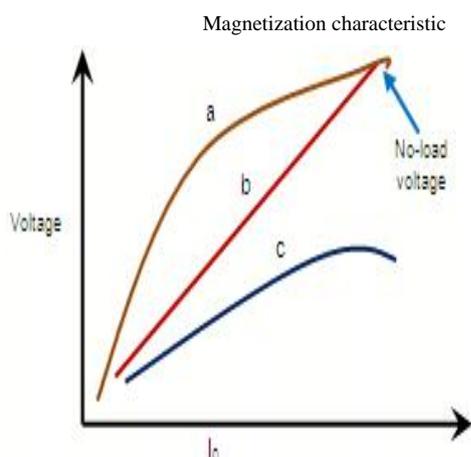
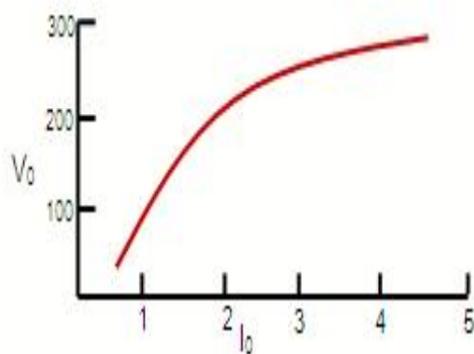


Fig.5. Self-excitation no-load condition

- a Magnetisation curve (V_o)
- b Capacitor load line
- c Induced e.m.f. ($E = V_o - XI_o$)

In every case, once excited, the speed can be reduced by about 10% before excitation is lost. This is illustrated in Fig. 6.

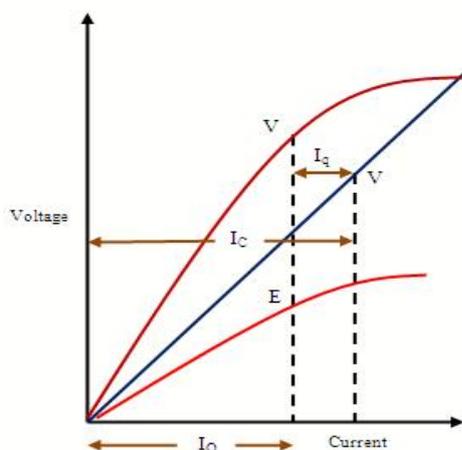


Fig.6. Self-excitation characteristics

- a Cut-in speed
- b Drop-out speed

III. LOAD EFFECT

In the self-excited state when in addition to the capacitor current I_c the generator is loaded, supplying an in-phase current I_p and a lagging reactive current I_q , regulation reduces the terminal voltage to V (illustrated in Fig. 7 for constant frequency).

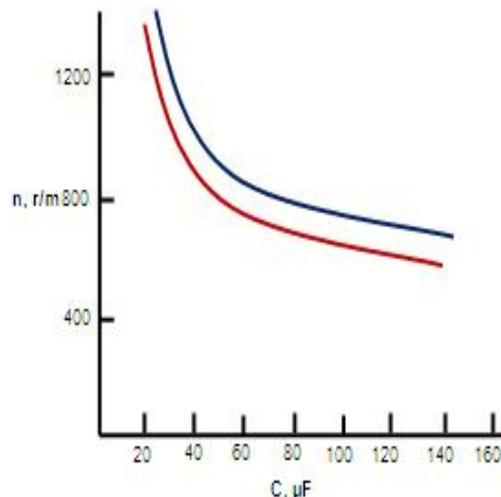


Fig.7. Reduction in voltage and excitation when loaded

The excitation current reduces to $I_o = I_c - I_q$. Since the induced e.m.f. is a function of the reactive excitation current, the internal e.m.f. E is correspondingly reduced. Considering the phasor relationships in Fig. 8, for relatively small-impedance voltage drops (taking the in-phase components) the terminal voltage is

$$V = E + XI_o - RI_p \quad (1)$$

However, at the new excitation current I_o the internal e.m.f. is still related to the experimentally derived magnetisation voltage V_o by

$$E = V_o - XI_o \quad (2)$$

The on-load terminal voltage is, therefore, approximately

$$V = V_o - RI_p \quad (3)$$

This model, taking into account both active and reactive components of load current, can now be used with the convertor relationships to predict the behaviour of the generator-rectifier system.

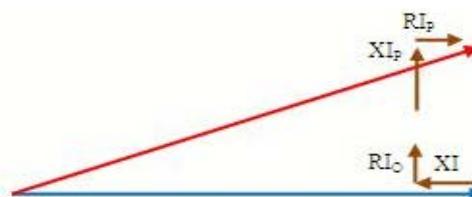


Fig.8. Phasor diagram for induction generator

IV. CONVERTOR-LOAD RELATIONSHIP

Equating active power on both sides of the convertor yields

$$V_d I_d = \sqrt{3} V I \cos \phi \quad (4)$$

where I , the fundamental current component, is approximately related to the direct current I_d by the expression [12]

$$I = \frac{\sqrt{6}}{\pi} I_d \frac{T_2}{T_1} \quad (5)$$

where T_1 and T_2 are the convertor transformer's primary and secondary number of turns. This assumes constant magnitude direct current which corresponds to the experimental conditions.

Substituting this expression in eqn. 4 yields

$$V_d = \frac{3\sqrt{2}}{\pi} V \frac{T_2}{T_1} \cos \phi \quad (6)$$

and the active and reactive current components of I can be expressed as

$$I_p = \frac{\sqrt{6}}{\pi} I_d \frac{T_2}{T_1} \cos \phi \quad (7a)$$

$$I_q = \frac{\sqrt{6}}{\pi} I_d \frac{T_2}{T_1} \sin \phi \quad (7b)$$

Furthermore, the following two expressions can be written for the d.c. voltage:

$$V_d = \frac{3\sqrt{2}}{\pi} V \frac{T_2}{T_1} \cos \phi - \frac{3X_c}{\pi} I_d \quad (8)$$

$$V_d = R_d I_d \quad (9)$$

Combining eqns. (6) and (9) gives

$$I_d = \frac{3\sqrt{2}}{\pi} \frac{V}{R_d} \frac{T_2}{T_1} \cos \phi \quad (10)$$

Substituting eqn. (10) in eqn. (8) yields

$$\frac{3\sqrt{2}}{\pi} V \frac{T_2}{T_1} \cos \phi = \left(R_d + \frac{3X_c}{\pi} \right) I_d \quad (11)$$

hence

$$\cos \alpha = \left(1 + \frac{3X_c}{R_d \pi} \right) \cos \phi \quad (12)$$

Finally, from eqns. 10 and 7 the following expressions are obtained:

$$I_p = \frac{\sqrt{6}}{\pi} \frac{3\sqrt{2}}{\pi} \frac{V}{R_d} \left(\frac{T_2}{T_1} \right)^2 \cos^2 \phi \quad (13)$$

$$I_q = \frac{\sqrt{6}}{\pi} \frac{3\sqrt{2}}{\pi} \frac{V}{R_d} \left(\frac{T_2}{T_1} \right)^2 \cos \phi \sin \phi \quad (14)$$

V. CONTROL STRATEGY FOR A RECTIFIER

In this section a comprehensive control strategy is proposed to achieve all the control objectives using the PWM rectifier and inverter based on the variable speed cage motor (VSCM) wind generating unit. The closed loop block diagram is shown in Fig. 9.

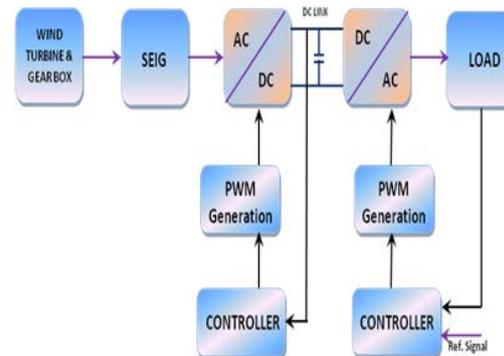


Fig.9. Closed loop block diagram

The double-sided pulse width modulator (PWM) converter system [13] helps to reduce the harmonics in the wind generation system. PWM produces a train of pulses with variable width, such that the mean value (filtered signal) is proportional to the desired signal. Such power electronics systems are usually considered very fast. Therefore, their time constants, compared with the rotor and the induction machine dynamics are neglected in simulation studies. With this assumption, the rectifier and the inverter can be modeled by nonlinear static functions. In order to perform an accurate simulation the following steps are taken:

- 1) Produce a triangular waveform with defined carrier frequency ω , by
- 2) Define a desired signal
- 3) Compare the desired signal with a triangular wave to produce the train of pulses. (e.g. the pulse value is 1 when the desired signal is greater than the triangular wave).

If harmonics are not of interest, the rectifiers and inverters can easily be modeled by simple gains [14]. In the study presented in this paper, because optimum operation and control is the main objective and the effect of harmonics is not considered, a current feedback and a gain is used to model the current-controlled PWM rectifier and inverter for each phase.

Consideration is now given to the behavior of the system when delay-angle control is used to provide a constant voltage V_d to a fixed load over the whole speed range. The d.c. voltage can be maintained

constant by delay-angle control, the speed range being only limited by excessive rise in a.c. voltage at the higher speeds. To obtain a wide speed range two or more different values of excitation capacitor are needed.

Line inductances are used on the input side of the PWM rectifier to allow operation without excessive switching transient current.

Synchronisation of gating signals with the source is very important and harmonics can unnecessarily stress the machine. Even with line inductors, after less than an hour of operation at half rated power the inverter duty induction machine was quite warm while the machine used to drive it was not.

The SEIG has to operate at variable frequency as wind turbines need to operate at variable speed to most effectively capture the wind. Along with the variable power operation the SEIG requires draws different amounts of reactive power for excitation. In the typical case, if the capacitance is too low the terminal voltage collapses and the generator freewheels. If the capacitance is too high over current and over voltage scenarios may cause damage to the system. The PWM rectifier is used to cater to these changing needs.

The first control objective is to limit the voltage rise. The second control objective is to capture maximum power from the wind. The best way to control the rotor speed is to change the frequency of the induction machine terminal voltage using the PWM rectifier. The third control objective is to maximize the induction machine efficiency. The efficiency of an induction generator is a function of the rotor speed and the flux.

VI. CONTROL STRATEGY FOR A INVERTER

The control of the inverter output voltage consists of pulse width modulation (PWM) of a reference sine wave with constant frequency and variable amplitude.

The amplitude of the sine wave is varied inversely proportional to the d.c. voltage V_{dc} as follows.

$$V_m^* = \frac{V_{dc}}{1.8} (PU) \quad (16)$$

Whereas V_{dc} is the rectified output voltage of induction generator.

And V_{dc}^* is the optimal dc voltage amplitude which is calculated as

$$V_{dc}^* = \frac{3\sqrt{3}V_{max}}{\pi} (V) \quad (17)$$

V_{max} denotes the amplitude of the rated per phase voltage.

The reference voltage waveform is expressed as:

$$V_{ref} = V_{max} \sin(\omega t), \quad \omega = 2\pi f$$

(18)

The sine wave reference voltage is modulated using a triangular carrier with constant frequency (i.e. 3kHz) and fixed amplitude of 1.5 times the rated amplitude of the reference voltage (i.e. $\sqrt{2} * 120(V)$). The output voltage V_{out} is made of pulse and is fed to the gate or base of the transistors to turn them *on* and *off* accordingly. Note that the same equation $V_{ref} = V_{max} \sin(\omega t)$ is used in the generation of three-phase reference voltage with the addition of phase shift 0° , -120° and $+120^\circ$ in the phase a, b and c respectively.

VII. SIMULATION RESULTS

Fig. 10 shows the output voltage magnitude and shaft speed of the generator during the start up of the system. The load and the asynchronous (AC-DC-AC) link are disconnected and the wind speed is 12 m/s. At 0.75 s the system reaches the steady state. Then the rated voltage is generated from the induction generator (at above synchronous speed) and connected to the utility.

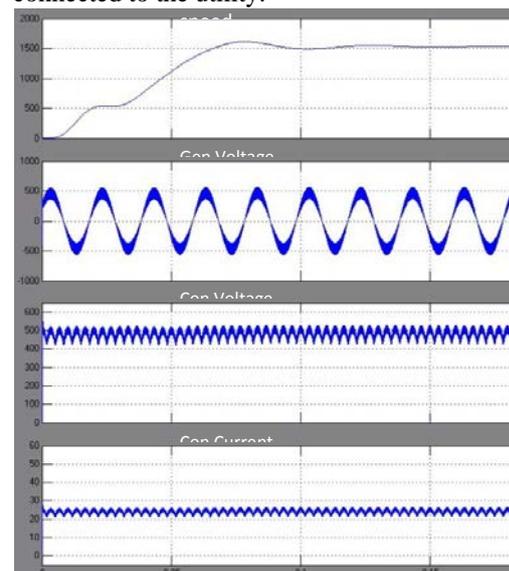


Fig.10. Start-up of the SEIG with the capacitor bank only.

Fig. 11 shows the response of the inverter output voltage (for phase A, B and C) to a load variation. The first load is switched in at $t = 0.4$ s and the second load is switched in at 0.5 s. At any instant output voltage of the inverter is maintained constant, which demonstrate the good regulating features of the proposed system.

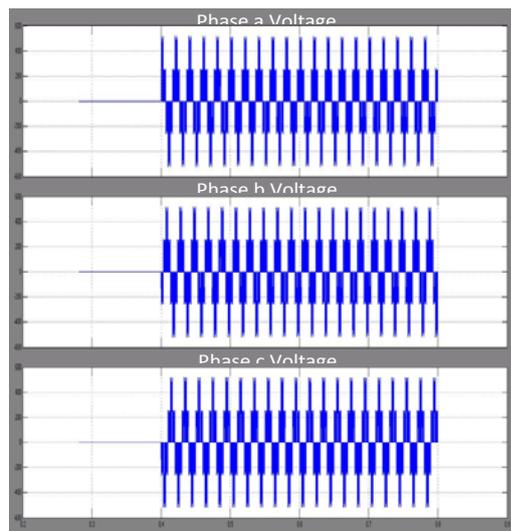


Fig.11. Behaviour of the system due to a load variation.

The transient response of the system to wind variation is shown in Fig. 12. The wind speed ramps down to 10 m/s at $t = 0.65$ s. Again, after transient periods, the voltage magnitude and frequency return to their rated values and the optimum power also generated by adjusting the delay angel of the rectifier (IGBT).

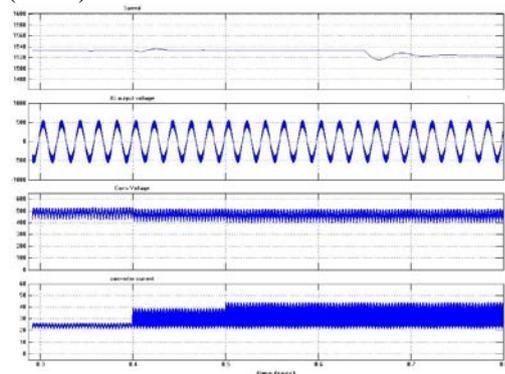


Fig.12. Behaviour of the system due to a wind speed variation.

VIII. CONCLUSION

This paper has presented the analysis of a stand-alone constant-voltage constant-frequency WECS based on a self-excited squirrel-cage induction generator without mechanical turbine control. For wind power generation schemes, variable speed is essential for modern wind turbines the main advantages of induction generator is reduced total unit cost and size. At any speed optimum power is generated from the induction generator by controlling the delay angle of the converter I then the constant voltage and constant frequency was maintained continuously by controlling the converter II. Simulation results were presented to analysis the response of the system under variable load and wind speed conditions.

REFERENCES

- [1] R. C. Bansal, "Three-phase self-excited induction generators: an overview," *IEEE Trans. Energy Convers.*, vol. 20, pp. 292-299, 2005.
- [2] E. Muljadi and T. Lipo, "Series compensated PWM inverter with battery supply applied to an isolated induction generator," *IEEE Trans. Ind. Appl.*, vol. 30, no. 4, pp. 1073-1082, Jul.-Aug. 1994.
- [3] R. Bonert and G. Hoops, "Stand alone induction generator with terminal impedance controller and no turbine controls," *IEEE Trans. Energy Convers.*, vol. 5, no. 1, pp. 28-31, Mar. 1990.
- [4] E.G.Marra and J.A. Pomilio, "Self-excited induction generator controlled by a VS-PWM bidirectional converter for rural applications," *IEEE Trans. Ind. Appl.*, vol. 35, no. 4, pp. 877-883, Jul.-Aug. 1999.
- [5] C. V. Nayar and J. H. Bundell, "Output power controller for a winddriven induction generator," *IEEE Trans. Aerosp. Electron. Syst.*, vol. AES-23, pp. 388-401, May 1987.
- [6] P. G. Casielles, J. G. Aleixandre, J. Sanz, and J. Pascual, "Design, installation and performance analysis of a control system for a wind turbine driven self-excited induction generator," in *Proc. ICEM '90*, Cambridge, MA, Aug. 1990, pp. 988-993.
- [7] R. Datta and V. T. Rangenathan, "Variable-speed wind power generation using doubly fed wound rotor induction machine—a comparison with alternative schemes," *IEEE Trans. Energy Convers.*, vol. 17, no. 3, pp. 414-421, Sep. 2002.
- [8] N. C. Scott, D. J. Atkinson, and J. E. Morrell, "Use of load control to regulate voltage on distribution networks with embedded generation," *IEEE Trans. Power Syst.*, vol. 17, no. 1, pp. 510-514, May 2002.
- [9] S. Hari, P. Trevor, and I. Syed, "Effect of pitch control and power conditioning on power quality of variable speed wind turbine generators," in *Proc. Australasian Universities Power Engineering Conf.*, 2001, pp. 95-100.
- [10] H. De Battista, P. F. Puleston, R. J. Mantz, and C. F. Christiansen, "Sliding mode control of wind energy systems with DOIG-power efficiency and torsional dynamics optimization," *IEEE Trans. Power Syst.*, vol. 15, no. 2, pp. 728-734, May 2000.
- [11] J. Arrillaga and D.B. Watson, "Static power conversion from self-excited induction generator", *Proc. IEE*, 1978, 125, pp. 743-746.
- [12] Adamson. C and HIngorani. N.G.: 'High-voltage direct-current power transmission' (Garraway, 1960)
- [13] R. Datta and V. T. Rangenathan, "Variable- speed wind power generation using doubly fed wound rotor induction machine—a comparison with alternative schemes," *IEEE Trans. Energy Convers.*, vol. 17, no. 3, pp. 414-421, Sep. 2002.
- [14] C.-M. Ong, *Dynamic Simulation of Electric Machinery*, Using MATLAB and SIMULINK. Upper Saddle River, NJ: Prentice-Hall, 1997.
- [15] J. R. Espinoza, G. Joos, M. Perez and T. L. A. Moran, "Stability issues in three-phase PWM current/voltage source rectifiers in the regeneration mode," *IEEE Proc. Int. Symp. Ind. Electron.*, vol. 2, pp. 453-458, 2000.

- [16] G. C. D. Souza, F. N. Martins, J. P. Rey, and J. A. Bruinsma, "An autonomous induction generator system with voltage regulations," in *Proc 4th IEEE Int. Conf. PEDS 2001*, vol. 1, Indonesia, Oct. 22–25, 2001, pp. 94–98.
- [17] M. G. Simões and F. A. Farret, *Renewable Energy Systems: Design and Analysis with Induction Generators*. Boca Raton, FL: CRC Press, 2004.
- [18] L. A. C. Lopes and R. G. Almeida, "Operation aspects of an isolated wind driven induction generator regulated by a shunt voltage source," in *Proc. 35th IEEE Ind. Appl. Soc. Annual Meeting, vol. 4, Oct. 8–12, 2000*, pp. 2277–2282.