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Fractional-order control and simulation of wind energy systems with PMSG/full-power converter topology

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ABSTRACT

This paper presents a new integrated model for the simulation of wind energy systems. The proposed model is more realistic and accurate, considering a variable-speed wind turbine, two-mass rotor, permanent magnet synchronous generator (PMSG), different power converter topologies, and filters. Additionally, a new control strategy is proposed for the variable-speed operation of wind turbines with PMSG/full-power converter topology, based on fractional-order controllers. Comprehensive simulation studies are carried out with matrix and multilevel power converter topologies, in order to adequately assert the system performance in what regards the quality of the energy injected into the electric grid. Finally, conclusions are duly drawn.

1. Introduction

Wind energy is the fastest growing energy technology in terms of percentage of yearly growth of installed capacity per technology source [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.

As wind energy is increasingly integrated into power systems, the stability of already existing power systems is becoming a concern of utmost importance [3]. Also, network operators have to ensure that consumer power quality is not deteriorated. Hence, the total harmonic distortion (THD) should be kept as low as possible, improving the quality of the energy injected into the electric grid [4]. The new technical challenges emerging due to increased wind power penetration, dynamic stability and power quality imply research of more realistic and accurate models for wind energy systems.

Power-electronic converters have been developed for integrating wind power with the electric grid. The use of power-electronic converters allows not only for variable-speed operation of a wind turbine, but also for enhancement on power extraction [5]. In a recent overview of different wind generator systems [6], it is shown that variable-speed conceptions equipped with power-electronic converters will continue to dominate and be very promising technologies for large wind farms.

Variable-speed control is better than constant-speed control and is known for at least a decade [7]. In a variable-speed wind turbine with full-power converter, the wind turbine is directly connected to the generator and the generator is completely decoupled from the electric grid. Of all the generators used in wind turbines, the permanent magnet synchronous generator (PMSG) is the one with a significant advantage: it is stable and secure under normal operating conditions; and comparing with a wound synchronous generator, it is smaller and does not need a direct current power source for field excitation.

Accurate modeling and control of wind turbines have high priority in the research activities all over the world [8]. Also, understanding the harmonic behavior of variable-speed wind turbines is essential in order to analyze their effect on the electric grids where they are connected [9]. At the moment, substantial documentation exists on modeling and control issues for the doubly fed induction generator (DFIG) wind turbine. But this is not the case for wind turbines with PMSG and full-power converter.

In this paper, a variable-speed wind turbine is considered with PMSG and different power converter topologies: matrix, and multilevel.

Matrix converters have received considerable attention during the past decades, since they may become a viable alternative to back-to-back converters [10]. The matrix converter is capable of converting the variable AC from the generator into constant AC

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Nomenclature

P_t	mechanical power of the turbine	ω_g	rotor angular speed at the generator
ρ	air density	J_g	moment of inertia for the rotor of the generator
A	area covered by the rotor	T_{dg}	resistant torque in the generator bearing
R	radius of the area covered by the blades	T_{ag}	resistant torque due to the viscosity of the airflow in the generator
u	wind speed value upstream of the rotor	T_g	electric torque
c_p	power coefficient	i_d, i_q	stator currents
θ	pitch angle of the rotor blades	L_d, L_q	stator inductances
λ	tip speed ratio	u_d, u_q	stator voltages
ω_t	rotor angular speed at the wind turbine	p	number of pairs of poles
J_t	moment of inertia for blades and hub	M	mutual inductance
T_t	mechanical torque	R_d, R_q	stator resistances
T_{dt}	resistant torque in the wind turbine bearing	i_f	equivalent rotor current
T_{at}	resistant torque in the hub and blades		
T_{ts}	torsional stiffness torque		

to the electric grid in one stage. A technology review of matrix converters can be seen in [11]. The converter is smaller, lighter and more reliable than conventional converters, representing a good alternative for variable-speed operation of wind energy systems [12]. One of the major drawbacks of a matrix converter is that 18 total switches are required, causing an increase in converter semiconductor cost. Also, industrial wide use of matrix converter is still very limited due to certain undesirable characteristics: its sensitivity to distortion in input power supply due to the lack of reactive component in the power circuit, and its sensitivity to the rapidly fluctuating input voltage frequency when used in wind energy systems [13].

Multilevel converters are widely used in high-voltage and high-power applications [14,15], because they allow operations at higher dc-link voltage levels, avoiding the problems of the series interconnection of devices [16]. Compared to the conventional two-level converter topology, multilevel converters provide several advantages: their ability to meet the increasing demand of power ratings and power quality associated with reduced harmonic distortion, lower electromagnetic interference, and higher efficiencies [17]. Hence, multilevel converters are a good tradeoff solution between performance and cost in high-power systems [18]. A survey of topologies, controls, and applications for multilevel inverters can be seen in [19]. Multilevel converters are, however, limited by the following drawbacks: voltage unbalances, high component count, and increased control complexity. A critical issue in multilevel converters is the design of the DC-link capacitors. Thus, special attention should be paid to the unbalance in the capacitors' voltage of multilevel converters, which may produce a malfunction of the control. One possible design of the DC-link is given in [20].

Several papers have been issued on matrix and multilevel power converters, but mainly using simplified models to describe the wind energy system or the control strategies themselves. However, the increased wind power penetration, as nowadays occurs for instance in Portugal, requires new models for the simulation of wind energy systems, more realistic and accurate, and new control strategies, improving performance of disturbance attenuation and system robustness. These concerns are all accounted for in our paper.

As a new contribution to earlier studies, an integrated model for the simulation of wind energy systems with different power converter topologies is presented in this paper. Additionally, a new fractional-order control strategy is proposed for the variable-speed operation of wind turbines with PMSG/full-power converter topology.

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 electric grids where they are connected [9]. Hence, comprehensive simulation studies are carried out with matrix and multilevel power converter topologies, in order to adequately assert the system performance in what regards the quality of the energy injected into the electric grid.

This paper is organized as follows. Section 2 presents the integrated modeling of the wind energy system with different power converter topologies: matrix and multilevel. Section 3 presents the new fractional-order control strategy for the variable-speed operation of wind turbines with PMSG/full-power converter topology. Section 4 provides the power quality evaluation by Fast Fourier Transform (FFT) and THD. Section 5 presents the simulation results obtained on a case study. Finally, concluding remarks are given in Section 6.

2. Integrated modeling

2.1. Wind turbine

The mechanical power of the turbine is given by:

$$P_t = \frac{1}{2}\rho A u^3 c_p \tag{1}$$

The computation of the power coefficient requires the use of blade element theory and the knowledge of blade geometry. The power coefficient is a function of the pitch angle of rotor blades and the tip seed ratio, which is the ratio between blade tip speed and wind speed upstream of the rotor. In this paper, the numerical approximation developed in [21] is followed, where the power coefficient is given by:

$$c_p = 0.73\left(\frac{151}{\lambda_i} - 0.58\ \theta - 0.002\ \theta^{2.14} - 13.2\right)e^{-\frac{18.4}{\lambda_i}} \tag{2}$$

$$\lambda_i = \frac{1}{\frac{1}{(\lambda - 0.02\ \theta)} - \frac{0.003}{(\theta^3+1)}} \tag{3}$$

The mechanical power acquired from the wind is given by (1)–(3). From (2), the maximum power coefficient is given for a null pitch angle and it is equal to:

$$c_{p_{\max}} = 0.4412 \tag{4}$$

corresponding to an optimal tip speed ratio equal to:

$$\lambda_{opt} = 7.057 \tag{5}$$