XIX International Conference on Electrical Machines - ICEM 2010, Rome

Vector Control of Squirrel Cage Induction Generator for Wind Power

José Luis Domínguez-García*, Oriol Gomis-Bellmunt*†, Lluís Trilla-Romero* and Adrià Junyent-Ferré†

***Abstract*—The paper deals with squirrel cage induction generator connected to the grid through a back-to-back converter, which is driven by vector control. The stator side converter controls the generator torque using an indirect vector control. The grid side converter controls the DC Bus voltage and the reactive power. The proposed control strategy is validated by simulation in Matlab/Simulink®.**

***Index Terms*—Back-to-back converter, squirrel cage induction generator (SCIG), vector control, wind power generation.**

NOMENCLATURE

	Symbols		*Superscripts*
λ	Flux linkage	$*$	Set point
Γ	Torque	e	synchronism reference
θ	Angle		*Subscript*
$\dot{\theta}$	Angular velocity	s	stator
s	slip	l	grid-side converter
r	Resistance	z	grid
L	Inductance	d	d-axis
M	Mutual inductance	q	q-axis

I. INTRODUCTION

WIND Power is one of the most promising renewable energy sources after the progress undergone during the last decades. In this field, SCIG has been used, specially, as a fixed-speed generator or for micro-generation [1], [2].
SCIG control can be done using different approaches: scalar or vector control, direct or indirect field orientation, rotor or stator field orientation [3]–[5], each one have advantages and disadvantages, for example, scalar control [6]is quite simple to implement but easily unstable, a better performance is direct vector control, which needs estimated and sensed flux values to define and control the field orientation references, but it is necessary to use hall-effect sensors, which is problematic, and expensive, in practise [7], [8].
It has been chosen an indirect field-orientation method, which is more sensitive to knowledge of the machine parameters, but it frees from the use of direct sensing [9], [10].
This paper proposes an indirect vector control strategy , with the voltages referred to a q-d synchronous frame aligned with the rotor flux vector, for the stator-side converter.

This paper has been organized as follows. In Section II, the global system under study has been described and analyzed. The control scheme has been presented in Section III. In section IV, the proposed control is validated by means of a simulation and discussed. And finally, the conclusions are summarized in Section V.

II. SQUIRREL CAGE INDUCTION GENERATOR WITH FULL POWER CONVERTER

The system which it is treated can be seen in Fig.1.
The SCIG is attached to the wind turbine by means of a gearbox. The SCIG stator windings are connected to a full power converter (back to back).

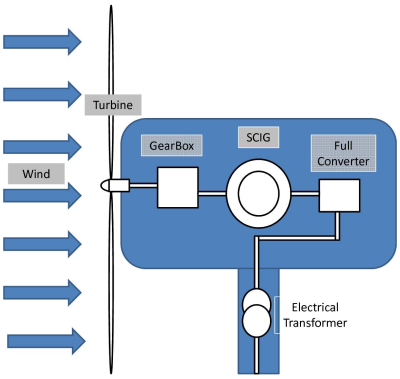

Figure 1. General System Scheme

The wind turbine is the responsible for transforming wind power into kinetic energy. Usefull power can be determined using the following equation:

$$P_{wind} = \frac{1}{2} \cdot c_p \cdot \rho \cdot A \cdot v_w^3 \tag{1}$$

The gearbox provides speed and torque conversions from a rotating power source to another device using gear ratios. In the analyzed system, it is described through one mass model which complies with:

---

[*] Catalonia Institute for Energy Research (IREC), Electrical Engineering Area, C Josep Pla, 2, edifici B2, Planta Baixa - 08019 Barcelona, Spain (email: jldominguez@irec.cat, ogomis@irec.cat, lltrilla@irec.cat)

[†] Centre d'Innovació Tecnològica en Convertidors Estàtics i Accionaments (CITCEA-UPC), Departament d'Enginyeria Elèctrica, Universitat Politècnica de Catalunya, ETS d'Enginyeria Industrial de Barcelona, and EU d'Enginyeria Tècnica Industrial de Barcelona, Barcelona - 08028, Spain (email: gomis@citcea.upc.edu, adria.junyent@citcea.upc.edu)

978-1-4244-4175-4/10/$25.00

$$\frac{d}{dt}\omega_g = \frac{\Gamma_g - \Gamma_t'}{J_{tot}}$$

$$\Gamma_t' = \frac{\Gamma_t}{K_{gear}} \tag{2}$$

$$\omega_t = K_{gear} \cdot \omega_g$$

For the machine equations, assuming the stator and rotor windings are sinusoidally and symmetrically [11], [12], the relation between voltage and currents on a synchronous reference qd can be written as:

$$\left\{ \begin{array}{c} v_{sq} \\ v_{sd} \\ 0 \\ 0 \end{array} \right\} = \begin{bmatrix} L_s & 0 & M & 0 \\ 0 & L_s & 0 & M \\ M & 0 & L_r & 0 \\ 0 & M & 0 & L_r \end{bmatrix} \frac{d}{dt} \left\{ \begin{array}{c} i_{sq} \\ i_{sd} \\ i_{rq} \\ i_{rd} \end{array} \right\}$$

$$+ \begin{bmatrix} r_s & L_s\omega_e & 0 & M\omega_e \\ -L_s\omega_e & r_s & -M\omega_e & 0 \\ 0 & sM\omega_e & r_r & sL_r\omega_e \\ -sM\omega_e & 0 & -sL_r\omega_e & r_r \end{bmatrix} \left\{ \begin{array}{c} i_{sq} \\ i_{sd} \\ i_{rq} \\ i_{rd} \end{array} \right\} \tag{3}$$

Linkage fluxes can be written as

$$\left\{ \begin{array}{c} \lambda_{sq} \\ \lambda_{sd} \\ \lambda_{rq} \\ \lambda_{rd} \end{array} \right\} = \begin{bmatrix} L_s & 0 & M & 0 \\ 0 & L_s & 0 & M \\ M & 0 & L_r & 0 \\ 0 & M & 0 & L_r \end{bmatrix} \left\{ \begin{array}{c} i_{sq} \\ i_{sd} \\ i_{rq} \\ i_{rd} \end{array} \right\} \tag{4}$$

The torque can be expressed as:

$$\Gamma_m = \frac{3}{2} P \cdot M \left(i_{sq} i_{rd} - i_{sd} i_{rq} \right) \tag{5}$$

The active and reactive power yields:

$$Q_s = \frac{3}{2} \left(v_{sq} i_{sd} - v_{sd} i_{sq} \right) \tag{6a}$$

$$P_s = \frac{3}{2} \left(v_{sq} i_{sq} + v_{sd} i_{sd} \right) \tag{6b}$$

The back to back converter is composed by the grid-side converter connected to the grid and the stator-side converter connected to the stator windings (see Fig.2). Both sides are linked by a DC Bus.
The DC Bus voltage can be expressed as

$$E = E_0 + \frac{1}{C} \int_0^t i_{DCE} dt = E_0 + \frac{1}{C} \int_0^t (i_{DCl} - i_{DCs}) dt \tag{7}$$

The converter set points are established by the so-called high-level controller. It uses the knowledge of the wind speed and the grid reactive power requirements, to determine the optimum turbine pitch angle and the torque and reactive power set points referenced to the converter.

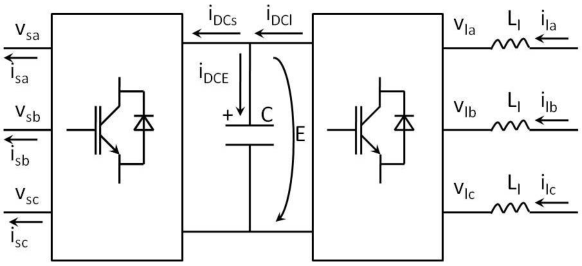

Figure 2. Back to Back converter

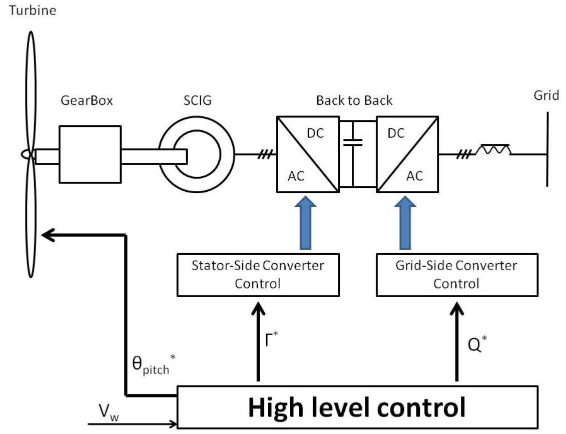

Figure 3. General Control Scheme

The stator-side converter controls torque, while the grid-side converter controls the dc voltage and grid-side reactive power.
The grid system equations in a synchronous reference frame can be written as:

$$\left\{ \begin{array}{c} v_{zq} \\ v_{zd} \end{array} \right\} - \left\{ \begin{array}{c} v_{lq} \\ v_{ld} \end{array} \right\} = \begin{bmatrix} r_l & -L_l\omega_e \\ L_l\omega_e & r_r \end{bmatrix} \left\{ \begin{array}{c} i_{lq} \\ i_{ld} \end{array} \right\}$$

$$+ \begin{bmatrix} L_l & 0 \\ 0 & L_l \end{bmatrix} \frac{d}{dt} \left\{ \begin{array}{c} i_{lq} \\ i_{ld} \end{array} \right\} \tag{8}$$

Active and reactive power provided by the grid.side converter can be expressed as:

$$Q_l = \frac{3}{2} \left(v_{zq} i_{ld} - v_{zd} i_{lq} \right) \tag{9a}$$

$$P_l = \frac{3}{2} \left(v_{zq} i_{lq} + v_{zd} i_{ld} \right) \tag{9b}$$

III. CONTROL SCHEME

The electrical control of the converter can be achieved using different kind of current loops [13], for both sides of

the back to back converter the references of the current loops through a vector control. As it have been explained before the power converter can be treated separately, as two different converters (stator-side and grid-side).
For stator-side converter, it is suggested a indirect field oriented control. However, for grid-side converter, it is used a common vector control [1], [14]–[16].

A. Stator-Side Converter

In the stator-side converter, the referenced torque and rotor flux determine the current references, which determine the voltages to be applied in the stator side.

1) Reference calculation: Referencing the voltage to q-d synchronous frame aligned with the rotor flux vector, the q-component of the rotor flux is null (λ_{qr}=0).
Then, the d-component of the rotor flux is always the maximum, it can be assure that $\frac{d}{dt}\lambda_{dr}$ and $\frac{d}{dt}\lambda_{qr}$ are null. These hypothesis are important to relate reference values (torque and rotor flux) with the current references.
Satisfying the condition for proper orientation and knowing which are the reference values, the current references can be calculate as follow:

$$\lambda_{dr}^{e*} = M \cdot i_{ds}^{e*} \approx \frac{r_r \cdot M}{r_r + L_r \cdot s} \cdot i_{ds}^{e*} \tag{10}$$

Both approaches allow to relate the d-component of the rotor flux with d-component of the stator current. To simplify calculations have been used the first one. Then, it is found the d-component of the stator current reference through the d-component of the rotor flux reference.

$$i_{ds}^{e*} = \frac{1}{M} \cdot \lambda_{dr}^{e*} \tag{11}$$

The d-component of the rotor flux reference, which is the rotor flux reference, can be determined with the following equation:

$$\lambda_{dr}^{e*} = \frac{U_{nominal}}{f_{nominal}} \tag{12}$$

where the nominal voltage is limited by the DC Bus voltage, and determined by the machine.
The torque equation in this orientation can be written as:

$$T_{em}^{*} = \frac{3}{2} \cdot P \cdot M \cdot \lambda_{dr}^{e*} \cdot i_{qs}^{e*} \tag{13}$$

As the rotor flux and torque are known referenced values, it is possible to determine the q-component of the stator current from:

$$i_{qs}^{e*} = \frac{2 \cdot L_r}{3 \cdot P \cdot M} \cdot \frac{T_{em}^{*}}{\lambda_{dr}^{e*}} \tag{14}$$

The reference torque is determined as the optimum value that it can be gotten from the turbine. [15]

$$T_{em}^{*} = -Kcp \cdot \omega_t^2 \tag{15}$$

Using the equations introduced before in the d-axis rotor voltage equation, it is known:

$$\underbrace{v_{qr}}_{=0} = r_r \cdot i_{qr} + \underbrace{\frac{d}{dt}\lambda_{qr}}_{=0} - (\omega_e - \omega_r)\lambda_{dr} \tag{16}$$

Substituting the chosen equation of 10 in 16, it is obtained:

$$\omega_{slip}^{*} = \omega_e - \omega_r = \frac{r_r}{L_r} \cdot \frac{i_{qs}^{e*}}{i_{ds}^{e*}} \tag{17}$$

Making the integration of 17, it is determined the angle of rotation, which will be use it to do and undo the Park Transformation.

$$\theta_e = \int \omega_e dt = \int (\omega_r + \omega_{slip})\, dt = \theta_r + \theta_{slip} \tag{18}$$

Figure 4 depicts the block diagram of the indirect rotor field-oriented control, which is based upon 11, 14 and 17.

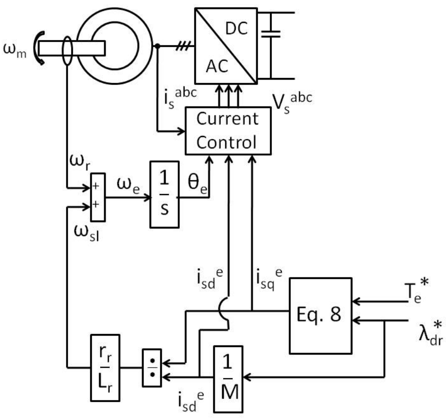

Figure 4. Stator Control Scheme

B. Grid Side Converter

The control of the electrical system of the grid is configured to control the DC Bus voltage and the reactive power which is consumed or supplied by the converter of the grid side. The DC Bus voltage and the reactive power references determine the current references, which determine the voltages to be applied in the grid side.

1) Reference calculation: The q-axis may be aligned to the grid voltage allowing active and reactive decoupled control. To control the reactive power, a i_{ld} reference is computed as:

$$i^*_{ld} = \frac{2 \cdot Q^*_l}{3 \cdot v_{zq}} \tag{19}$$

The active power, which is responsible for the evolution of the dc bus is controlled by the i_{lq}. A linear controller is usually designed to control the dc bus voltage, and keep it constant.

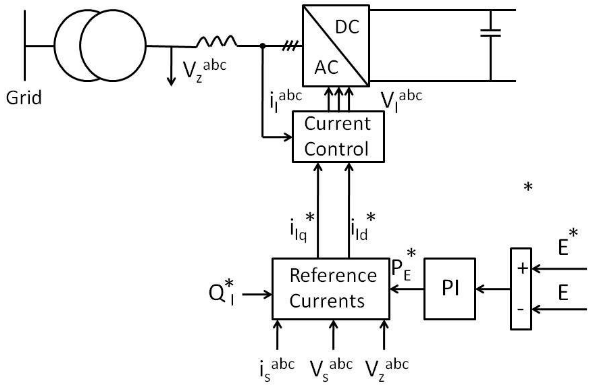

Figure 5. Grid Control Scheme

Figure 5 depicts the block diagram of grid side control.

2) Current Loops: The current control is done by the following state linearization feedback:

$$\begin{Bmatrix} v_{lq} \\ v_{ld} \end{Bmatrix} = \begin{Bmatrix} -\widehat{v}_{lq} + v_{zq} - L_l \cdot \dot{\theta}_g \cdot i_{ld} \\ -\widehat{v}_{ld} + L_l \cdot \dot{\theta}_g \cdot i_{lq} \end{Bmatrix} \tag{20}$$

where $\widehat{v}_{lq}$ and $\widehat{v}_{ld}$ are the voltage control value. The decoupling can be described as:

$$\frac{d}{dt}\begin{Bmatrix} i_{lq} \\ i_{ld} \end{Bmatrix} = \begin{bmatrix} -\frac{r_l}{L_l} & 0 \\ 0 & -\frac{r_l}{L_l} \end{bmatrix}\begin{Bmatrix} i_{lq} \\ i_{ld} \end{Bmatrix} + \begin{bmatrix} \frac{1}{L_l} & 0 \\ 0 & \frac{1}{L_l} \end{bmatrix}\begin{Bmatrix} \widehat{v}_{lq} \\ \widehat{v}_{ld} \end{Bmatrix} \tag{21}$$

C. Current Controllers Tuning

Controllers have been designed using the so-called internal model control (IMC) [17]. The parameters of a PI controller to obtain a desired bandwidth α, which appear because of a low-pass filter included by the IMC,are:

$$K_p = \alpha \cdot L_x \quad K_i = \alpha \cdot r_x \tag{22}$$

Table I
MECHANICAL PARAMETERS (S.I UNITS)

J_{gen}	J_{turb}	R	K_{gear}
100	$5 \cdot 10^6$	33	92.5

IV. SIMULATION RESULTS

The mechanical parameters and the electrical parameters [18], [19], can be seen in Tables I and II.
During the simulation the system has been exposed to a wind speed variation to see the response of the control to these new states. These variation can be seen in the figure 6.

Table II
ELECTRICAL PARAMETERS (S.I UNITS)

r_s	r_r	L_s	L_r	M
$1.1 \cdot 10^{-3}$	$1.3 \cdot 10^{-3}$	$3.0636 \cdot 10^{-3}$	$3.0686 \cdot 10^{-3}$	$2.9936 \cdot 10^{-3}$
r_l	L_l	C	P	
0.01	$5.35 \cdot 10^{-4}$	$15.3 \cdot 10^{-3}$	2	

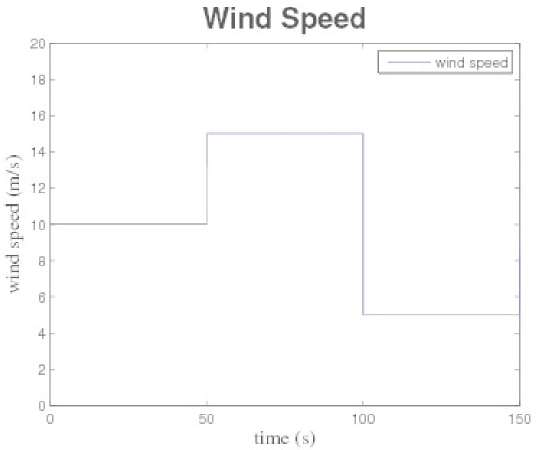

Figure 6. Input wind speed variation

In the Figure 7 is possible to see how the system evolves following the reference value. This is not constant due to our feedback of the rotation speed of the turbine, which either is constant as it can be observed in Figure 8, make it change until searching the optimum value. Can be observed how the torque change to a new steady space every wind speed change.

In the Figure 9 is represented the Active Power value evolution, which is almost constant. This is due to the control, what compensate the torque, which is not constant as can be seen in Figure 7)with the rotation speed turbine.

In the Figure 10 appears represented the difference between the qd currents real values and the qd reference values. As it can be seen, the system is working with the reference values because the error is almost zero permanently. There are peaks

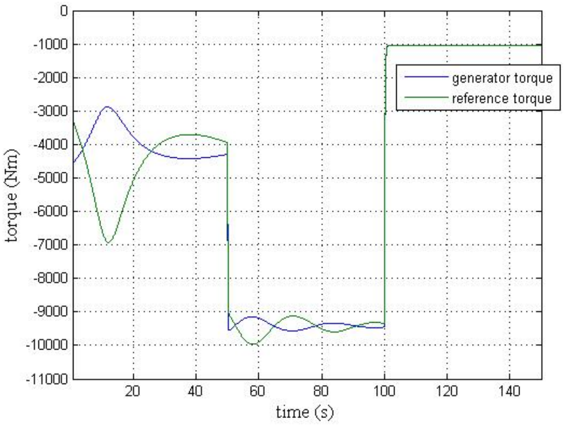

Figure 7. System torque evolution

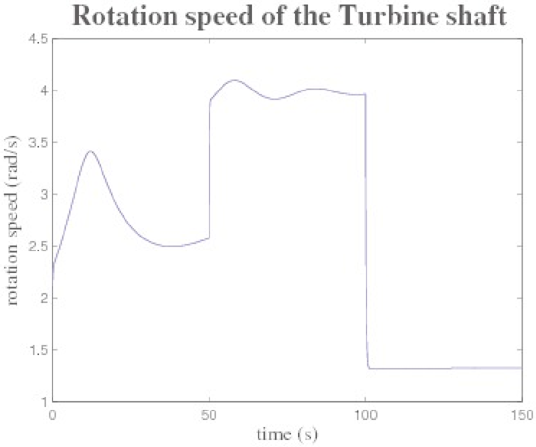

Figure 8. Turbine rotation velocity

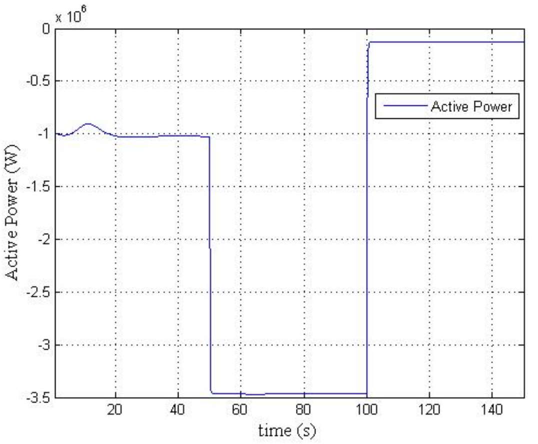

Figure 9. Active power system evolution

on the starting point and the where the wind speed is changing.

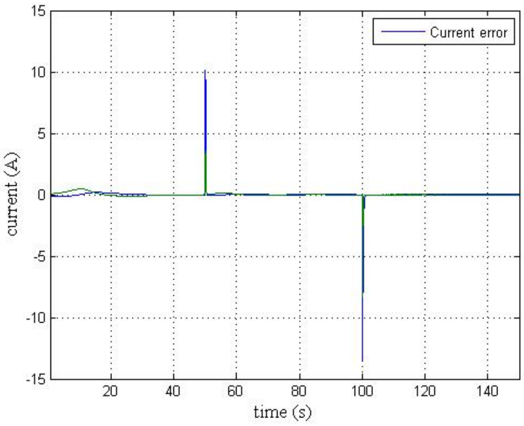

Figure 10. Current error of the control system

V. CONCLUSION

This paper has presented a control technique to deal with SCIG connected to the grid through a full power converter. Both stator- and grid-side are considered, which detail the control scheme to be used in each converter. The proposed technique allow control the stator-side without flux sensor inside the machine, which assure less mechanical problems. The control strategy has been validated by means of simulations.

REFERENCES

[1] R. Teodorescu, "Flexible control of small wind turbines with grid failure detection operating in stand-alone and grid-connected mode," *IEEE Transactions on Power Electronics*, vol. 19, pp. 1323–1332, 2004.

[2] A. Sikorski and A. Kuzma, "Cooperation of induction squirrel-cage generator with grid connected ac/dc/ac converter," *Bulletin of the Polish Academy of Sciences; Technical Sciences*, vol. 57, pp. 317–322, 2009.

[3] M. Imecs, "A survey of speed and flux control structures of squirrel-cage induction motor drives," Acta Universitatis Sapientiae Electrical and Mechanical Engineering, Tech. Rep., 2009.

[4] J. Holtz, "Sensorless control of induction motor drives," *Proceedings of the IEEE*, vol. 90, pp. 1359–1394, 2002.

[5] M. Imecs, C. Szabó, and J. J. Incze, "Stator-field-oriented control of the variable-excited synchronous motor: Numerical simulation," in *7th International Symposium of Hungarian Researchers on Computational Intelligence, Budapest, Hungary*, 2006.

[6] V. Vongmanee, "Emulator of wind turbine generator using dual inverter controlled squirrel-cage induction motor," in *The Eighth International Conference on Power Electronics and Drive Systems, Taipei, Taiwan,*, 2009.

[7] R. Leidhold, G. García, and M. I. Valla, "Field-oriented controlled induction generator with loss minimization," *IEEE Transactions on Industrial Electronics*, vol. 49, pp. 147–156, 2002.

[8] J. Faria, E. Margato, and M. Resende, "Self-excited induction generator for micro-hydro plants using water current turbines type," *Proceedings INTELEC'05*, pp. 107–112, 2005.

[9] C.-M. Ong, *Dynamic Simulation of Electric Machinery using Matlab/Simulink*. Prentice Hall, 1998.

[10] P. C. Krause, O. Wasynczuk, and S. D. Sudhoff, *Analysis of Electric Machinery and Drive Systems*, 2nd ed., M. E. El-Hawary, Ed. IEEE Press, 2002.

[11] P. C. Krause, *Analysis of Electric Machinery*, S. Rao, Ed. McGraw-Hill, 1986.

[12] O. Gomis-Bellmunt, A. Junyent-Ferre, A. Sumper, and J. Bergas-Jane, "Ride-through control of a doubly fed induction generator under unbalanced voltage sags," *IEEE Transactions on Energy Conversion*, vol. 23, pp. 1036–1045, 2008.

[13] J. Bergas-Jane, “Control del motor d’inducció considerant els límits del convertidor i del motor,” Ph.D. dissertation, Universitat Politècnica de Catalunya, 2000.

[14] B. K. Bose, *Modern Power Electronics and AC Drives*. Prentice Hall PTR, 2001.

[15] A. Junyent-Ferré, “Modelització i control d’un sistema de generació elèctrica de turbina de vent,” Master’s thesis, ETSEIB-UPC, 2007.

[16] M. Molinas, B. Naess, W. Gullvik, and T. Undeland, “Cage induction generators for wind turbines with power electronics converters in the light of the new grid codes,” in *European Conference on Power Electronics and Applications*, 2005.

[17] L. Harnefors and H.-P. Nee, “Model-based current control of ac machines using the internal model control method,” *IEEE Transactions on Industry Applications*, vol. 34, no. 1, pp. 133–141, Jan.-Feb. 1998.

[18] J. G. Slootweg, *Wind Power in Power Systems*. Wiley, 2005, ch. Reduced-order Modelling of Wind Turbines, pp. 555–585.

[19] Y. X. Dafeng Fu, “Study on linear dynamic model and analysis of operating characteristics of high-power vscf wind energy conversion system,” *World Non-Grid-Connected Wind Power on Energy Conference*, 2009.

José Luis Domínguez-García (M’10) was born in Barcelona, Spain, in 1985. He received the Bs and Ms degrees in industrial engineering from the School of Industrial Engineering of Barcelona (ETSEIB), Technical University of Catalonia (UPC), Barcelona, Spain, in 2009. He developed his Ms Thesis in Oulun Yliopisto, Oulu, Finland. He is currently student of Ph. D. degree in electrical engineering. His research interest are modelling and control of electrical machines and power converters, renewable energy integration in power systems and dynamic system theory.

Oriol Gomis-Bellmunt (S’05-M’07) received the degree in industrial engineering and the Ph.D. degree in electrical engineering from the School of Industrial engineering of Barcelona (ETSEIB), Universitat Politècnica de Catalunya (UPC), Barcelona, Spain in 2001 and 2007, respectively.
In 1999, he joined Engitrol S.L. where as a Project Engineer in the automation and control industry implementing control and supervision systems in several cement, chemical, papel, and transportation industries. In 2003, he developed part of his Ph.D. thesis in the DLR (German Aerospace Center) in Braunschweig, Germany. Since 2004, he has been with the Electrical Engineering Department (DEE) of the UPC, where he is currently a Lecturer and participates in the CITCEA-UPC research group. Since 2009, he is also with the Catalonia Institute for Energy Research (IREC). His research interests include the fields linked with smart actuators, electrical machines, power electronics, renewable energy integration in power systems, industrial automation, and engineering education.

Lluís Trilla-Romero was born in Barcelona, Spain, in 1981. He received the Bs and Ms degrees in industrial engineering from the School of Industrial Engineering of Barcelona (ETSEIB), Technical University of Catalonia (UPC), Barcelona, Spain, in 2006 and the Ms degree in Automatic Control and Robotics from the UPC in 2009. His current research interest include modelling and control of electrical machines and power converters, its application renewable generation system and its integration in the power system.

Adrià Junyent-Ferré (SM’09) was born in Barcelona, Spain, in 1982. He received the Bs and Ms degrees in industrial engineering from the School of Industrial Engineering of Barcelona (ETSEIB), Technical University of Catalonia (UPC), Barcelona, Spain, in 2007 and the Ms degree in Automatic Control and Robotics from the UPC in 2009. He has been working on research projects as a grant student in the Electrical Engineering Department of the UPC since 2007. His current research interests include the modeling and control of electrical machines and power converters and its use in renewable generation systems.