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DYNAMIC MODEL OF WIND ENERGY CONVERSION SYSTEMS WITH FRACTIONAL ORDER CONTROLLERS FOR THE VARIABLE-SPEED OPERATION OF WIND TURBINE

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Abstract

This paper presents a dynamic model for variable speed wind energy conversion systems, equipped with a transient stability of variable-speed wind turbines and Z-source matrix converter, specially developed for its use in power system stability studies involving large networks, with a high number of buses and a high level of wind generation penetration. The validity of the necessary simplifications has been contrasted against a detailed model that allows a thorough insight into the mechanical and electrical behavior of the system, and its interaction with the grid. This paper also analyze 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.

Index Terms: *computer simulation, power electronics, transient stability, Power system stability; Wind power generation*

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1. INTRODUCTION

Electrical energy production from renewable sources, and particularly wind power, is increasingly important in industrialized countries. Indeed, wind power is now a not-so-small percentage of the power generation industry and it is rapidly becoming higher. With the massive penetration of wind energy conversion systems in the power network, some new problems arise, not only in technical areas, but also in economy, policy and regulatory fields [1–5]. The results presented in this paper are related to the development of new tools needed to face the technical problem of integrating a large number of wind generators (WGs) in the power grid.

Dynamic models for conventional generators and other power network components, and their corresponding control systems, are generally well described in the literature and known by power system engineers [6,7]. When studying the dynamic behavior of an electric power system with high wind generation penetration, the level of detail of the models used does not need to be so high. Furthermore, detailed models do not work well because of the high number of state variables and the small time constants involved. Thus, simplified models are used for representing WGs in power system dynamics simulations that facilitate the investigation of the impact of a large number of WGs on the behavior of a large power system [7-9].Besides, wind power plants are composed of a large number of few megawatt generators, linked together by a medium voltage network. Obviously, the dynamic behavior of such clusters does not fit well in the models of conventional generators, so reduced-order or aggregation models have been investigated [12–17]. An additional application of the model described in this paper is the assessment of aggregation models for this class of WGs.

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.

2. MODEL DESCRIPTION

2.1. Wind Turbine

The mechanical power of the wind turbine is given by

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

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.

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. for the tip speed ratio given by $\lambda = 3.475$

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.

2.2 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]

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

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].

2.3. 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].

2.4. 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].

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	π/2
2	Vortex tower interaction	0.08	$3\,\omega_t$	1	1	1/2	0
					2	1/2	π/2
3	Blades	0.15	9 π	$1/2\,(g_{11}+g_{21})$	1	1	0

2.5. Two-level Converter

The two level converter is an AC-DC-AC converter with six unidirectional commanded IGBTs, S_{ik} used as rectifier and with the same number of unidirectional commanded IGBTs used as an inverter. between this capacity bank and a first order The rectifier is connected between the PMSG and a capacity bank. The inverter is connected filter, which in turn is connected to an e lectrical 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.

2.6. Multi-level 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 multi level converter is shown in Fig-2.

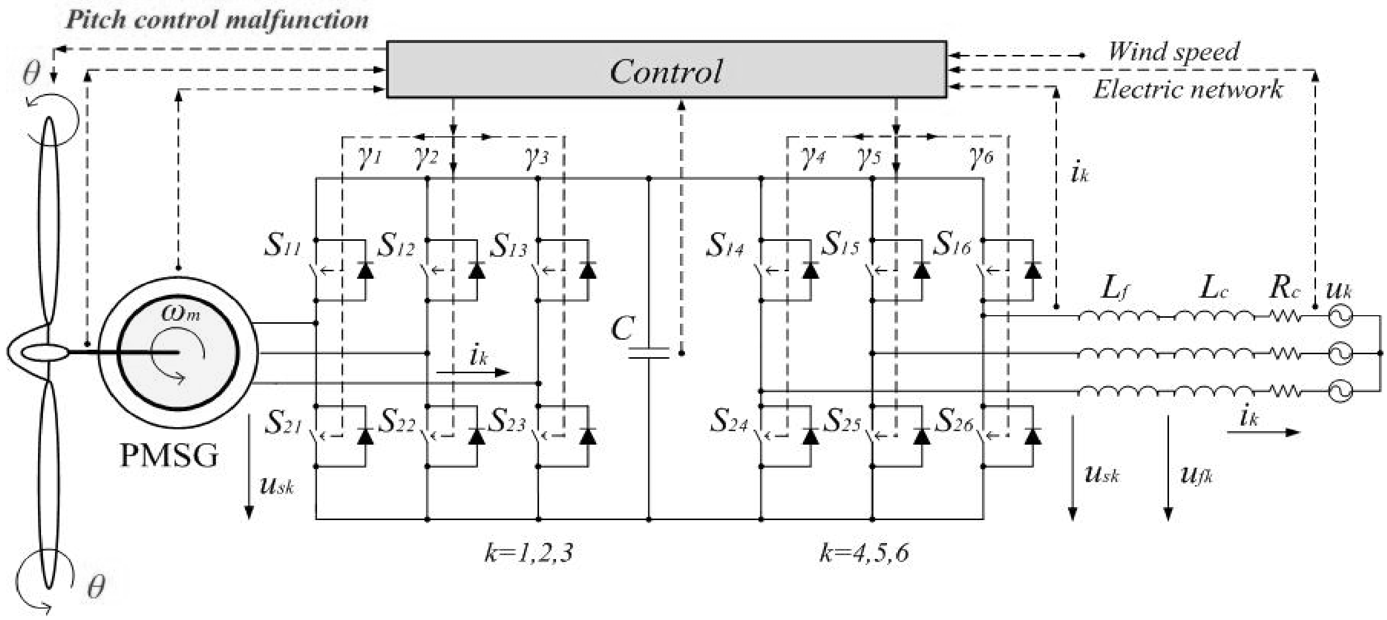

Fig. 1. Wind power system with two-level converter.

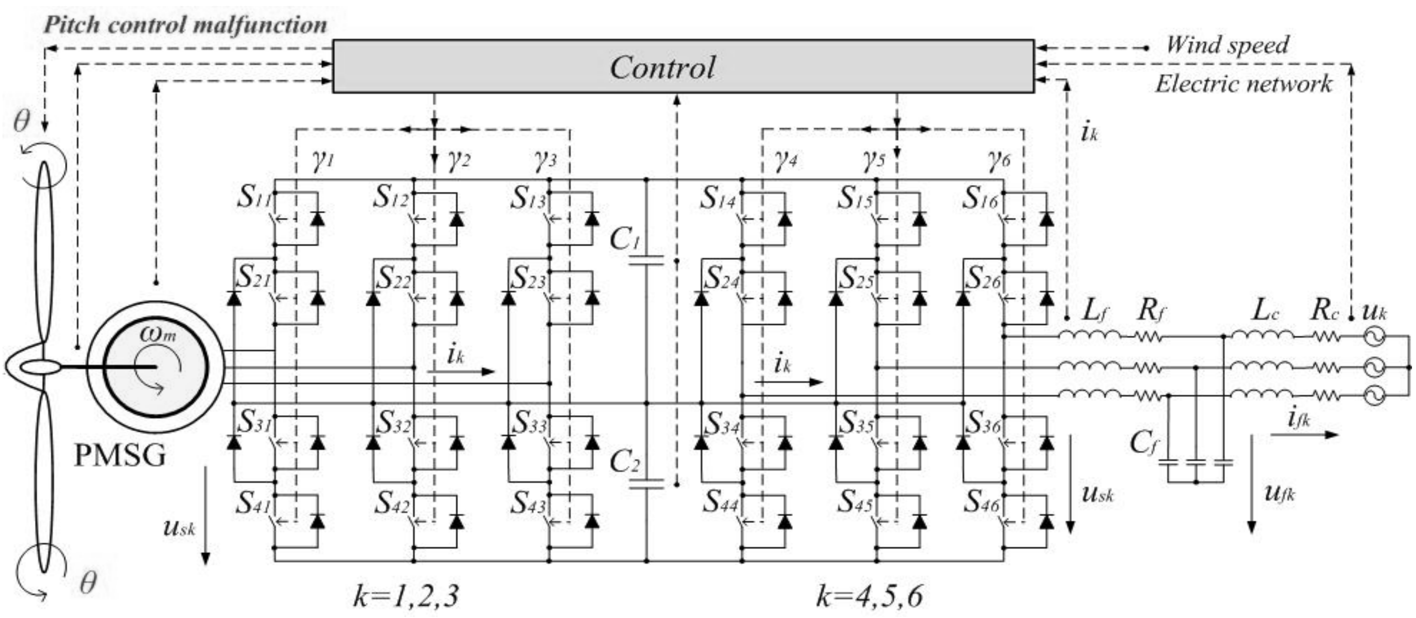

Fig. 2. Wind power system with multilevel converter.

3. CONTROL STRATEGY

3.1 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 $_aD_t^{\alpha}$ given by

$$_aD_t^{\alpha} = \begin{cases} \dfrac{d^{\alpha}}{dt^{\alpha}}, & \Re(\alpha) > 0 \\ 1, & \Re(\alpha) = 0 \\ \int_a^t (d\tau)^{-\alpha}, & \Re(\alpha) < 0 \end{cases}$$

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

$$_aD_t^{\alpha} f(t) = \lim_{h \to 0} \frac{1}{h^{\alpha}} \sum_{j=0}^{[(t-a)/h]} (-1)^j \binom{\alpha}{j} f(t - jh)$$

The differentiation using the Riemann–Liouville definition is given by

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

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

3.2 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

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

4. 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

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

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

5. 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.

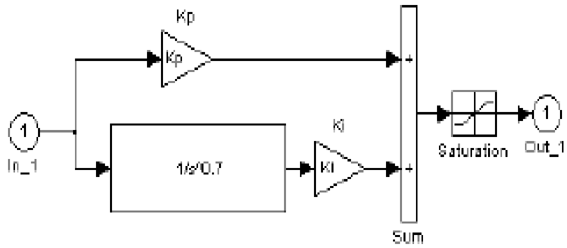

Fig. 3. Configuration of the fractional-order $PI^{7/10}$ controller.

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 eigens wings, and the electrical power of the generator. A pitch control malfunction is simulated between 2 and 2.5 s .The rotor speed of the wind turbine n_{tt} and the rotor speed of the generator n_e are shown in Fig. 5, The power coefficient variation is shown in Fig. 6,

Fig. 7 shows Output RMS current for the two-level converter, The capacitors voltages for the multilevel converter are shown in Fig. 8. As can be seen, the capacitors voltages drop only 258 V during the pitch control malfunction. The RMS current injected in the electrical grid for the multilevel converter is shown in Fig. 9,and the THD of the current injected in the grid with the multilevel converter is shown in Fig. 10.

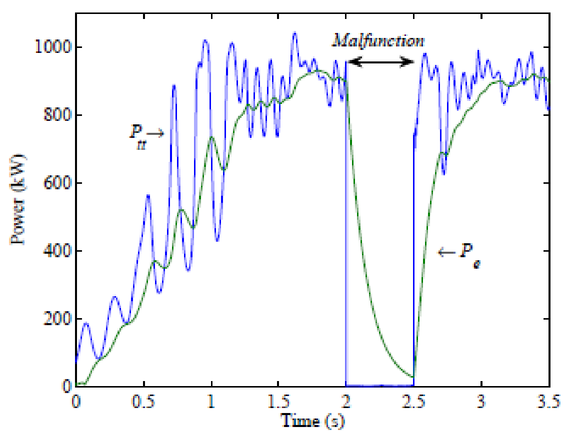

Fig. 4. Mechanical power and electrical power.

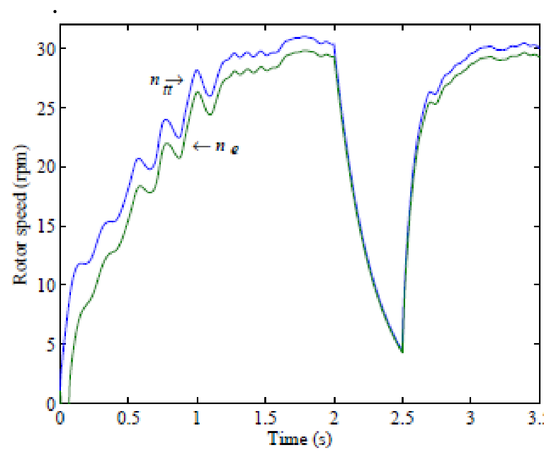

Fig. 5. Rotor speed of the wind turbine and generator.

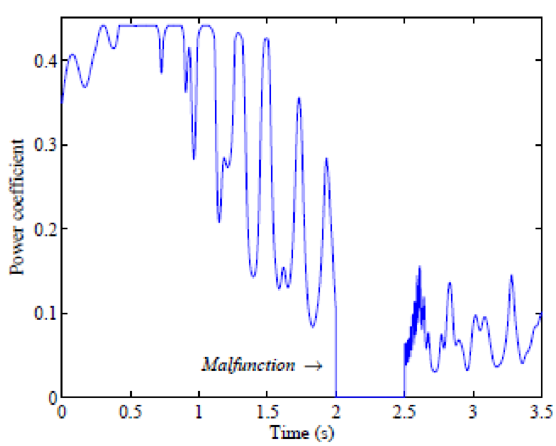

Fig.6 .Power coefficient variation

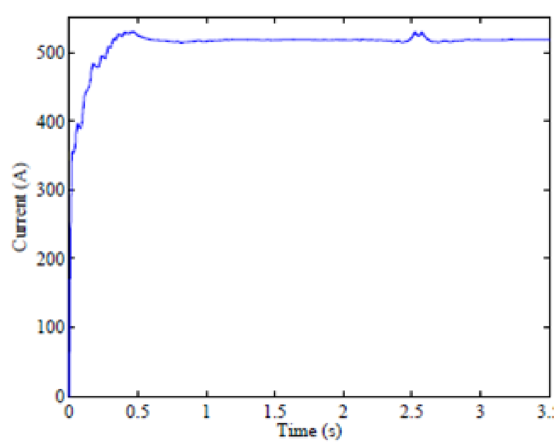

Fig. 7. Output RMS current for the two-level converter

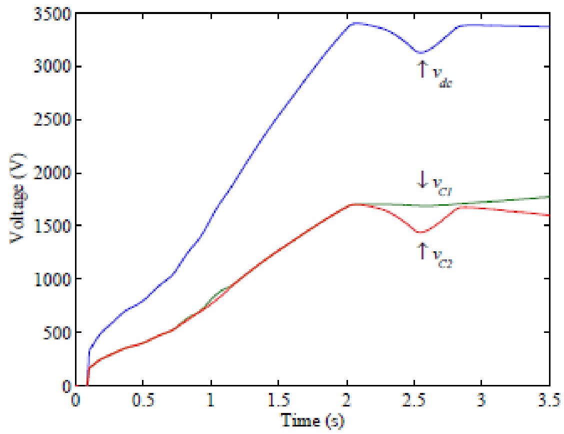

Fig. 8. Capacitors voltages for the multilevel converter.

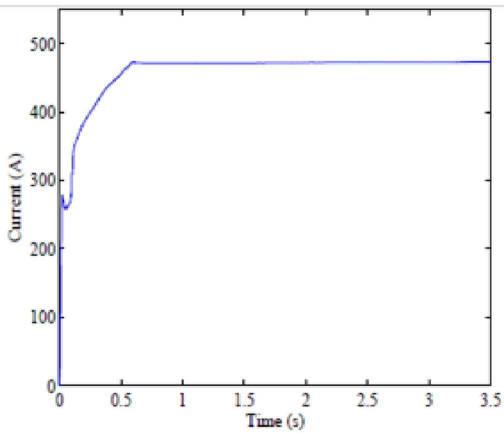

Fig. 9. Output RMS current for the multilevel converter.

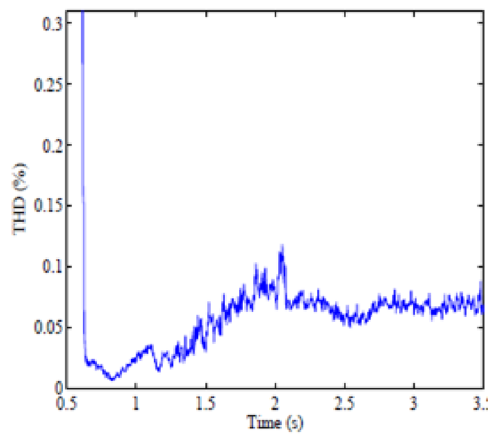

Fig. 10. THD of the current injected in the grid with the multilevel converter.

6. 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.

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