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Electrical Grid Integration and Power Quality Studies of a Variable-Speed Wind Energy Conversion System

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Abstract—This paper is concerned with the behavior of a variable-speed wind energy conversion system, in order to assess the power quality injected in the electrical grid. Different topologies for the power-electronic converters are considered, namely two-level and multilevel converters. We use pulse width modulation by space vector modulation associated with sliding mode for controlling the converters, and we introduce power factor control at the output of the converters. We present the total harmonic distortion and the fast Fourier transform of the current injected in the electrical grid, considering each power-electronic converter. Finally, conclusions are duly drawn.

***Index Terms*—Fast Fourier transform, power electronics, power quality, total harmonic distortion, wind energy.**

I. Nomenclature

The notation used throughout the paper is stated as follows:

u_0 Wind speed value.

u Wind speed value subject to the disturbance.

A_K Magnitude of the *k*th kind of eigenswing.

ω_K Eigenfrequency of *k*th kind of eigenswing excited in the turbine rotating.

P_{tt} Mechanical power of the wind turbine.

P_t Mechanical power of the wind turbine subject to the disturbance.

m Harmonic of the given eigenswing.

g_{Km} Distribution between the harmonics of *k*th kind of eigenswing for the *m*th harmonic.

a_{Km} Normalized magnitude of g_{Km}.

φ_{Km} Phase of *k*th kind of eigenswing for *m*th harmonic.

h_K Modulation of *k*th kind of eigenswing excited in the turbine rotating.

$e_{\alpha\beta}$ Error between the reference value and the control value.

X_H Root mean square value of the total harmonics of the signal.

X_F Root mean square value of fundamental component.

v_{dc} Capacitor voltage for the two-level converter.

v_{C1}, v_{C2} Capacitors voltages for the multilevel converter in the capacitor banks C_1 and C_2.

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II. 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. The total installed wind power capacity reached 2771 MW in November 2008, and continues growing.

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].

In this paper, we consider a variable-speed wind turbine with PMSG and different power-electronic converter topologies: two-level and multilevel. We use pulse width modulation (PWM) by space vector modulation (SVM) associated with sliding mode for controlling the converters, and we introduce power factor control at the output of the converters. We present the current THD and Fast Fourier Transform (FFT) at the output of the converters, thus assessing the power quality injected in the electrical grid.

This paper is organized as follows. Section 3 presents the modeling of the wind energy conversion system (WECS) with two-level and multilevel converters. Section 4 presents the control method. Section 5 presents the power quality evaluation by THD and FFT. Section 6 presents the simulation results. Finally, concluding remarks are given in Section 7.

III. Modeling

A. 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 the frequency range 0.1–10 Hz [8]

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

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 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 [9]

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

where g_{Km} is given by

$$g_{Km} = \sin\left(\int_0^t m \, \omega_K(t') \, dt' + \varphi_{Km} \right) \quad (3)$$

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_t are given in the Table I [9].

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 WECS used in this paper was reported by the authors in [10]-[11].

D. Generator

The generator considered in this paper is a PMSG. The equations for modeling a PMSG can be found in the literature [12]. In order to avoid demagnetization of permanent magnet in the PMSG, a null stator current is imposed [13].

E. Two-level Converter

The two-level converter is an AC-DC-AC converter, with six unidirectional commanded insulated gate bipolar transistors (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 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. The model for the two-level converter used in this paper was reported by the authors in [10]-[11].

The configuration of the simulated WECS 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 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 [10]-[11].

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

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	$9\,\pi$	$1/2\,(g_{11}+g_{21})$	1	1	0

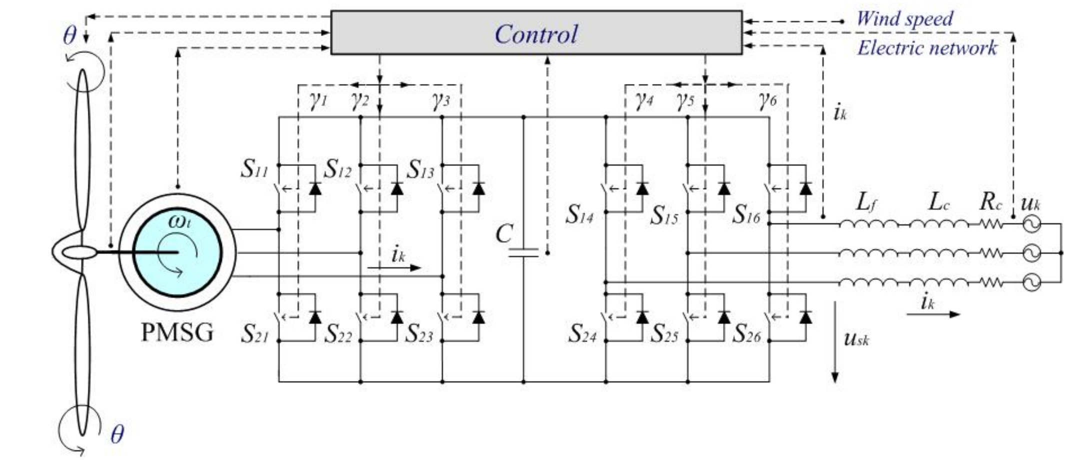

Fig. 1. WECS with two-level converter.

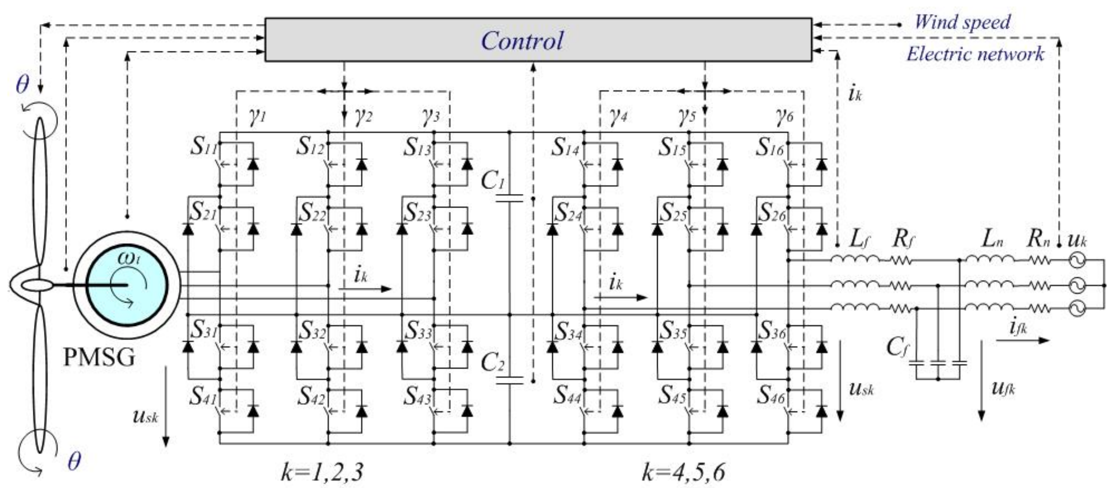

Fig. 2. WECS with multilevel converter.

IV. Control Method

Power converters are variable structure systems, because of the on/off switching of their IGBTs. The controllers used in the converters are PI controllers. PWM by 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 [14].

Sliding mode control is 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

$$S(e_{\alpha\beta},t)\ \frac{dS(e_{\alpha\beta},t)}{dt} < 0 \tag{4}$$

V. Power Quality Evaluation

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

$$\text{THD}\ (\%) = 100\ \frac{\sqrt{\sum_{H=2}^{50} X_H^2}}{X_F} \tag{5}$$

The harmonic behavior computed by the FFT is based on Fourier analysis. If $X(\omega)$ is a continuous periodical signal and satisfies Dirichlet condition, the Fourier series is given by

$$X(\omega) = \sum_{n=1}^{N} x(n)\, e^{-j\omega\, n} \quad \text{for} \quad 0 \le \omega \le 2\pi \tag{6}$$

In order to implement Fourier analysis in a computer, the signal in both time and frequency domains is discrete and has finite length with N points per cycle. Hence, Discrete Fourier Transform (DFT) is introduced, given by

$$X(k) = \sum_{n=1}^{N} W^{(n-1)(k-1)} x(n) \quad \text{for} \quad k = 1,2,...,N \qquad (7)$$

where $x(n)$ is the Fourier coefficient at kth harmonic, $W = e^{(-j2\pi n/N)}$ is the spectrum of $x(n)$.

VI. Simulation

The WECS simulated has a rated electrical power of 900 kW. The mathematical models for the WECS with the two-level and multilevel converters were implemented in Matlab/Simulink.

We consider in the simulation a ramp increase wind speed, taking 2.5 s between 5 and 25 m/s. Also, a time horizon of 3.5 s is considered.

Fig. 3 shows the mechanical power of the wind turbine disturbed by the mechanical eigenswings, and the electrical power of the generator. Also, it shows the difference between the two powers, i.e., the accelerating power.

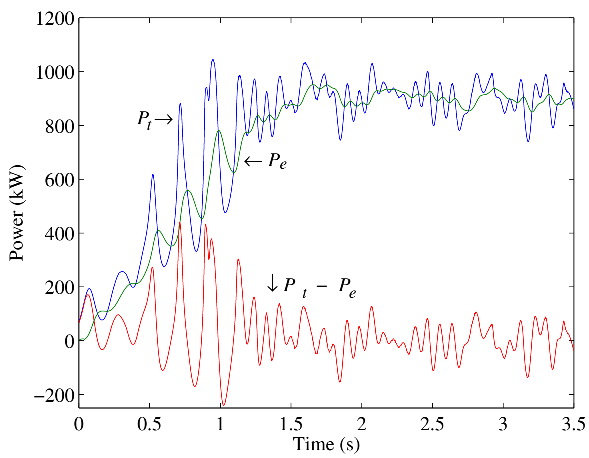

Fig. 3. Mechanical and electrical power.

The harmonic behavior computed by the FFT for the mechanical power of the turbine is shown in Fig. 4.

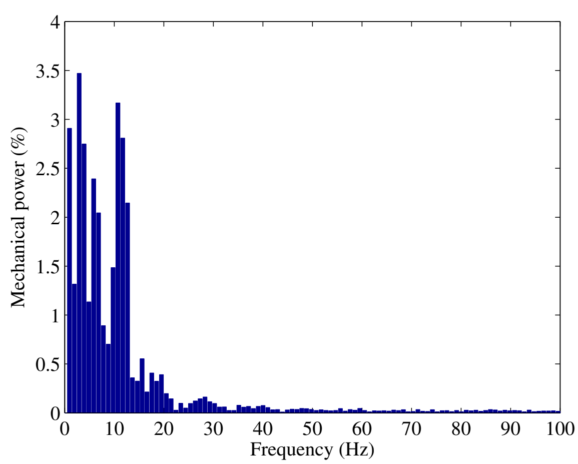

Fig. 4. Harmonic behavior for the mechanical power of the turbine.

The harmonic behavior computed by the FFT for the electrical power of the generator is shown in Fig. 5.

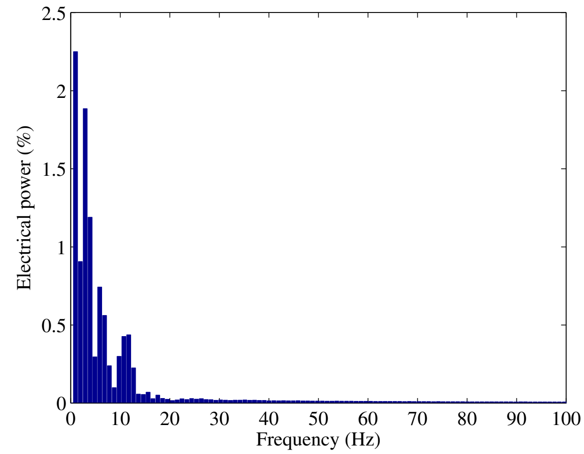

Fig. 5. Harmonic behavior for the electrical power of the generator.

The wind speed operation of the WECS produces different frequency due to different rotation speed. Hence, Fig. 6 shows the mechanical frequency of the turbine and the generator.

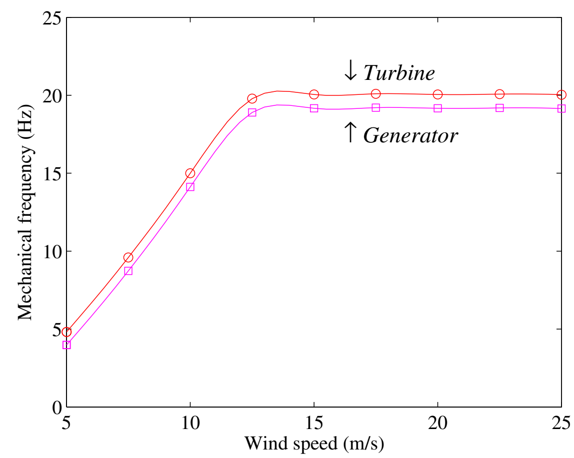

Fig. 6. Mechanical frequency of the turbine and the generator.

The capacitors voltages for the two-level and multilevel converters are shown in Fig. 7. These capacitors voltages are of the utmost importance for the converters, since an unbalance may increase the THD values.

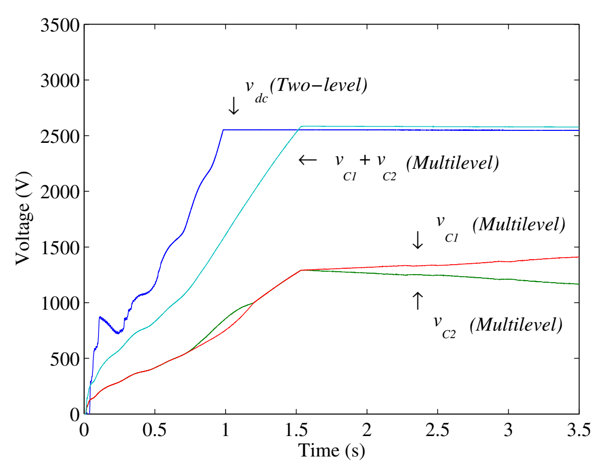

Fig. 7. Capacitors voltages for the two-level and multilevel converters.

The THD of the current injected in the electrical grid with the two-level converter is shown in Fig. 8. These results were obtained for wind speed range from 5-25 m/s, with and without wind speed disturbances. The harmonic behavior computed by the FFT is shown in Fig. 9.

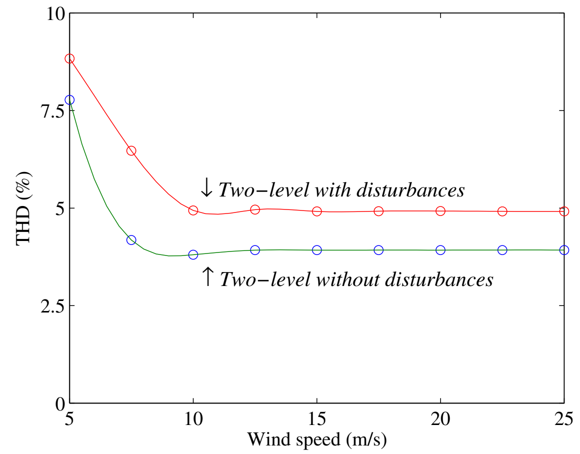

Fig. 8. THD of the current injected in the electrical grid: two-level converter.

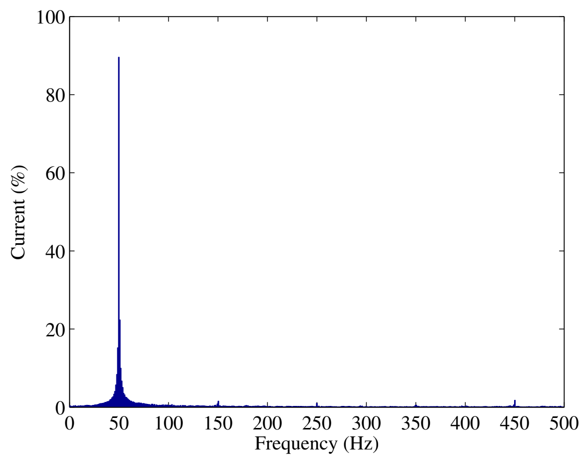

Fig. 9. Harmonic behavior for the current: two-level converter.

The THD of the current injected in the electrical grid with the multilevel converter is shown in Fig. 10. The harmonic behavior computed by the FFT is shown in Fig. 11.

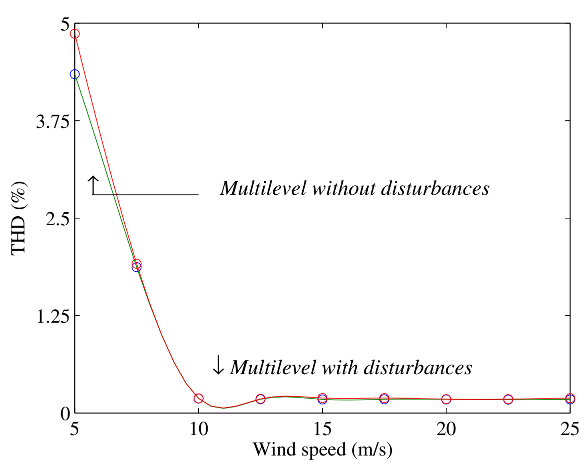

Fig. 10. THD of the current injected in the electrical grid: multilevel converter.

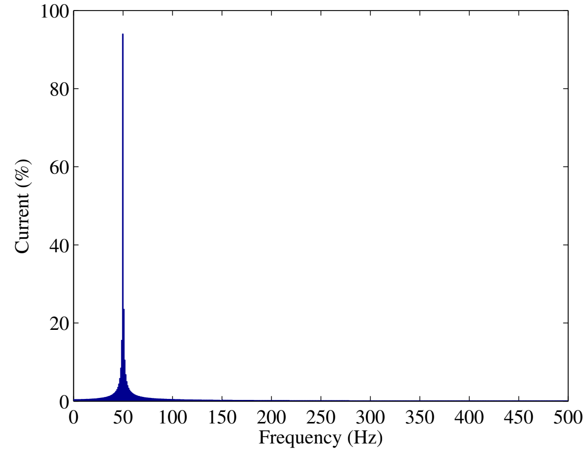

Fig. 11. Harmonic behavior for the current: multilevel converter.

The current THD for the proposed WECS with multilevel converter is much lower than the 5% limit imposed by IEEE-519 standard [15], which does not occur when we consider the two-level converter.

Although IEEE-519 standard might not be applicable in such situation, it is used as a guideline for comparison purposes [16].

Additionally, theoretical converter output voltage quality time domain evaluation may be carried out using methodology [17] by PWM ripple voltage successive averaging first on a switching period and then on a fundamental one. It is an asymptotic approach in the sense that converter switching frequency is assumed much higher than a fundamental one.

VII. Conclusions

As wind power generation undergoes rapid growth, new technical challenges emerge: dynamic stability and power quality. The objective of this paper is to assess the power quality of a grid-connected variable-speed WECS with two-level and multilevel converters. The simulation results show that the current THD for the proposed WECS with multilevel converter is much lower than 5% limit imposed by IEEE-519 standard.

VIII. Acknowledgment

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