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 matrix 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 electric grid. Conclusions are duly drawn.

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].

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 electric grid [5].

II. 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 [6].
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 \( n \), \( \omega_n \) 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 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

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

where \( P_n \) 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 \( \varphi_{nm} \) is the phase of the harmonic \( m \) in the eigenswing \( n \).

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 \( A_n \) 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.

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

### Table I. Mechanical Eigenswings Excited in the Wind Turbine

<table>
<thead>
<tr>
<th>Source</th>
<th>( A_n )</th>
<th>( \omega_n )</th>
<th>( h_n )</th>
<th>( m )</th>
<th>( a_{nm} )</th>
<th>( \varphi_{nm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Asymmetry</td>
<td>0.01</td>
<td>( \omega_1 )</td>
<td>1</td>
<td>1</td>
<td>4/5</td>
<td>0</td>
</tr>
<tr>
<td>2 Vortex tower interaction</td>
<td>0.08</td>
<td>( 3 \omega_1 )</td>
<td>1</td>
<td>1</td>
<td>1/2</td>
<td>0</td>
</tr>
<tr>
<td>3 Blades</td>
<td>0.15</td>
<td>( 9 \pi )</td>
<td>( 1/2 (g_{11}+g_{21}) )</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

### D. Generator

The generator considered in this paper is a PMSG. The equations for modeling 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 imposed [12].

### E. Matrix Converter

The matrix converter is an AC-AC converter, with nine bidirectional commanded insulated gate bipolar transistors (IGBTs) \( S_{ij} \). It is connected between a first order filter and a second order filter. The first order filter is connected to a PMSG, while the second order filter is connected to an electric network. A switching strategy can be chosen so that the output voltages have nearly sinusoidal waveforms at the desired frequency, magnitude and phase angle, and the input currents are nearly sinusoidal at the desired displacement power factor [13]. A three-phase active symmetrical circuit in series models the electric network. The model for the matrix converter used in this paper was reported by the authors in [10].

The configuration of the simulated WECS with matrix converter is shown in Fig. 1.

### F. Multilevel Converter

The multilevel converter is an AC-DC-AC converter, with twelve 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 second order filter, which in turn is connected to an electric network. 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 electric network. The model for the multilevel converter used in this paper was reported by the authors in [10].

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

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

while the definition of fractional-order derivatives is

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

where

$$\Gamma(x) = \int_0^\infty y^{x-1} e^{-y} \, dy,$$  \hspace{1cm} (7)

is the Gamma function, $a$ and $t$ are the limits of the operation, and $\mu$ is the fractional order which can be a complex number. In this paper, $\mu$ 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: $0D_t^\mu f(t) = D_t^{-\mu} f(t).$

The differential equation of the fractional-order $PI^\mu$ controller is given by

$$aD_t^\mu f(t) = \frac{1}{\Gamma(\mu)} \int_a^t (t-\tau)^{\mu-1} f(\tau) \, d\tau,$$  \hspace{1cm} (5)
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 $\mu = 0.5$. A good tradeoff, presented in [17], between robustness and dynamic performance is in favor of the range $0.4 \leq \mu \leq 0.6$ for the order of integration. Using the Laplace transform of fractional calculus, the transfer function of the fractional-order $P^{\mu}I$ controller is obtained, given by

$$G(s) = K_p + K_i s^{-0.5}.$$  

### 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 fractional sliding mode control [16] 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 electric grid disturbances [18].

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. The 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 $e_{\text{off}}$ will exist between the reference value and the control value. In order to guarantee that the system slides along the sliding surface $S(e_{\text{off}}, t)$, it has been proven that it is necessary to ensure that the state trajectory near the surfaces verifies the stability conditions [19] given by

$$S(e_{\text{off}}, t) \frac{dS(e_{\text{off}}, t)}{dt} < 0.$$  

### IV. POWER QUALITY EVALUATION

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

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

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

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

where $x(n)$ is the input signal and $X(k)$ is the amplitude and phase of the different sinusoidal components of the $x(n)$. The harmonic behavior computed by the THD is given by

$$\text{THD (\%)} = 100 \sqrt{\frac{\sum_{n=2}^{N} X^2_n}{X_F}},$$

where $X_F$ is the root mean square (RMS) value of the signal, and $X_n$ is the RMS value of the fundamental component.

### V. SIMULATION RESULTS

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

$$\omega = \sum_{n} n t A_{uu} \sin(10 + 0.5) \quad \text{for} \quad 0 \leq \omega \leq 4,$$

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 electric power of the generator, and the difference between these two powers, i.e., the accelerating power, are shown in Fig. 3. The harmonic content of the mechanical power of the turbine, computed by the DFT, is shown in Fig. 4.
The harmonic content of the electric power of the generator, computed by the DFT, is shown in Fig. 5.

The first harmonic of the output current, computed by the DFT, for the WECS with the matrix converter is shown in Fig. 6. The THD of the output current for the WECS with the matrix converter is shown in Fig. 7. Both classical and fractional-order controllers are considered.

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

The presence of the energy-storage elements allows the proposed WECS with the multilevel converter to achieve the best performance, in comparison with the matrix converter.

The new fractional-order control strategy provides better results comparatively to a classical integer-order control strategy, in what regards the harmonic behavior computed by the DFT and the THD.
The THD of the output current is lower than 5% limit imposed by IEEE-519 standard [20], for both power converter topologies considered. Although IEEE-519 standard might not be applicable in such situation, it is used as a guideline for comparison purposes [21].

VI. CONCLUSIONS

The harmonic behavior 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 in this paper, which achieves superior dynamic characteristics and output power quality. Simulation studies revealed a better performance of the proposed WECS with the multilevel converter, in comparison with the matrix converter. Also, the harmonic behavior computed by the DFT and the THD revealed that the power quality injected in the electric 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.

REFERENCES