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Modelling and Simulation of a Wind Energy System with Fractional Controllers

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Abstract. This paper is on wind energy conversion systems with full-power converter and permanent magnet synchronous generator. Different topologies for the power-electronic converters are considered, namely two-level and multilevel converters. Also, a new fractional-order control strategy is proposed for the variable-speed operation of the wind turbines. Simulation studies are carried out in order to adequately assess the quality of the energy injected into the electrical grid. Conclusions are duly drawn.

Key words

Power converters, power quality, wind energy.

1. 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].

Concerning renewable energies, wind power is a priority for Portugal's energy strategy. The wind power goal foreseen for 2010 was established by the government as 5100 MW. 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.

An overview of the Portuguese technical approaches and methodologies followed in order to plan and accommodate the ambitious wind power goals to 2010/2013, preserving the overall quality of the power system, is given in [2].

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 deteriorated. Hence, the total harmonic distortion (THD) coefficient 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 in this paper is 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].

In this paper, a variable-speed wind turbine is considered with PMSG and different power-electronic converter topologies: two-level and multilevel. Additionally, a new fractional-order control strategy is proposed for the variable-speed operation of wind turbines with PMSG/full-power converter topology. Simulation studies are carried out in order to adequately assess the quality of the energy injected into the electrical grid. Hence, the harmonic behavior of the output current is computed by Discrete Fourier Transform (DFT) and THD. A comparison with a classical integer-order control strategy is also presented, illustrating the improvements introduced by the proposed fractional-order control strategy.

2. Modelling

A. Wind Speed

The wind speed usually varies considerably and has a stochastic character. The wind speed variation can be modelled as a sum of harmonics with the frequency range 0.1–10 Hz [8]:

$$u = u_0 \left[1 + \sum_n A_n \sin(\omega_n \, t) \right] \qquad (1)$$

where u is the wind speed value subject to the disturbance, u_0 is the average wind speed, n is the kind of the mechanical eigenswing excited in the rotating wind turbine, A_n is the magnitude of the eigenswing n, ω_n is the eigenfrequency of the eigenswing n.

Hence, the physical wind turbine model is subjected to the disturbance given by the wind speed variation model [9].

B. Wind Turbine

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 [8]. The mechanical eigenswings are mainly due to the following phenomena: asymmetry in the turbine, vortex tower interaction, and eigenswings in the blades.

The mechanical part of the wind turbine model can be simplified by modelling 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:

$$P_t = P_{tt} \left[1 + \sum_{n=1}^{3} A_n \left(\sum_{m=1}^{2} a_{nm} \, g_{nm}(t) \right) h_n(t) \right] \qquad (2)$$

$$g_{nm} = \sin \left(\int_0^t m \, \omega_n(t') \, dt' + \varphi_{nm} \right) \qquad (3)$$

where P_{tt} is the mechanical power of the wind turbine, m is the harmonic of the given eigenswing, g_{nm} is the distribution between the harmonics in the eigenswing n, a_{nm} is the normalized magnitude of g_{nm}, h_n is the modulation of the eigenswing n, and φ_{nm} is the phase of the harmonic m in the eigenswing n.

The eigenfrequency range of the wind turbine model with mechanical eigenswings is from 0.1 to 10 Hz. The values used for the calculation of are given in the Table I [9].

C. Mechanical Drive Train Model

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.

Table I. - Mechanical Eigenswigs Excited in the Wind Turbine

n	Source	A_n	ω_n	h_n	m	a_{nm}	φ_{nm}
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	$9\,\pi$	$1/2\ (g_{11}+g_{21})$	1	1	0

The model for the dynamics of the mechanical drive train for the WECS used in this paper was reported by the authors in [10].

D. Generator

The generator considered in this paper is a PMSG. The equations for modelling a PMSG can be found in the literature [11].

In order to avoid demagnetization of permanent magnet in the PMSG, a null stator current is usually imposed [12].

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 capacitor bank. The inverter is connected between this capacitor bank and a second 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. The model for the two-level converter used in this paper was reported by the authors in [10].

The configuration of the simulated WECS with two-level converter is shown in Figure 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 capacitor bank. The inverter is connected between this capacitor 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. The model for the multilevel converter used in this paper was reported by the authors in [13].

The configuration of the simulated WECS with multilevel converter is shown in Figure 2.

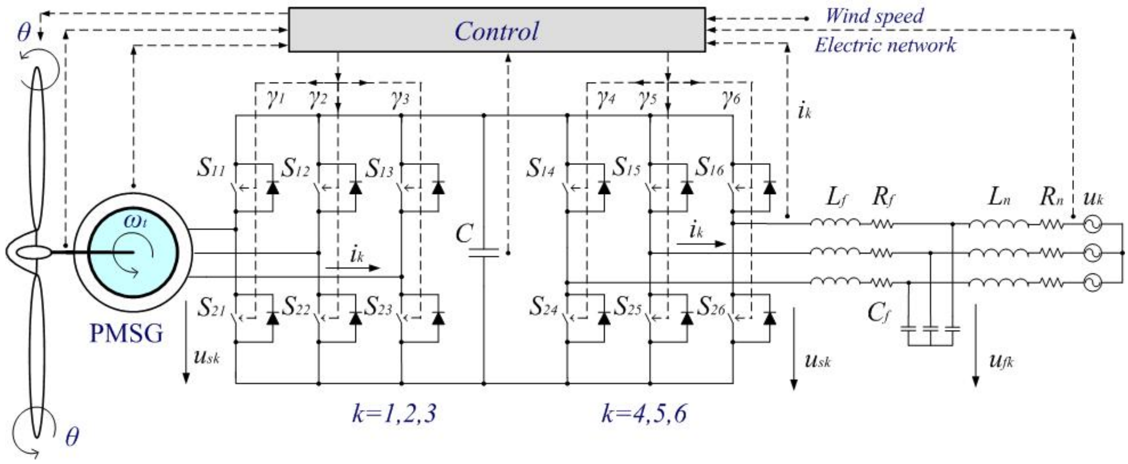

Fig. 1. WECS with two-level converter

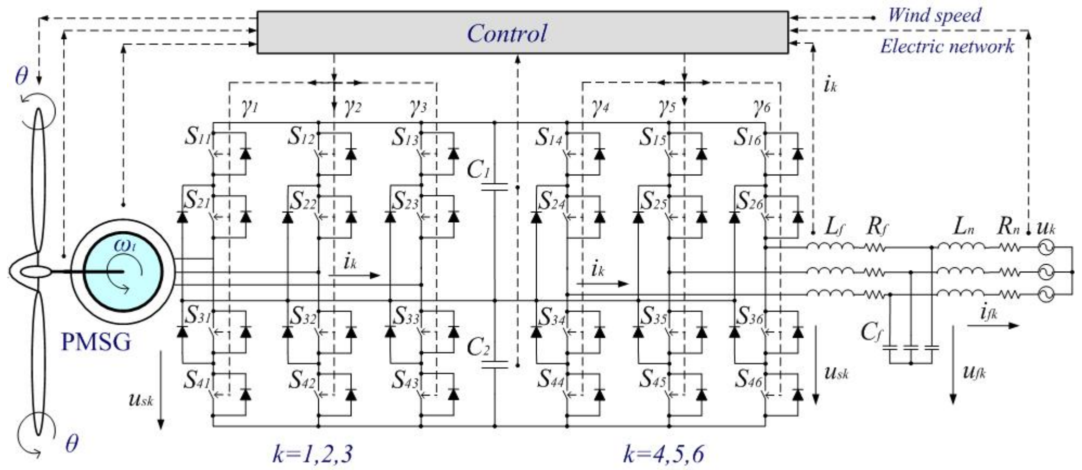

Fig. 2. WECS with multilevel converter

3. Control Strategy

A. Fractional-Order Controllers

A new control strategy based on fractional-order PI^{μ} controllers is proposed 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 [14]. Recently, applications of fractional calculus theory in practical control field have increased significantly [15].

The fractional-order differentiator can be denoted by a general operator ${}_aD_t^{\mu}$ [16], given by:

$$ {}_aD_t^{\mu} = \begin{cases} \dfrac{d^{\mu}}{dt^{\mu}}, & \Re(\mu) > 0 \\ 1, & \Re(\mu) = 0 \\ \int_a^t (d\tau)^{-\mu}, & \Re(\mu) < 0 \end{cases} \quad (4) $$

The mathematical definition of fractional derivatives and integrals has been the subject of several approaches. The most frequently encountered definition is called Riemann–Liouville definition, in which the fractional-order integrals are defined as:

$$ {}_aD_t^{-\mu} f(t) = \frac{1}{\Gamma(\mu)} \int_a^t (t-\tau)^{\mu-1} f(\tau)\, d\tau \quad (5) $$

while the definition of fractional-order derivatives is:

$$ {}_aD_t^{\mu} f(t) = \frac{1}{\Gamma(n-\mu)} \frac{d^n}{dt^n} \left[\int_a^t \frac{f(\tau)}{(t-\tau)^{\mu-n+1}}\, d\tau \right] \quad (6) $$

where:

$$ \Gamma(x) \equiv \int_0^{\infty} y^{x-1} e^{-y}\, dy \quad (7) $$

is the Gamma function, a and t are the limits of the operation, and μ is the fractional order which can be a complex number. In this paper, μ is assumed as a real number that satisfies the restrictions $0 < \mu < 1$. Also, a can be taken as a null value. The following convention is used: ${}_0D_t^{-\mu} \equiv D_t^{-\mu}$.

The differential equation of the fractional-order controller is given by:

$$ u(t) = K_p\, e(t) + K_i\, D_t^{-\mu}\, e(t) \quad (8) $$

where K_p is the proportional constant and K_i is the integration constant. Taking $\mu = 1$, a classical PI controller is obtained. In this paper, it is assumed that $\mu = 0.5$. Using the Laplace transform of fractional calculus, the transfer function of the fractional-order PI^{μ} controller is obtained, given by:

$$G(s) = K_p + K_i \, s^{-0.5} \tag{9}$$

B. Converters Control

Power converters are variable structure systems, because of the on/off switching of their IGBTs. 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 [17].

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 has been proven that it is necessary to ensure that the state trajectory near the surfaces verifies the stability conditions [18] given by:

$$S(e_{\alpha\beta}, t) \, \frac{dS(e_{\alpha\beta}, t)}{dt} < 0 \tag{10}$$

4. Power Quality Evaluation

The harmonic behavior computed by the DFT is given by:

$$X(k) = \sum_{n=0}^{N-1} e^{-j2\pi \, k \, n / N} \, x(n) \quad \text{for } k = 0, \ldots, N-1 \tag{11}$$

where $x(n)$ is the input signal and $X(k)$ is a complex giving the amplitude and phase of the different sinusoidal components of $x(n)$.

The harmonic behavior computed by the THD is given by:

$$\text{THD}\,(\%) = 100 \, \frac{\sqrt{\sum_{H=2}^{50} X_H^2}}{X_F} \tag{12}$$

where X_H is the root mean square (RMS) value of the individual harmonic H components of the signal, and X_F is the RMS value of the fundamental component.

5. Simulation Results

The mathematical models for the WECS with the two-level and multilevel power converter topologies were implemented in Matlab/Simulink. The WECSs simulated in this case study have a rated electrical power of 900 kW. The wind speed variation model is given by:

$$u = u_0 \left[1 + \sum_n A_n \sin(\omega_n \, t) \right] \qquad 0 \le t \le 4 \tag{13}$$

The operational region of the WECS was simulated for wind speed range from 5-25 m/s. The switching frequency used in the simulation results is 5 kHz.

The mechanical power of the wind turbine, the electrical power of the generator, and the difference between these two powers, i.e., the accelerating power, are shown in Figure 3.

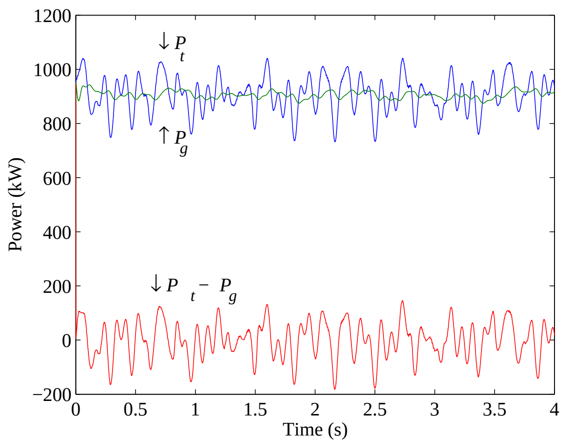

Fig. 3. Mechanical, electrical and accelerating power.

The harmonic content of the mechanical power of the turbine, computed by the DFT, is shown in Figure 4.

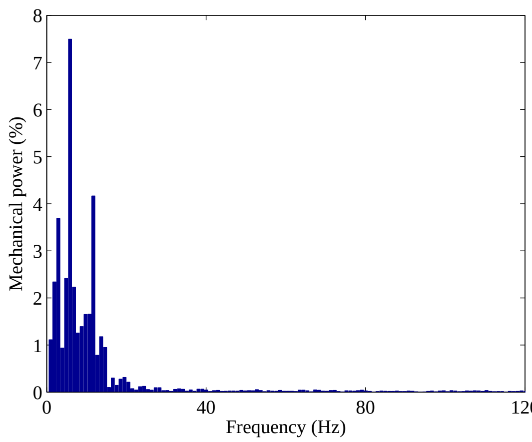

Fig. 4. Harmonic content of the mechanical power of the turbine.

The harmonic content of the electrical power of the generator, computed by the DFT, is shown in Figure 5.

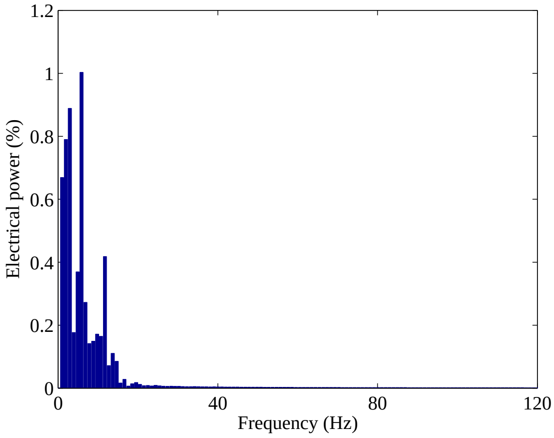

Fig. 5. Harmonic content of the electrical power of the generator.

The WECS with the two-level converter has the first harmonic of the output current, computed by the DFT, shown in Figure 6 and the THD of the output current shown in Figure 7. Both classical and fractional-order controllers are considered.

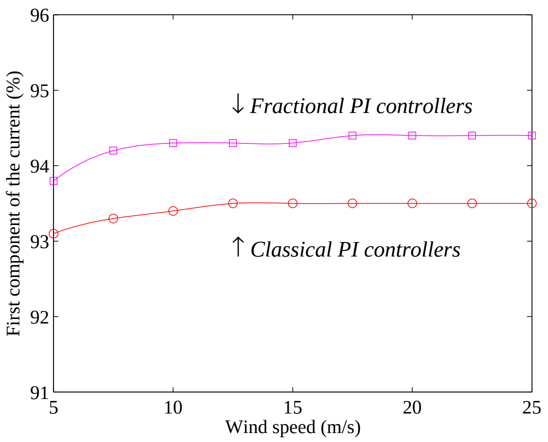

Fig. 6. First harmonic of the output current, two-level converter; the first harmonic is expressed in percentage of the fundamental component.

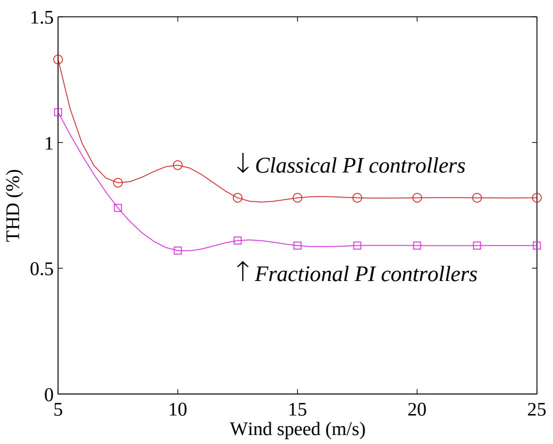

Fig. 7. THD of the output current, two-level converter.

The WECS with the multilevel converter has the first harmonic of the output current, computed by the DFT, shown in Figure 8 and the THD of the output current shown in Figure 9. Again, both classical and fractional-order controllers are considered.

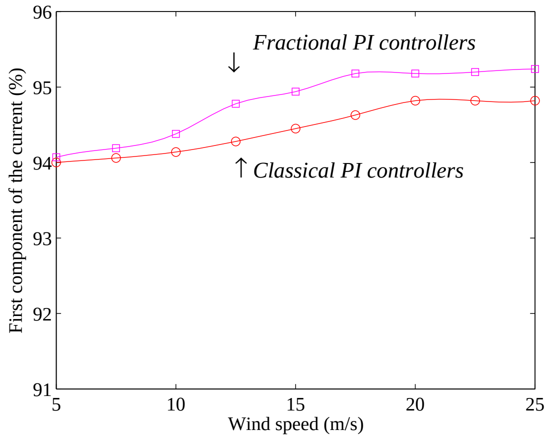

Fig. 8. First harmonic of the output current, multilevel converter; the first harmonic is expressed in percentage of the fundamental component.

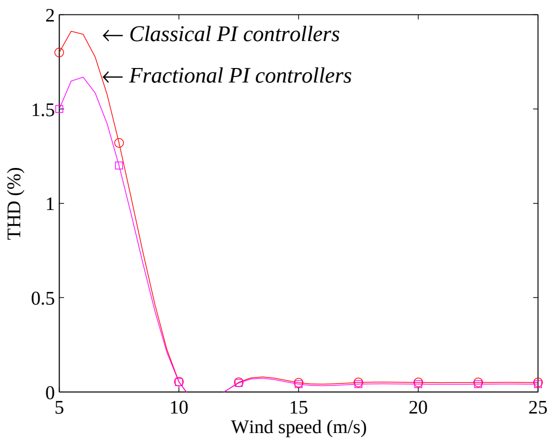

Fig. 9. THD of the output current, multilevel converter.

The new fractional-order control strategy provides better results comparatively to a classical integer-order control strategy, in what regards the first harmonic computed by DFT and the harmonic behaviour computed by THD.

Also, the THD of the output current is lower than the 5% limit imposed by IEEE-519 standard [19], for both power converter topologies considered.

6. Conclusion

The harmonic behaviour of variable-speed wind turbines with PMSG/full-power converter topology is studied in this paper. As a new contribution to earlier studies, a new fractional-order control strategy is proposed, which achieves superior dynamic characteristics and output power quality. The power quality injected in the electrical grid is enhanced using the new fractional-order control strategy, in comparison with a classical integer-order control strategy, for both power converter topologies considered.

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