Fuzzy control of a doubly fed induction generator based wind power system

MAROUANE EL AZZAOUI and HASSANE MAHMOUDI
Power electronics and control team,
Department of electrical engineering, Mohammadia School of Engineers,
Mohamed V University Agdal, Rabat, MAROCCO
marouane.elazzaoui@research.emi.ac.ma

Abstract: - This paper deals with the vector control based on fuzzy logic of active and reactive power of a doubly fed induction generator (DFIG) integrated in a wind turbine system. The power transfer between the stator and the grid is achieved by acting on the rotor signals via a bidirectional converter. For a comparative study, the independent control of active and reactive power is ensured in the first step by conventional controllers (PI) and the second step by the fuzzy controller. The performance and robustness are analysed and compared by simulation based on Matlab / Simulink environment.

Key-Words: - Doubly fed induction generator, fuzzy logic, Proportional Integral, Vector control, wind energy.

1 Introduction

During the last years, there was a strong development of wind energy. Renewable and clean, this energy of the future has a major role to play in meeting the current and future climate challenges. DFIG is considered one of the most adequate solution to integrate it into a wind system. It offers many advantages, such as reduction of inverter cost.

In this paper, we focus on the control strategy of the doubly fed induction generator (DFIG) based wind power system. At first, the modeling of the turbine and the DFIG will be presented. Then, the vector control of active and reactive power is achieved by adjusting the rotor magnitudes, while applying the PI and fuzzy controllers.

Finally, to validate the proposed controls, we will conduct a series of numerical simulations using Matlab Simulink software.

2 Modeling of wind turbine

Fig.1 shows the conversion chain based DFIG connected to the electrical power grid. The turbine converts the kinetic energy of wind into electrical energy. This processing depends on the air density, the area swept by the rotor and wind speed [1]. The aerodynamic power appearing at the rotor of the turbine is written [2] [3]:

$$P_{aer} = \frac{1}{2}.\rho.S.C_p(\lambda,\beta).v^3 \tag{1}$$

Where: ρ – air density, S – turbine area, v – wind speed, $C_p(\lambda,\beta)$ – power coefficient.

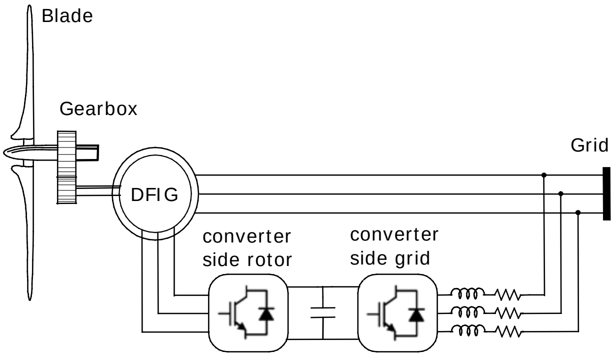


Fig.1 Structure of a wind energy system based on DFIG

The speed ratio is defined by:

$$\lambda = \frac{\Omega_t.R}{v} \tag{2}$$

Where Ω_t represents the rotational speed of turbine. In our study, the expression of the power coefficient is given by [4]:

$$C_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)\exp\left(\frac{c_5}{\lambda_i}\right) + c_6\lambda \tag{3}$$

With: $\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3+1}$, $c_1 = 0.5176$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 5$, $c_5 = 21$, $c_6 = 0.0068$

Knowing the speed of the turbine, the aerodynamic torque is therefore determined by [5].

$$T_{aer} = \frac{P_{aer}}{\Omega_t} = \frac{1}{2.\Omega_t}C_p(\lambda,\beta)\rho S v^3 \tag{4}$$

The multiplier is modeled by the following equations:

$$\Omega_m = G\Omega_t \tag{5}$$

$$T_{aer} = GT_g \tag{6}$$

The Model proposed considers that the total inertia J is given by:

$$J = \frac{J_t}{G^2} + J_g \tag{7}$$

By applying the fundamental law of dynamics, the relationship between the rotation speed and torques is expressed by:

$$J\frac{d\Omega_m}{dt} = T_{mec} = T_g - T_{em} - f\Omega_m \tag{8}$$

Where: T_{em} – electromagnetic torque, T_g – torque derived from multiplier, f – Coefficient of viscous friction.

3 Mathematical model of the DFIG

The generator chosen for the wind power system is the DFIG. In addition, the DFIG controlled by inverters through its rotor operates over a range of ±30% variation around the synchronous speed. This choice allows the converters dimensioned to transit 30% of nominal power. Therefore, it will be economic [6]. The model of the DFIG is expressed in the (dq) reference frame by the following equations [7] [8] [9].

$$\begin{cases} V_{sd} = R_s I_{sd} + \dfrac{d\varphi_{sd}}{dt} - \omega_s \varphi_{sq} \\ V_{sq} = R_s I_{sq} + \dfrac{d\varphi_{sq}}{dt} + \omega_s \varphi_{sd} \\ V_{rd} = R_r I_{rd} + \dfrac{d\varphi_{rd}}{dt} - \omega_r \varphi_{rq} \\ V_{rq} = R_r I_{rq} + \dfrac{d\varphi_{rq}}{dt} + \omega_r \varphi_{rd} \end{cases} \tag{9}$$

$$\begin{cases} \varphi_{sd} = L_s I_{sd} + L_m I_{rd} \\ \varphi_{sq} = L_s I_{sq} + L_m I_{rq} \\ \varphi_{rd} = L_r I_{rd} + L_m I_{sd} \\ \varphi_{rq} = L_r I_{rq} + L_m I_{sq} \end{cases} \tag{10}$$

$$T_{em} = p(\varphi_{sd} I_{sq} - \varphi_{sq} I_{sd}) \tag{11}$$

$$\omega_r = \omega_s - p\Omega_m \tag{12}$$

Where: s / r are stator/rotor subscript, V / I voltage/current, R_r / R_s rotor/stator resistance, L_r / L_s rotor/stator leakage inductance, L_m mutual inductance, p number of pairs of poles of the DFIG, ω_r / ω_s rotor/stator pulsation, φ flux, T_{em} electromagnetic torque, Ω_m mechanical speed of DFIG.

4 Control strategy

To be able to control the DFIG easily, we will achieve independent control of active and reactive power by the stator flux orientation. The principle is to align the stator flux along the axis (d) of the rotating frame; this can be written in the form of equations as follows:

$$\varphi_{sd} = \varphi_s, \varphi_{sq} = 0 \tag{13}$$

The stator is assumed supply by a stable grid. Moreover, the stator resistance can be neglected since it is a realistic assumption for high power machines used for wind power [10], these simplifying assumptions allows us to write the following equations:

$$V_{sd} = 0 \ , \ V_{sq} = V_s \tag{14}$$

The stator active and reactive powers are written [11]:

$$P_s = V_{sd} I_{sd} + V_{sq} I_{sq} \tag{15}$$

$$Q_s = V_{sq} I_{sd} - V_{sd} I_{sq} \tag{16}$$

Considering the simplifications mentioned above, expressions of power becomes:

$$P_s = -V_s \frac{L_m}{L_s} I_{rq} \tag{17}$$

$$Q_s = -\frac{L_m V_s}{L_s} I_{rd} + \frac{V_s^2}{\omega_s L_s} \tag{18}$$

Thereafter, we establish the equations showing the relationship between the rotor voltages and rotor currents:

$$V_{rd} = R_r I_{rd} + \sigma L_r \frac{dI_{rd}}{dt} - g\sigma L_r \omega_s I_{rq} \tag{19}$$

$$V_{rq} = R_r I_{rq} + \sigma L_r \frac{dI_{rq}}{dt} + g\sigma L_r \omega_s I_{rd} + g\frac{L_m V_s}{L_s} \tag{20}$$

Where: g – Slip of the DFIG, $\sigma = 1 - \frac{L_m^2}{L_r L_s}$ – the dispersion coefficient of the DFIG.

Equations (17), (18), (19) and (20) allow us to establish the electrical system of the block diagram of the DFIG to regulate (Fig.2).

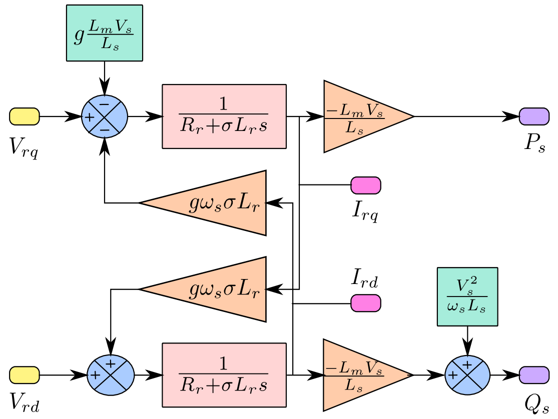


Fig.2 Structure of a wind energy system based on DFIG

5 PI control of the DFIG

The currents and voltages are related by a first order transfer function. Since the slip value is weak, we will set up a control loop on each power with an independent regulator (PI) while compensating the disturbance terms (Fig.3).

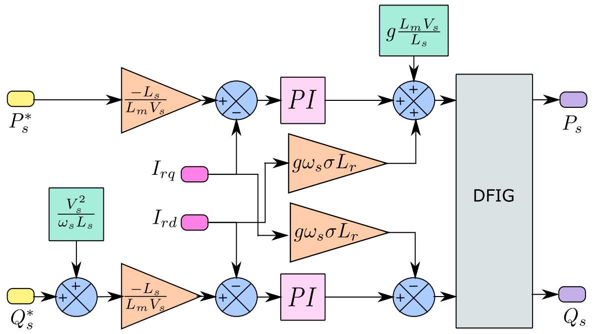


Fig.3 Diagram of control of the DFIG by PI regulators

The Proportional Integral controller (PI) is still the most commonly used for controlling the DFIG [12], as well as in many industrial control systems. It is easy and quick to implement while providing acceptable performance [13]. Regulators each axis role is to eliminate the gap between the active and reactive power references and the measured active and reactive power. The synthesis of PI controllers is presented in [14].

6 Fuzzy control of the DFIG

The fuzzy control approaches to some extent the flexibility of human reasoning; he manages to offer satisfactory performance without the need of the mathematical model of the system, just by incorporating experts' knowledge [15].

As presented in Fig.4, the fuzzy control based on Mamdani model. This mechanism is divided into three part. First, using input membership functions, the inputs are fuzzified and then based on rule bases and inference system, outputs are produced and finally the fuzzy outputs are defuzzified and applied to the system. Error and the error change rate are selected as inputs.

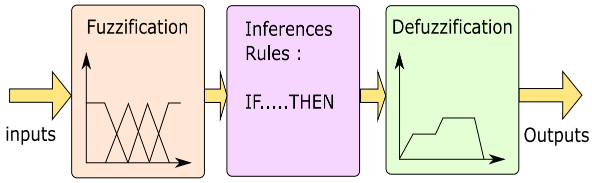


Fig.4 Block diagram of fuzzy control

Fig.5 shows the block diagram where fuzzy controllers are integrated into the vector control block of DFIG. The active and reactive powers are controlled independently, each with its own fuzzy controller.

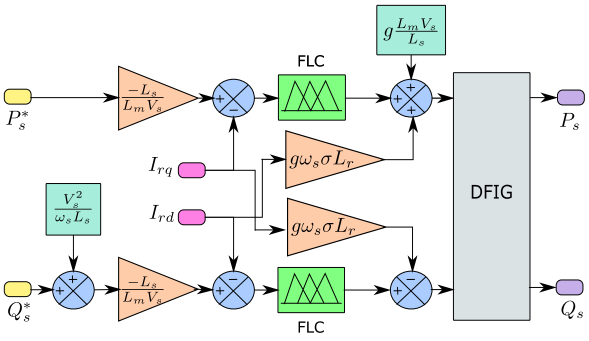


Fig.5 Fuzzy control of DFIG

The design of the fuzzy controller is shown in the block diagram of fig.6. The gains G_e , $G_{\Delta e}$, and $G_{\Delta u}$ are scaling factors (normalization). We vary these factors until we can get a proper control. Indeed, it is they who will decide the performance of control.

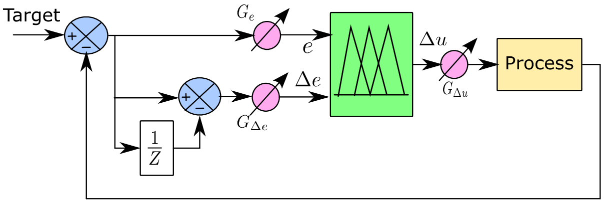


Fig.6 Design of a fuzzy controller

Generally, the design of a fuzzy controller for the control of electric drives requires the choice of the following parameters: linguistic variables, membership functions, inference method, and defuzzification strategy [16]. Fuzzy controller inputs are the error and its derivative, while the output is the command itself. Triangular and trapezoidal membership functions are used on a universe of discourse normalized in the range [-1; 1] for each variable as shown in Fig.7 and Fig.8 respectively for the inputs (error, error variation) and output (input process).

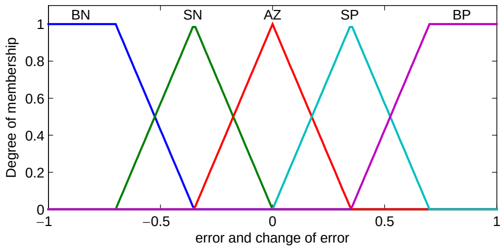


Fig.7 Membership functions of error and change of error

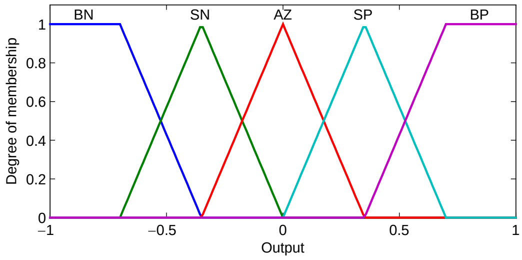


Fig.8 Membership functions of output

The subsets fuzzy membership were noted as follows: BN: Big-Negative; SN: Small-Negative; AZ: About-Zero; SP: Small-Positive; BP: Big-Positive.

The fuzzy rules, for determining output variable of the controller as a function of input variables are grouped in the Table 1.

Table 1. Inference matrix

Δu		e				
		BN	SN	AZ	SP	BP
Δe	BN	BN	BN	SN	SN	AZ
	SN	BN	SN	SN	AZ	SP
	AZ	BN	SN	AZ	SP	BP
	SP	BN	AZ	SP	SP	BP
	BP	AZ	SP	SP	BP	BP

Fig.9 shows the surface generated by the fuzzy system.

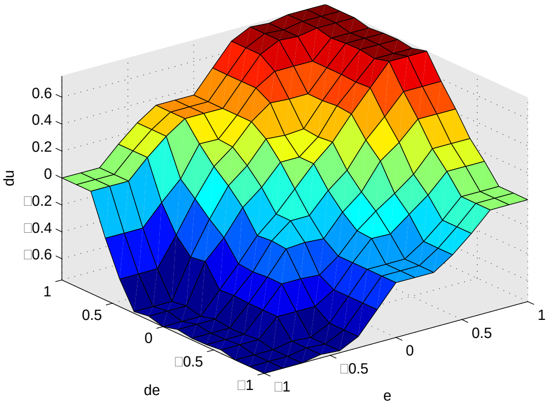


Fig.9 Surface generated by the fuzzy system

7 Simulation results

The simulation of the control of the DFIG associated with wind system was made with the Matlab / Simulink environment (Fig.10).

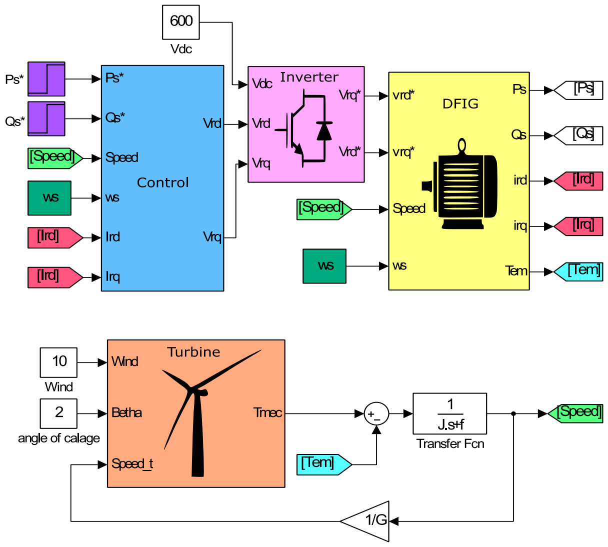
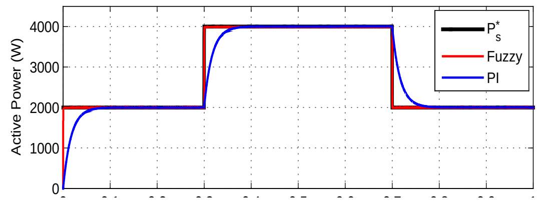
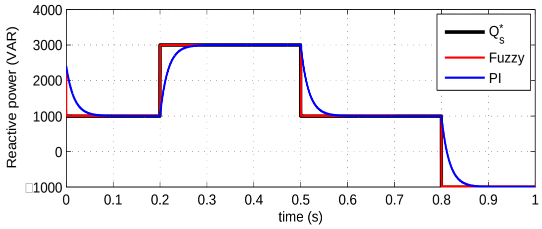


Fig.10 Block diagram of the control in Matlab/Simulink

The results plotted in the following figures show powers generated when the reference signals are applied. Fig.11 displays the results of PI and fuzzy controllers using the targets in the form of echelons. Fig.12 shows the results with variable targets of powers. The test of robustness is presented in fig.13.



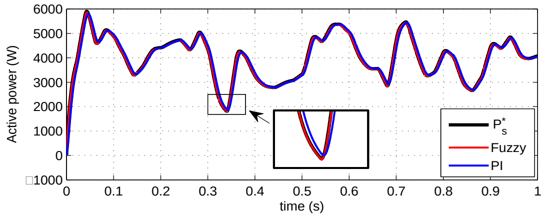
(a) Stator active power



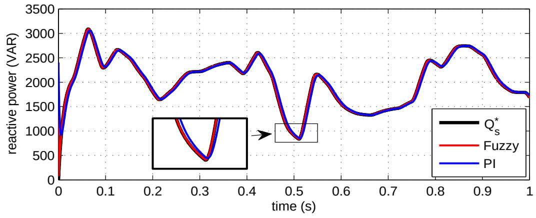
(b) Stator reactive power

Fig.11 Responses with fuzzy and PI controllers

It is clear that the active and reactive power of the system follow perfectly the reference levels. Static error is almost equal to zero. In transient state, the time response of the fuzzy controller is much faster than the PI controller (Fig.11).



(a) Stator active power



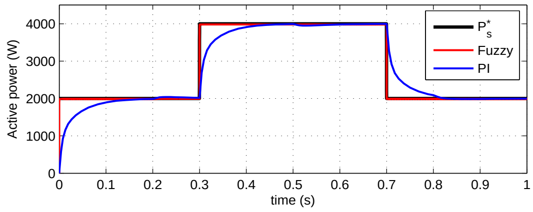
(b) Stator reactive power

Fig.12 Responses with fuzzy and PI controllers for variables powers

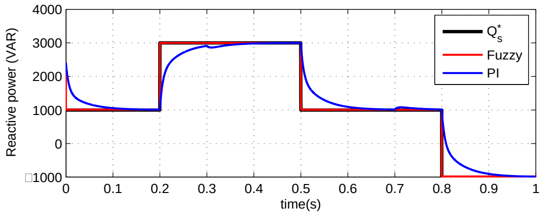
Fig.12 shows that the two controllers follow their references, but the fuzzy present better performance than the PI in terms of response time and static error.

The simulation results in Fig.13 show the robustness of PI and Fuzzy controllers to variations in several parameters:

- Variation of rotor resistance R_r of +40% of its nominal value.
- Variations of the stator inductances L_s , rotor inductances L_r and mutual inductances L_m of −20% of their nominal value.



(a) Stator active power



(b) Stator reactive power

Fig.13 Responses with fuzzy and PI controllers

The comparison between the two controllers shows that the fuzzy controller has good performance. By cons, for the PI controller, its performance is lost.

8 Conclusion

The control of a wind energy system equipped with a doubly fed induction generator has been described in this paper. At first, a model of the turbine and the generator are proposed. Then, a control strategy based on fuzzy logic and PI controllers allowing independent control of power has been presented. Through the response characteristics obtained by the simulation results, the good performance is observed even in the presence of variations of targets. Moreover, by comparing the controller PI and fuzzy, it's clear that the fuzzy control is robust against parametric variations of the machine, provides fast convergence, not affected by noise and spurious signals, and easy to implement it in a calculator.

Appendix

Parameters of the wind power system.

DFIG nominal parameters

$V_s = 230V$, $50\ Hz$, $p = 2$, $R_s = 0.455\Omega$,
$R_r = 0.19\Omega$ $L_s = 0.07H$, $L_r = 0.0213H$,

$L_m = 0.034H$

Turbine nominal parameters

$Number\ of\ blades = 3$, $Diameter = 60\ m$

$Gearbox = 70$

DFIG + Turbine parameters

$J = 32Kg.m^2$, $f = 0.046N.m.d / rad$

References:

[1] C. NICHITA, D. LUCA, B. DAKYO, E. CEANGA, and N. A. CUTULULIS, “Modelling non-stationary wind speed for renewable energy systems control,” *The annals of ”Dunarea de Jos” University of Galati, Fascicle III*, pp. 29–34, 2000.

[2] M. Arifujjaman, “Vector control of a dfig based wind turbine,” *Journal of Electrical and Electronics Engineering*, vol. 2, no. 9, pp. 1057–1065, 2009.

[3] I. Munteanu, A. I. Bratcu, N. A. Cutululis, and E. Ceanga, “Optimal control of wind energy systems,” *Springer*, 2008.

[4] Z. M. Lubosny and B. Anjan, “Wind turbine operation in electric power systems,” *Springer*, 2003.

[5] M. GOSSA, K. JEMLI, M. B. MOHAMED, and M. JEMLI, “Doubly fed induction generator (dfig) in wind turbine, modeling and power control,” *IEEE International Conference on Industrial Technology*, pp. 580–584, 2004.

[6] F. Poitiers, B. Toufik, and A. Machmoum, “Advanced control of a doubly-fed induction generator for wind energy conversion,” *Electric Power Systems Research*, no. 79, pp. 1085–1096, 2009.

[7] H. Bekka, S. Taraft, D. Rekioua, and S. Bacha, “Power control of a wind generator connected to the grid in front of strong winds,” *Journal of Electrical Systems*, vol. 3, no. 9, pp. 267– 278, 2013.

[8] D. Rekioua, “Wind power electric systems: Modeling, simulation and control, green energy and technology,” *Springer*, 2014.

[9] A. Boyette, P. Poure, and S. Saadate, “Direct and indirect control of a doubly fed induction generator wind turbine including a storage unit,” in 32*th edition of Industrial Electronics Conference IECON’2006, IEEE*, Paris, France, November 6-10 2006, pp. 2517–2522.

[10] A. Tapia, G. Tapia, J. X. Ostolaza, and J. R. Saenz, “Modeling and control of a wind turbine driven doubly fed induction generator,” *IEEE Transactions on Energy Conversion*, vol. 18, no. 2, pp. 194 – 204, June 2003.

[11] R. PENA, J. C. CLARE, and G. M. ASHER, “Doubly fed induction generator using back-to-back pwm converters and its application to variable- speed wind-energy generation,” *IEE Puoc.-Electr. Power Appl*, vol. 143, no. 3, May 1996.

[12] M. LOPEZ, “Contribution à l’optimisation d’un système de conversion éolien pour une unité de production isolée,” Ph.D. dissertation, Sciences et Technologies de l’Information des Télécommunications et des Systèmes Université Paris Sud 11, France, 2008.

[13] G. A. Smith and K. A. Nigim, “Wind-energy recovery by a st atic scherbius induction generator,” in *Proc. IEE*, 1981, pp. 317–324.

[14] N. CHERFIA, D. KERDOUN, and A. BOUMASSATA, “Correction of the mechanical speed for the dfig wind turbine,” *International Journal of Research in Engineering and Technology*, vol. 2, no. 11, pp. 29–38, November 2014.

[15] H. K. Davijani, A. Sheikholeslami, H. Livani, and M. K. Davijani, “Fuzzy logic control of doubly fed induction generator wind turbine,” *World Applied Sciences Journal*, vol. 6, no. 4, pp. 499–508, 2009.

[16] M. GODOY, B. SIMGES, K. BOSE, and R. J. SPIEGEL, “Fuzzy logic based intelligent control of a variable speed cage machine wind generating system,” in *PESC*, 1995.