Off-Grid Fuel Cell System for High Power Quality Applications

Ricardo J. S. Lima[*], Aníbal T. de Almeida[**], André M. S. Mendes[***], A. J. Marques Cardoso[****]

[*] ISR - University of Coimbra, Dep. of Electrical and Computer Engineering, rjslima@isr.uc.pt
[**] ISR - University of Coimbra, Dep. of Electrical and Computer Engineering, adealmeida@isr.uc.pt
[***] University of Coimbra, Dep. of Electrical and Computer Engineering, amsmendes@ieee.org
[****] University of Coimbra, Dep. of Electrical and Computer Engineering, ajmcardoso@ieee.org
Portugal

ABSTRACT

There are a large number of critical loads, such as information technology, telecommunication, medical equipment and industrial process controls, which require high power quality. Conventional approaches to provide high power quality levels include battery based uninterruptible power supplies (UPSs) and emergency generators, using in most cases fossil fuels. These approaches suffer from reliability/maintenance problems associated with battery operating constraints, and from environmental impacts associated with the emissions of particles by the emergency generators. Systems that use fuel cells as electric energy sources are starting to be seen as a possibility for onsite energy production since they can work with high efficiency and without harmful emissions. In this work it is proposed a structure of a fuel cell system composed by a GenCore^{TM} proton exchange membrane (PEM) 5kW Fuel Cell system from Plug Power and a single-phase inverter, which can operate either as an off-grid system or as a backup system in a high power quality system.

Keywords: Fuel Cells, PWM Inverters, Passive Filters, Power Quality

1 INTRODUCTION

A large number of electric applications possess a great variety of critical loads usually related with the areas of information technology, telecommunications, medical equipment and critical industrial process controls. All these critical loads request a system of high power quality.

Conventional approaches to provide high power quality levels include battery based uninterruptible power supplies (UPSs) and emergency generators, using in most cases fossil fuels.

To feed remote areas that cannot be connected to the grids, small generators located at load sites are used for that purpose. The conventional generation technology for this application is diesel engines. Where gas is available, gas engines may be used or, for larger installations, gas turbines. For smaller applications petrol engines may be used rather than diesels.

These approaches suffer from reliability/maintenance problems associated with battery operating constraints, and from environmental impacts associated with the emissions of particles by the emergency generators.

This demands a change on the energy source used, which can be done by increasing the share of clean energy sources in the global production of electrical and thermal energy.

The replacement of conventional technologies such as diesel generators and/or batteries with hydrogen technologies, including fuel cells, can be used to provide electrical power to compensate a supply interruption or to feed remote locations where the regional or national grid is absent, with environmental advantages, due to the absence of harmful emissions and due to low noise operation.

In this work it is proposed a structure of a fuel cell system composed by a GenCore^{TM} proton exchange membrane (PEM) 5kW Fuel Cell system from Plug Power and a single-phase inverter, which can operate either as an off-grid system or as a backup system in a high power quality system. The computational results of the proposed system, for different kinds of loads, using the Matlab/Simulink platform, with the SimPowerSystems toolbox according to the scheme presented in Figure 1, are presented.

A prototype of high-efficiency single-phase inverter controlled by a DSP-based digital control system using a TMS320F2812 DSP is being developed using the control system focused in this work.

2 STRUCTURE OF THE DC/AC CONVERTER SYSTEM

The innovative system couples the PEM fuel cell with a high performance inverter system based on a single-phase PWM inverter, composed by four IGBT power switches, a step-up power transformer and a LC output filter.

The inverter has a DC voltage source input with a constant value of 48V, corresponding to the output voltage of the GenCore^{TM} fuel cell system.

The inverter output voltage is then applied to the step-up power transformer and filtered through the LC filter to obtain a high quality output AC voltage of 230VRMS/50Hz to be applied to the load. The structure of the proposed system is showed in Figure 1.

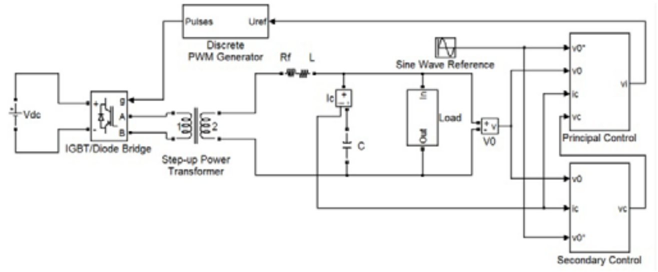


Figure 1: Block diagram of the single-phase PWM inverter system

3 DESCRIPTION OF THE SYSTEM CONTROL

The control structure of the single-phase PWM inverter system is based on a principal control block and a secondary control block, as presented in the Figure 1. The main control block is composed by two loops; the capacitor current feedback loop and the voltage feedback loop. The secondary control is composed by a PLL compensator loop [2].

The voltage feedback control loop is responsible for the control of both magnitude and phase angle of the output voltage generated by the inverter.

The capacitor current feedback loop is responsible for providing low output impedance against load variations and nonlinear load conditions, due to its decoupling effect [3].

An important aspect that needs to be considered is the fact that the current in the capacitor usually has many high frequency harmonics, generating a large amount of ripple in the output current waveform. For that reason, the current signal cannot be directly applied to the controller and must be first filtered through a low pass filter with second order Butterworth pole location.

The output voltage and capacitor current feedback loops, both uses a P type controller. These controllers need a very high gain values for reducing the steady-state error.

The PLL compensator is used in the control loop to minimize the steady-state error and to allow the use of lower gains in the P controllers of the main control.

The presented PLL compensator has two PI type controllers for the magnitude regulation and for the phase angle regulation.

The input compensation voltage, obtained from the PLL compensator is then applied to the main controller as it can be seen in the Figure 1. The two control blocks are described in detail in [2].

The output voltage of the main control is the reference voltage for the single-phase PWM inverter.

4 COMPUTATIONAL SIMULATION AND RESULTS

In this section, simulation results accomplished in Matlab/Simulink platform, through the use of the SimPowerSystems toolbox are presented. The model was built according to the block diagram presented in the Figure 1.

The selection of loads to perform the simulations had in consideration the typical loads used in remote residential applications. This way, the simulations carried out were prepared for three different types of loads: resistive load, presented in a great variety of residential loads such as lamps, ventilation heaters, radiators, etc.; full wave rectifier, presented in switching DC power supplies used in computers, LCD TV’s, etc.; and single-phase induction motor, presented in washing machines, freezers, air conditioners, water pumps, etc.

In all the simulations a discrete solver with a fixed-step integration of 5μs was used. The reference output voltage used was $v_0^* = 230\sqrt{2}\cos\omega^* t$ with a frequency of 50Hz and the frequency of the carrier of the PWM generator was 3 kHz.

Figure 2(a)-(b) shows the load voltage and load current waveforms for a resistive load, respectively. The corresponding voltage and current spectrograms are presented in the Figure 2(c)-(d), respectively.

In the Table 1 and Table 2 some measurements and power quality factors, related with both load voltage and load current are presented.

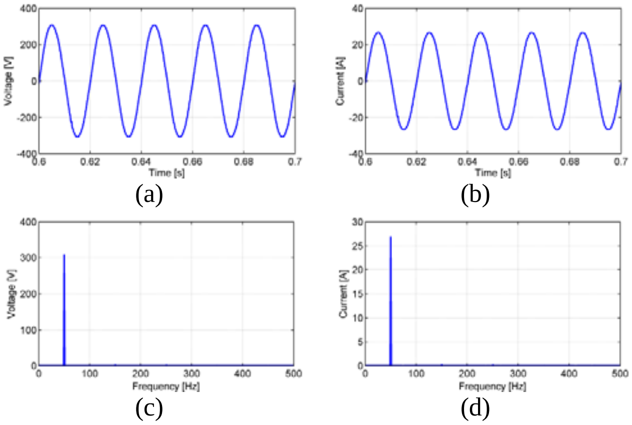


Figure 2: Load voltage (a) and load current (b) waveforms and load voltage (c) and load current (d) spectrograms for a resistive load.

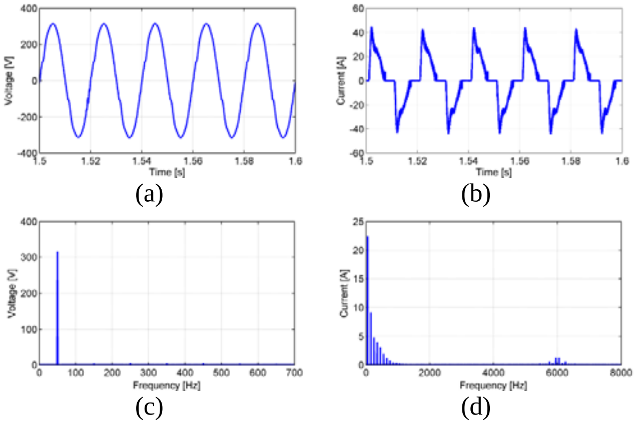
Load Type	**Voltage [V_{rms}]**	**Current [A_{rms}]**
Resistive	218.715	19.019

Table 1: Measurements of both load voltage and load current

Load Type		**Resistive**
Power Factor		1
Displacement Factor		1
Active Power [W]		4159.67
Apparent Power [VA]		4159.67
T.H.D. [%]	**Voltage**	1.7
	Current	1.7

Table 2: Output power quality factors

The obtained load voltage and load current waveforms results when the inverter feeds a full wave rectifier with a resistive load and a capacitor load filter are presented in Figure 3(a)-(b), respectively. The corresponding load voltage and load current spectrograms are shown in Figure 3(c)-(d), respectively. Table 3 and Table 4 present the load measurements and power quality factors results.



(a) (b)

(c) (d)

Figure 3: Load voltage (a) and load current (b) waveforms and load voltage (c) and load current (d) spectrograms for a full wave rectifier with a DC capacitor filter and load resistor.

Load Type	**Voltage [V_{rms}]**	**Current [A_{rms}]**
Rectifier Load	223.812	17.961

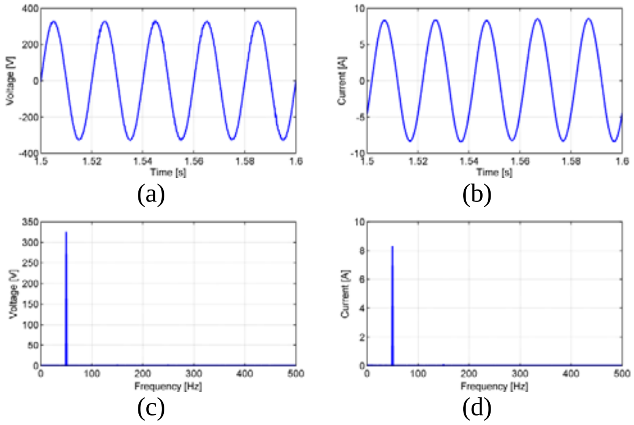
Table 3: Measurements of both load voltage and load current

Load Type		**Rectifier Load**
Power Factor		0.759
Displacement Factor		0.859
Active Power [W]		3052.9
Apparent Power [VA]		4019.97
T.H.D. [%]	**Voltage**	2.9
	Current	52.9

Table 4: Output power quality factors

In Figure 4(a)-(b) the load voltage and load current waveforms, for the single-phase induction motor of 1kW, with start capacitor of 254,7μF are presented.

The load voltage and load current spectra are shown in Figure 4(c)-(d), respectively. Table 5 and Table 6 present some load measurements and power quality factors results, respectively.



(a) (b)

(c) (d)

Figure 4: Load voltage (a) and load current (b) waveforms and load voltage (c) and load current (d) spectrograms for a single-phase 1kW induction motor.

Load Type	**Voltage [V_{rms}]**	**Current [A_{rms}]**
Motor – Full Load	230.155	5.871

Table 5: Measurements of both load voltage and load current

Load Type		**Motor Full Load**
Power Factor		0.839
Displacement Factor		0.839
Active Power [W]		1133.98
Apparent Power [VA]		1351.14
T.H.D. [%]	**Voltage**	1.6
	Current	1.2

Table 6: Output power quality factors

As it can be seen from Table 1 and Table 3 the output voltage is lower than the reference voltage. This fact is related to the voltage drop in the windings of the step-up transformer. This fact does not occur in the case of the single-phase induction motor of 1kW, with start capacitor due to its low power, as it can be seen from Table 5.

According to Table 2 and Table 6 it can be seen that the T.H.D. value of the load voltage corresponding to the cases of the resistive load and the single-phase induction motor is low. However, from Table 4, for the full wave rectifier case, the value of T.H.D. of the load voltage is more pronounced, when compared to the previous cases, but it still presents acceptable values.

From Figure 2(c), Figure 3(c) and Figure 4(c) it can be seen that the spectrograms of the load voltage present the 3th, 5^{th} and 7th harmonics with small amplitudes. These harmonics are not eliminated because of the cut-off frequency of the LC filter that is greater than the frequency of this harmonics.

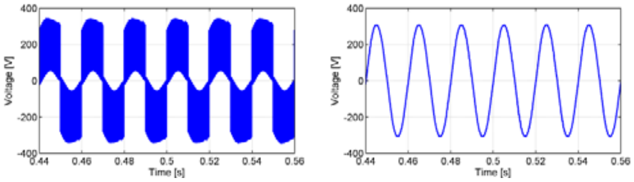
In all the studied cases, the T.H.D. of the output voltage of the system is less than 8%, which is the maximum value allowed for the grid voltage, according to EN50160.

To demonstrate the effectiveness of the system output filter, the Figures 5(a)-(b) show the voltage waveforms at output terminals of both step-up transformer and LC filter, respectively, for a resistive load.

In the Figures 6(a)-(b) the corresponding spectrograms of the previous mentioned voltages are presented. The RMS and T.H.D. values for those voltages waveforms are presented in the Table 7.

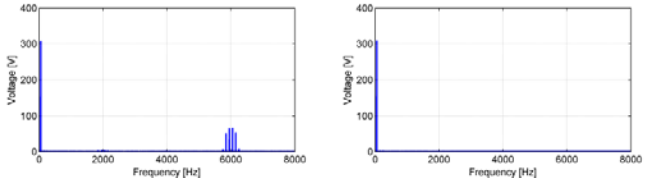
As it can be seen from Figure 6, the spectrum of the output voltage of the step-up transformer has high frequency components around the 6 kHz, due to the commutation frequency of the IGBT inverter power switches. In this case a voltage T.H.D value of 52.4% (Table 7) is obtained at the set-up power transformer output terminals.

Analyzing the spectrogram of the filter output voltage (Figure 6(b)), it can be seen that those components are fully eliminated and consequence of that the output voltage applied to the load presents a low T.H.D value of only 1.7% comparatively with the 52.4% obtained at the output step-up power transformer.



(a) (b)

Figure 5: The voltage waveforms at step-up power transformer output terminals(a) and filter output terminals (b) for a resistive load.



(a) (b)

Figure 6: Spectrograms of the step-up transformer output voltage (a) and filter output voltage (b) for a resistive.

	Step-up power transformer output terminals voltage	**Filter output terminal voltage**
RMS [V]	245.792	218.715
T.H.D. [%]	52.4	1.7

Table 7: RMS and T.H.D. voltage values

CONCLUSIONS

In this work a control strategy for a single-phase PWM inverter for stand-alone single-phase power generation applications, feed by a fuel cell as a DC voltage source was analyzed.

Computational simulations for linear and non-linear load types that are typically used in individual residential and small remote-site applications were developed, in order to evaluate the effectiveness of a high-precision control of a single-phase PWM inverter.

This control allows applying constant values of both voltage and frequency to the load terminals. From the obtained results, it can be seen that this control is suitable to feed properly the principal types of loads with very low T.H.D. which demonstrates the effectiveness of the control and of the output LC filter.

The T.H.D. value of the output voltage of the inverter system for all the load types simulated is small and beneath the maximum value of 8% pointed in the European Norm EN50160 for the grid voltage.

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