

Computer Simulation of Wind Power Systems: Power Electronics and Transient Stability Analysis

R. Melício, V. M. F. Mendes, J. P. S. Catalão

Abstract--This paper is concerned with the transient stability of variable-speed wind turbines with permanent magnet synchronous generators at a pitch control malfunction. As wind power generation undergoes rapid growth, new technical challenges emerge: dynamic stability and power quality. We study the influence of a pitch control malfunction on the quality of the energy injected into the electrical grid, analyzing the transient stability with different topologies for the power-electronic converters. Computer simulations obtained by using Matlab/Simulink are presented, and conclusions are duly drawn.

Keywords: computer simulation, power electronics, transient stability, wind power.

I. INTRODUCTION

THE general consciousness of finite and limited sources of energy on earth, and international disputes over the environment, global safety, and the quality of life, have created an opportunity for new more efficient less polluting wind and hydro power plants with advanced technologies of control, robustness, and modularity [1].

In Portugal, the wind power goal foreseen for 2010 was established by the government as 3750 MW and that will constitute some 25% of the total installed capacity by 2010 [2]. This value has recently been raised to 5100 MW, by the most recent governmental goals for the wind sector. Hence, Portugal has one of the most ambitious goals in terms of wind power, and in 2006 was the second country in Europe with the highest wind power growth.

Power system stability describes the ability of a power system to maintain synchronism and maintain voltage when subjected to severe transient disturbances [3]. As wind energy is increasingly integrated into power systems, the stability of already existing power systems is becoming a concern of utmost importance [4]. Also, network operators have to ensure that consumer power quality is not compromised. Hence, the total harmonic distortion (THD) should be kept as low as possible, improving the quality of the energy injected into the electrical grid [5].

The development of power electronics and their applicability in wind energy extraction allowed for variable-speed operation of the wind turbine [6]. The variable-speed wind turbines are implemented with either doubly fed induction generator (DFIG) or full-power converter. In a variable-speed wind turbine with full-power converter, the wind turbine is directly connected to the generator, which is usually a permanent magnet synchronous generator (PMSG).

Harmonic emissions are recognized as a power quality problem for modern variable-speed wind turbines. Understanding the harmonic behavior of variable-speed wind turbines is essential in order to analyze their effect on the electrical grids where they are connected [7].

Variable-speed wind turbines usually employ active pitch control, where blade pitch angle increases reduce the captured wind power by reducing the angle of attack [8]. The pitch control may have a considerable effect on the dynamical behavior of wind generators. However, previous papers were mainly focused on the transient stability of variable-speed wind turbines at external grid faults [8], [9].

This paper focuses on the transient stability of variable-speed wind turbines with PMSG at a pitch control malfunction. Hence, we study the influence of a pitch control malfunction on the quality of the energy injected into the electrical grid, analyzing the transient stability with different topologies for the power-electronic converters. Additionally, we propose a new control strategy based on fractional-order controllers for the variable-speed operation of wind turbines with PMSG/full-power converter topology. The performance of disturbance attenuation and system robustness is ascertained. Computer simulations obtained by using Matlab/Simulink are presented, and conclusions are duly drawn.

II. MODELING

A. Wind Turbine

The mechanical power of the wind turbine is given by

$$P_t = \frac{1}{2} \rho A u^3 c_p \quad (1)$$

where ρ is the air density, A is the area covered by the rotor, u is the wind speed value, and c_p is the power coefficient.

The power coefficient c_p is a function of the pitch angle θ of rotor blades, and of the tip speed ratio λ , which is the ratio between blade tip speed and wind speed upstream of the rotor.

R. Melício and J. P. S. Catalão are with the University of Beira Interior, Covilha, Portugal (e-mail of corresponding author: catalao@ubi.pt).

V. M. F. Mendes is with the Instituto Superior de Engenharia de Lisboa, Lisbon, Portugal.

For the simulation of pitch control malfunction, we consider that the pitch angle control of the blades imposes momentarily the position of wind gust on the blades, i.e., the blades go to the maximum pitch angle.

The maximum pitch angle $\theta_{\max} = 55^\circ$ is given for the minimum power coefficient, given by

$$c_{p_{\min}} = 0.0025 \quad (2)$$

for the tip speed ratio given by

$$\lambda = 3.475 \quad (3)$$

During the conversion of wind energy into mechanical energy, various forces (e.g. centrifugal, gravity and varying aerodynamic forces acting on blades, gyroscopic forces acting on the tower) produce various mechanical effects [10]. The mechanical eigenswings are mainly due to the following phenomena: asymmetry in the turbine, vortex tower interaction, and eigenswing in the blades.

The mechanical part of the wind turbine model can be simplified by modeling the mechanical eigenswings as a set of harmonic signals added to the power extracted from the wind. Therefore, the mechanical power of the wind turbine disturbed by the mechanical eigenswings may be expressed by

$$P_u = P_t \left[1 + \sum_{K=1}^3 A_K \left(\sum_{m=1}^2 a_{Km} g_{Km}(t) \right) h_K(t) \right] \quad (4)$$

$$g_{Km} = \sin \left(\int_0^t m \omega_K(t') dt' + \varphi_{Km} \right) \quad (5)$$

where K is the kind of the mechanical eigenswing excited in the rotating wind turbine, m is the harmonic of the given eigenswing, A_K is the magnitude of the eigenswing, g_{Km} is the distribution between the harmonics in the eigenswing, a_{Km} is the normalized magnitude of g_{Km} , h_K is the modulation of eigenswing, ω_K is the eigenfrequency of the eigenswing, and φ_{Km} is the phase of the harmonic. The frequency range of the wind turbine model with mechanical eigenswings is from 0.1 to 10 Hz. The values used for the calculation of P_u are given in Table I [11].

TABLE I
MECHANICAL EIGENSWINGS EXCITED IN THE WIND TURBINE

K	Source	A_K	ω_K	h_K	m	a_{Km}	φ_{Km}
1	Asymmetry	0.01	ω_t	1	1	4/5	0
					2	1/5	$\pi/2$
2	Vortex tower interaction	0.08	$3 \omega_t$	1	1	1/2	0
					2	1/2	$\pi/2$
3	Blades	0.15	9π	$1/2 (g_{11} + g_{21})$	1	1	0

B. Wind Speed

The wind speed usually varies considerably and has a stochastic character. The wind speed variation can be modeled as a sum of harmonics with frequency range 0.1–10 Hz [10]

$$u = u_0 \left[1 + \sum_K A_K \sin(\omega_K t) \right] \quad (6)$$

where u_0 is the wind speed value, u is the wind speed value subject to the disturbance.

Hence, the physical wind turbine model is subjected to the disturbance given by the wind speed variation model [11].

C. Rotor

The mechanical drive train considered in this paper is a two-mass model, consisting of a large mass and a small mass, corresponding to the wind turbine rotor inertia and generator rotor inertia, respectively. The model for the dynamics of the mechanical drive train for the wind power system used in this paper was previously reported by the authors in [12], [13].

D. Generator

The generator considered in this paper is a PMSG. The equations for modeling a PMSG can be found in the literature [14]. The electrical power P_e was reported in [12], [13]. In order to avoid demagnetization of permanent magnet in the PMSG, a null stator current $i_d = 0$ is imposed [15].

E. Two-level Converter

The two-level converter is an AC-DC-AC converter, with six unidirectional commanded IGBTs S_{ik} used as a rectifier, and with the same number of unidirectional commanded IGBTs used as an inverter. The rectifier is connected between the PMSG and a capacity bank. The inverter is connected between this capacity bank and a first order filter, which in turn is connected to an electrical grid. The groups of two IGBTs linked to the same phase constitute a leg k of the converter. A three-phase active symmetrical circuit in series models the electrical grid [12], [13].

The configuration of the simulated wind power system with two-level converter is shown in Fig. 1.

F. Multilevel Converter

The multilevel converter is an AC-DC-AC converter, with twelve unidirectional commanded IGBTs S_{ik} used as a rectifier, and with the same number of unidirectional commanded IGBTs used as an inverter. The rectifier is connected between the PMSG and a capacity bank. The inverter is connected between this capacity bank and a second order filter, which in turn is connected to an electrical grid. The groups of four IGBTs linked to the same phase constitute a leg k of the converter. A three-phase active symmetrical circuit in series models the electrical grid [12], [13].

The configuration of the simulated wind power system with multilevel converter is shown in Fig. 2.

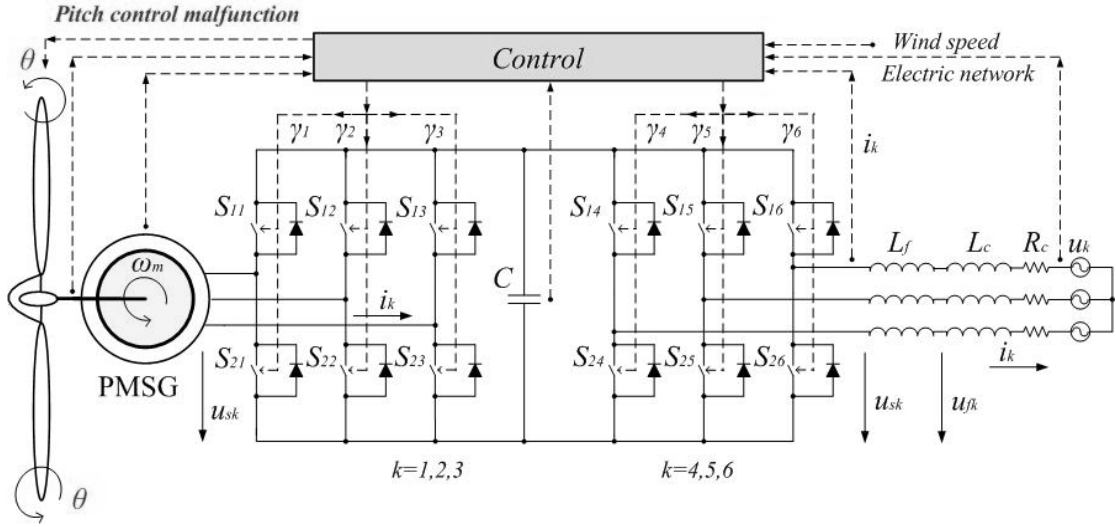


Fig. 1. Wind power system with two-level converter.

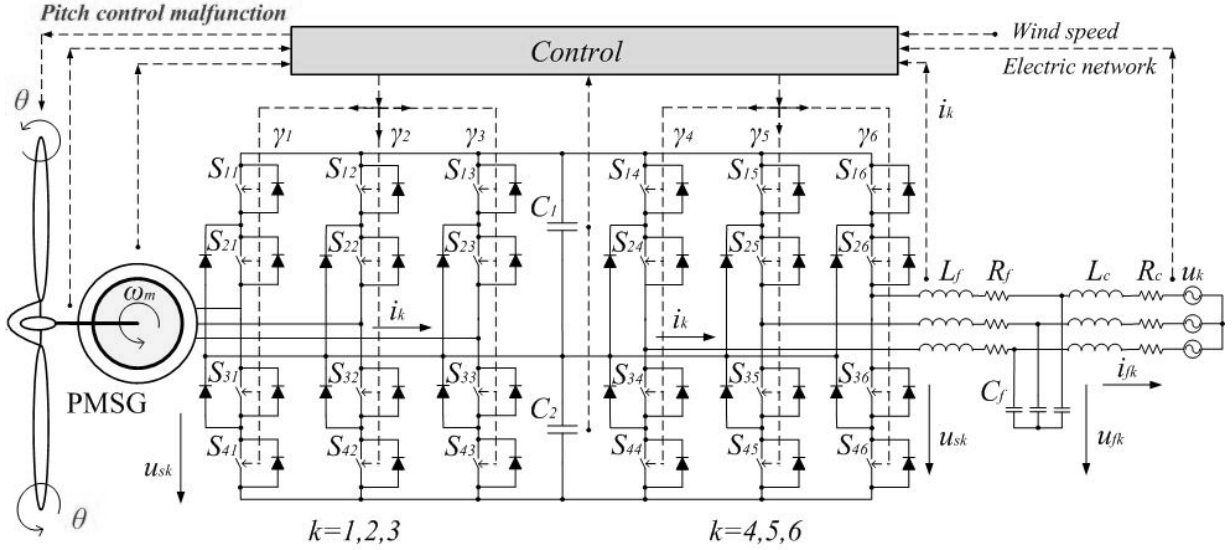


Fig. 2. Wind power system with multilevel converter.

III. CONTROL STRATEGY

A. Fractional-Order Controller

We propose a new control strategy based on fractional-order PI^α controllers for the variable-speed operation of wind turbines with PMSG/full-power converter topology. Fractional-order controllers are based on fractional calculus theory, which is a generalization of ordinary differentiation and integration to arbitrary (non-integer) order [16].

The fractional-order differentiator can be denoted by a general operator ${}_a D_t^\alpha$ [17], given by

$${}_a D_t^\alpha = \begin{cases} \frac{d^\alpha}{dt^\alpha}, & \Re(\alpha) > 0 \\ 1, & \Re(\alpha) = 0 \\ \int_a^t (d\tau)^{-\alpha}, & \Re(\alpha) < 0 \end{cases} \quad (7)$$

There are two commonly used definitions for the general fractional differentiation and integration, respectively, the Grünwald–Letnikov definition and the Riemann–Liouville definition. The differentiation using the Grünwald–Letnikov definition is given by

$${}_a D_t^\alpha f(t) = \lim_{h \rightarrow 0} \frac{1}{h^\alpha} \sum_{j=0}^{[(t-a)/h]} (-1)^j \binom{\alpha}{j} f(t-jh) \quad (8)$$

The differentiation using the Riemann–Liouville definition is given by

$${}_a D_t^\alpha f(t) = \frac{1}{\Gamma(n-\alpha)} \frac{d^n}{dt^n} \int_a^t \frac{f(\tau)}{(t-\tau)^{\alpha-n+1}} d\tau \quad (9)$$

where α can be an integer, rational, irrational, or complex number, but in our paper it is a real number satisfying the restrictions $0 < \alpha < 1$, a and t are the limits of the operation. Usually a can be taken as a null value, Γ is the gamma function and h is the step.

The differential equation of the fractional order controller is given by

$$y(t) = K_p e(t) + K_{i0} D_t^{-\alpha} e(t) \quad (10)$$

where K_p is the proportional gain and K_i is the integration gain. We assume $\alpha = 7/10$, and for simplicity we write ${}_0D_t^{7/10} \equiv D_t^{7/10}$. Using the Laplace transform, the transfer function of the fractional-order PI^α controller is given by

$$G(s) = K_p + K_i s^{-\frac{7}{10}} \quad (11)$$

B. Converters Control

Power converters are variable structure systems, because of the on/off switching of their IGBTs. As mentioned previously, the controllers used in the converters are fractional-order PI^α controllers. Pulse width modulation (PWM) by space vector modulation (SVM) associated with sliding mode is used for controlling the converters.

The sliding mode control strategy presents attractive features such as robustness to parametric uncertainties of the wind turbine and the generator as well as to electrical grid disturbances [18].

Sliding mode controllers are particularly interesting in systems with variable structure, such as switching power converters, guaranteeing the choice of the most appropriate space vectors. Their aim is to let the system slide along a predefined sliding surface by changing the system structure.

The power semiconductors present physical limitations, since they cannot switch at infinite frequency. Also, for a finite value of the switching frequency, an error $e_{\alpha\beta}$ will exist between the reference value and the control value. In order to guarantee that the system slides along the sliding surface $S(e_{\alpha\beta}, t)$, it is necessary to ensure that the state trajectory near the surfaces verifies the stability conditions given by

$$S(e_{\alpha\beta}, t) \frac{dS(e_{\alpha\beta}, t)}{dt} < 0 \quad (12)$$

IV. POWER QUALITY EVALUATION

In order to evaluate the harmonic content of the current injected in the electrical grid, we use the THD. The harmonic content of the current is expressed in percentage of the fundamental component. The THD is given by

$$\text{THD (\%)} = 100 \frac{\sqrt{\sum_{H=2}^{50} X_H^2}}{X_F} \quad (13)$$

where X_H is the root mean square (RMS) value of the total harmonics of the signal, and X_F is the RMS value of its fundamental component.

V. SIMULATION

The wind power system simulated has a rated electrical power of 900 kW. The mathematical models for the wind power system with the two-level and multilevel converters were implemented in Matlab/Simulink. The parameter α has been chosen within $[0,1]$ and equal to $7/10$. The configuration of the fractional-order $PI^{7/10}$ controller is shown in Fig. 3.

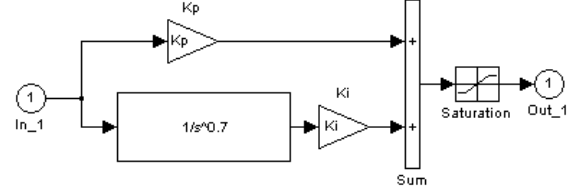


Fig. 3. Configuration of the fractional-order $PI^{7/10}$ controller.

We consider in the simulation a ramp increase wind speed u_0 , taking 2.5 s between 5 and 25 m/s. Also, a time horizon of 3.5 s is considered. Fig. 4 shows the mechanical power of the wind turbine disturbed by the mechanical eigenswings, and the electrical power of the generator. A pitch control malfunction is simulated between 2 and 2.5 s.

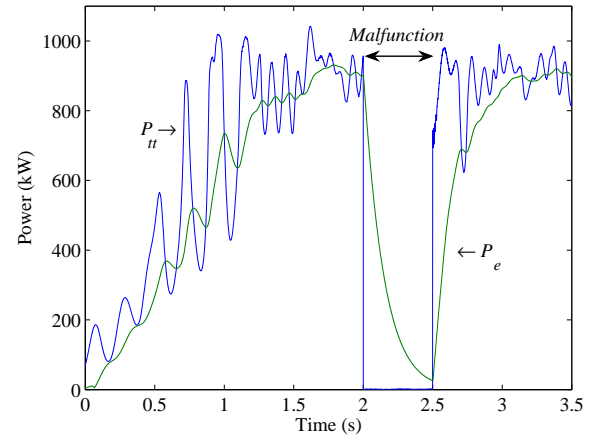


Fig. 4. Mechanical power and electrical power.

The rotor speed of the wind turbine n_{tt} and the rotor speed of the generator n_e are shown in Fig. 5.

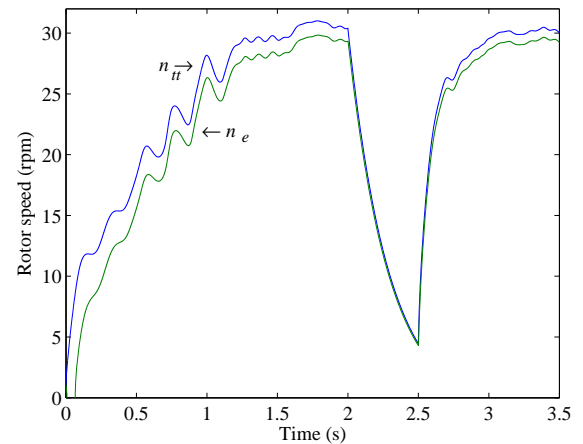


Fig. 5. Rotor speed of the wind turbine and generator.

The power coefficient variation is shown in Fig. 6.

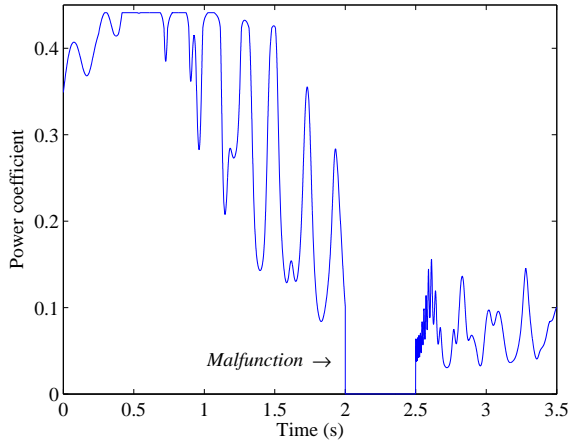


Fig. 6. Power coefficient variation.

The pitch angle variation is shown in Fig. 7.

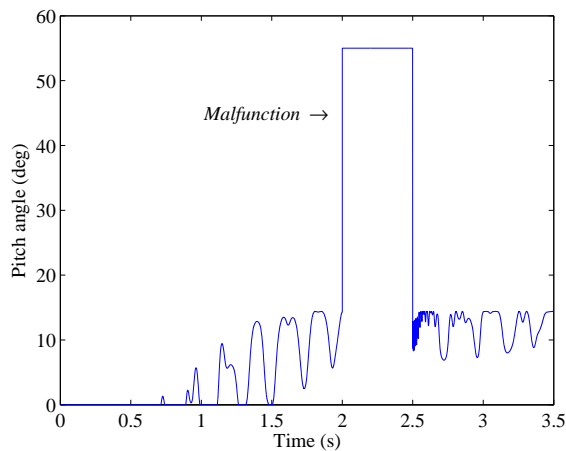


Fig. 7. Pitch angle variation.

The capacitor voltage for the two-level converter is shown in Fig. 8. As can be seen, the capacitor voltage drops almost 1720 V during the pitch control malfunction.

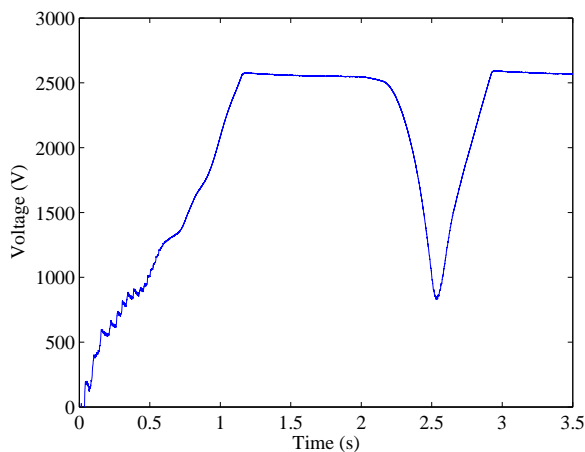


Fig. 8. Capacitor voltage for the two-level converter.

The RMS current injected in the electrical grid for the two-level converter is shown in Fig. 9.

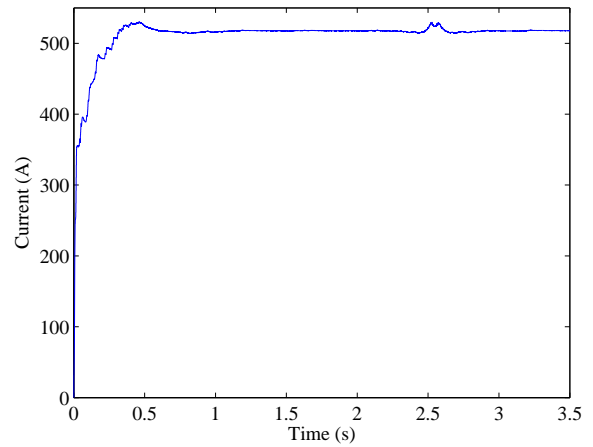


Fig. 9. Output RMS current for the two-level converter.

The THD of the current injected in the grid with the two-level converter is shown in Fig. 10.

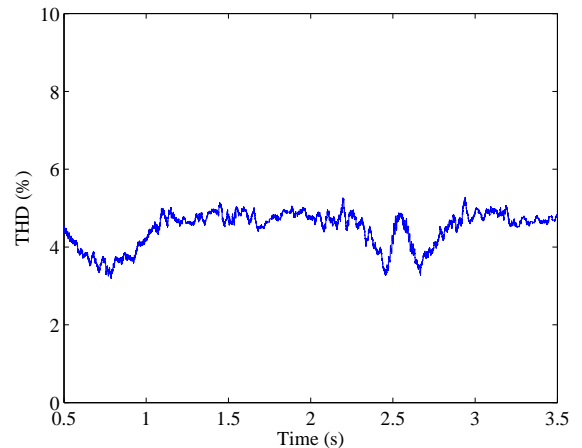


Fig. 10. THD of the current injected in the grid with the two-level converter.

The capacitors voltages for the multilevel converter are shown in Fig. 11. As can be seen, the capacitors voltages drop only 258 V during the pitch control malfunction.

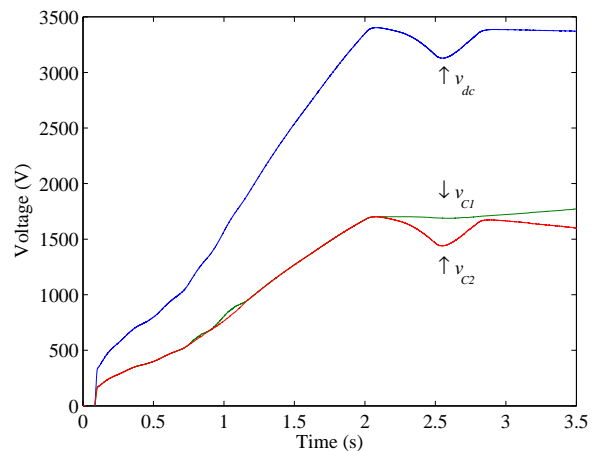


Fig. 11. Capacitors voltages for the multilevel converter.

The RMS current injected in the electrical grid for the multilevel converter is shown in Fig. 12.

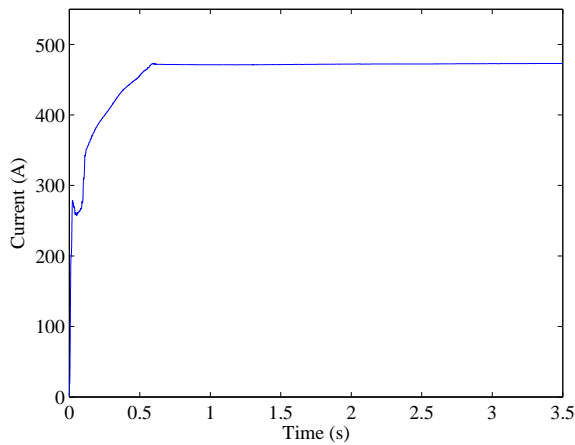


Fig. 12. Output RMS current for the multilevel converter.

The THD of the current injected in the grid with the multilevel converter is shown in Fig. 13.

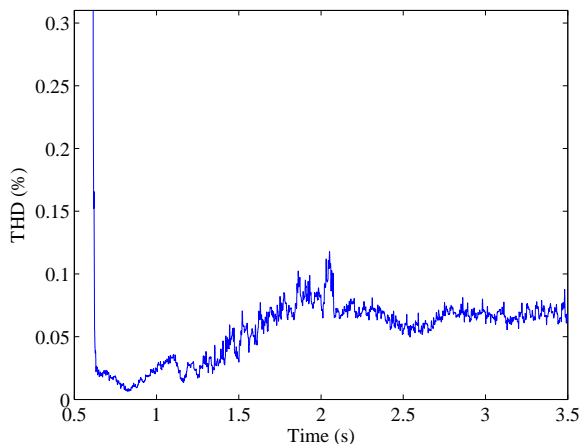


Fig. 13. THD of the current injected in the grid with the multilevel converter.

Table II summarizes an overall comparison between a classical PI controller and fractional-order $PI^{5/10}$ and $PI^{7/10}$ controllers, concerning the THD of the current injected in the grid.

TABLE II
THD OF THE CURRENT INJECTED IN THE GRID

Controller	THD (%)	
	Wind power system with two-level converter	Wind power system with multilevel converter
PI	5.10	0.67
$PI^{5/10}$	4.58	0.45
$PI^{7/10}$	4.31	0.38

The fractional-order controllers improve the performance of disturbance attenuation and system robustness. Also, the current THD for the wind power system with multilevel converter is much lower than the 5% limit imposed by IEEE-519 standard [19]. Although IEEE-519 standard might not be applicable in such situation, it is used as a guideline for comparison purposes [20].

VI. CONCLUSIONS

As wind power generation undergoes rapid growth, new technical challenges emerge: dynamic stability and power quality. The novel contributions of this paper are twofold. The transient stability of variable-speed wind turbines with PMSG/full-power converter topology has been studied in this paper, considering not only wind speed disturbances, but also a pitch control malfunction. The simulation results show that the new fractional-order control strategy proposed improves the performance of disturbance attenuation and system robustness. Also, we show that the current THD for the wind power system with multilevel converter is much lower than 5% limit imposed by IEEE-519 standard.

VII. REFERENCES

- [1] T. Ahmed, K. Nishida, and M. Nakaoka, "Advanced control of PWM converter with variable-speed induction generator," *IEEE Trans. Industry Applications*, vol. 42, pp. 934-945, Jul.-Aug. 2006.
- [2] A. Estanqueiro, R. Castro, P. Flores, J. Ricardo, M. Pinto, R. Rodrigues, and J. Peças Lopes, "How to prepare a power system for 15% wind energy penetration: the Portuguese case study," *Wind Energy*, vol. 11, pp. 75-84, Jan.-Feb. 2008.
- [3] Y. Coughlan, P. Smith, A. Mullane, and M. O'Malley, "Wind turbine modelling for power system stability analysis - A system operator perspective," *IEEE Trans. Power Systems*, vol. 22, pp. 929-936, Aug. 2007.
- [4] N. R. Ullah and T. Thiringer, "Variable speed wind turbines for power system stability enhancement," *IEEE Trans. Energy Conversion*, vol. 22, pp. 52-60, Mar. 2007.
- [5] J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galvan, R. C. P. Guisado, A. M. Prats, J. I. Leon, and N. Moreno-Alfonso, "Power-electronic systems for the grid integration of renewable energy sources: A survey," *IEEE Trans. Industrial Electronics*, vol. 53, pp. 1002-1016, Aug. 2006.
- [6] J. A. Baroudi, V. Dinavahi, and A. M. Knight, "A review of power converter topologies for wind generators," *Renewable Energy*, vol. 32, pp. 2369-2385, Nov. 2007.
- [7] S. T. Tenzrakis and S. A. Papathanassiou, "An investigation of the harmonic emissions of wind turbines," *IEEE Trans. Energy Conversion*, vol. 22, pp. 150-158, Mar. 2007.
- [8] J. F. Conroy and R. Watson, "Low-voltage ride-through of a full converter wind turbine with permanent magnet generator," *IET Renewable Power Generation*, vol. 1, pp. 182-189, Sep. 2007.
- [9] T. Sun, Z. Chen, and F. Blaabjerg, "Transient stability of DFIG wind turbines at an external short-circuit fault," *Wind Energy*, vol. 8, pp. 345-360, Jul.-Sep. 2005.
- [10] Z. X. Xing, Q. L. Zheng, X. J. Yao, and Y. J. Jing, "Integration of large doubly-fed wind power generator system into grid," in: *Proc. 8th Int. Conf. Electrical Machines and Systems*, pp. 1000-1004, Sep. 2005.
- [11] V. Akhmatov, H. Knudsen, and A. H. Nielsen, "Advanced simulation of windmills in the electric power supply," *Int. Journal of Electr. Power Energy Syst.*, vol. 22, pp. 421-434, Aug. 2000.
- [12] R. Melício, V.M.F. Mendes, and J.P.S. Catalão, "Two-level and multilevel converters for wind energy systems: a comparative study," in: *Proc. 13th Int. Power Electronics and Motion Control Conf.*, pp. 1682-1687, Sep. 2008.
- [13] R. Melício, V.M.F. Mendes, and J.P.S. Catalão, "Evaluating power quality in wind power generation systems with two-level and multi-level converters," presented at the 6th Mediterranean Conf. and Exhibition on Power Generation, Transmission and Distribution, Thessaloniki, Greece, Nov. 2008.
- [14] C.-M. Ong, *Dynamic Simulation of Electric Machinery: Using Matlab/Simulink*. NJ: Prentice-Hall, 1998, pp. 259-350.

- [15] T. Senjyu, S. Tamaki, N. Urasaki, and K. Uezato, "Wind velocity and position sensorless operation for PMSG wind generator," in: *Proc. 5th Int. Conf. on Power Electronics and Drive Systems*, pp. 787-792, Nov. 2003.
- [16] I. Podlubny, "Fractional-order systems and PI-lambda-D-mu-controllers," *IEEE Trans. Automatic Control*, vol. 44, pp. 208-214, Jan. 1999.
- [17] A. J. Calderón, B.M. Vinagre, and V. Feliu, "Fractional order control strategies for power electronic buck converters," *Signal Processing*, vol. 86, pp. 2803-2819, Mar. 2006.
- [18] B. Beltran, T. Ahmed-Ali, and M. E. H. Benbouzid, "Sliding mode power control of variable-speed wind energy conversion systems," *IEEE Trans. Energy Conversion*, vol. 23, pp. 551-558, Jun. 2008.
- [19] *IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters*, IEEE Standard 519-1992.
- [20] T. M. H. Nick, K. Tan, and S. Islam, "Mitigation of harmonics in wind turbine driven variable speed permanent magnet synchronous generators," in: *Proc. 7th Int. Power Engineering Conf.*, pp. 1159-1164, Nov.-Dec. 2005.