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Distributed Generations Systems Integrating Renewable Energy Resources

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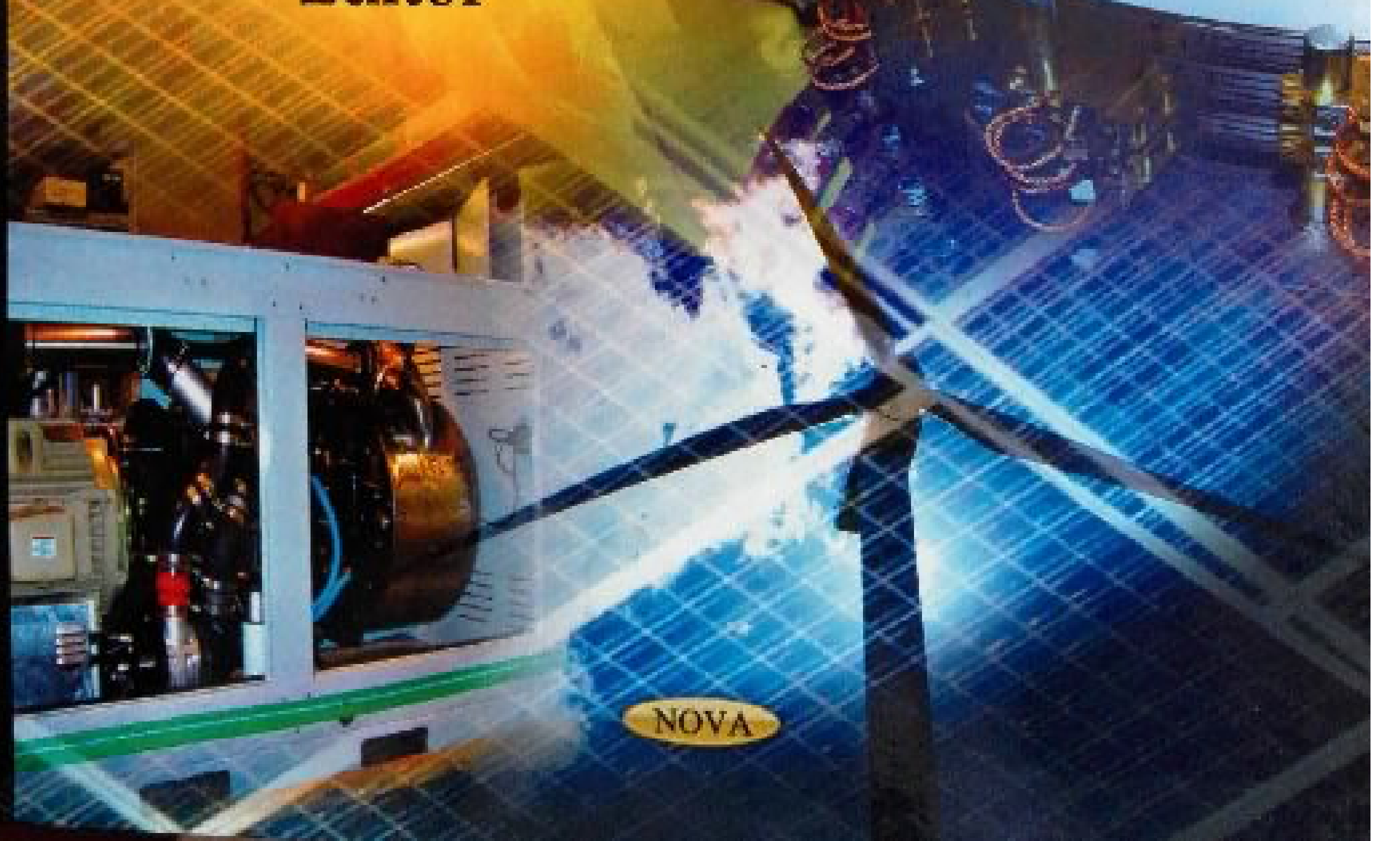
Editor



CHAPTER 9
TECHNIQUES TO MITIGATE THE FUEL CELL CURRENT RIPPLE

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Keywords: Fuel cell, current ripple, passive filters, active control, power interfaces, energy.
Abstract: In this chapter are briefly presented the main mitigation techniques of the low frequency fuel cell current ripple: filtering by passive filters on high voltage bus and/or low voltage bus, designing of appropriate structures for inverter system powered by fuel cell, and active control of power converters from inverter system, or the active control of power interface that operate as an active filter. The designing of models used in simulation is also shown, especially for fuel cell model used to evaluate the low frequency fuel cell current ripple. The simulation results are validated by measurements performed in different experiments.

INTRODUCTION

The Polymer Electrolyte Membrane Fuel Cell (PEMFC) is one of the most promising solutions to be utilized in Energy Generation System (EGS) and portable applications because of its relatively lightweight and small size, ease of construction, fast start-up and low operating temperature. Unfortunately, the relatively short PEMFC's life represents for moment a major obstacle to their commercialization (Suddhasatwa, 2007).

Inverter current ripple represents the main factor responsible for performance degradation of PEMFC energy efficiency (Wajiha, Rahul, & Arefeen, 2006; Choi, & al., 2007; Fontes & al., 2007) and PEMFC life cycle (Gemmen, 2001; Woojin, Gyubum, Prasad, & Jo, 2004; Schmittinger, & Vahidi, 2008). The PEMFC low frequency (LF) current ripple affects in much measure the PEMFC life cycle, causes hysteretic losses and subsequently more fuel consumption. Recent experimental results shown that LF inverter current ripple contributes with up to 10% reduction in the available output power (Liu, & Lai, 2007; Thounthong, Davat, Raël, & Sethakul, 2009). Therefore some restrictions of the fuel cell current ripple on frequencies bands are specified. It is known that fuel cell with is high intolerance for LF current ripple (for example in case of back propagation of harmonics in 50Hz load applications) or slower load transients. The fuel cell electrical equivalent model has a rather large capacitance shunting the device. This suggests that the fuel cell can in-fact tolerate high frequency (HF) current ripple. The USA National Energy Technology Laboratory (NETL) first published the following guidelines for fuel cell current ripple (NETL, 2001):

- *100/120 Hz ripple < 15% from 10% to 100% load, not to exceed 0.6 A for lighter loads;*
- *50/60 Hz ripple: < 10% from 10% to 100% load, not to exceed 0.4 A for lighter loads;*
- *10 kHz and above: < 60% from 10% to 100% load, not to exceed 2.4 A for lighter loads;*
- *>100/120 Hz to <10 kHz, limit linearly interpolated between the 120 Hz and 10 kHz limits;*
- *Transients below 50/60 Hz represent "load following" action of the system, and should track the maximum available current signal from the fuel cell to within 1% for purposes of both fuel cell integrity and efficiency.*

The new current ripple limits are given experimentally as Ripple Factor (RF) for different frequency bands (for example, LF RF must be up to 5% from 10% to 100% load, not to exceed 0.5 A for lighter loads; HF RF must be up to 40% from 10% to 100% load, not to exceed 2 A for lighter loads). Lower values for RF are recommended to increase PEMFC performances and the use of paralleling power converters with interleaved technique may be a solution (Hwang, Chen, & Yeh, 2007; Thounthong, & Davat, 2010). Transients below grid frequency (50/60 Hz) represent "load following" action of the EGS control, and should track the Maximum Power Point (MPP) signal from the PEMFC to within 1% for purposes of both PEMFC reliability and efficiency (see figure 1) (Zhong, Huo, Zhu, Cao, & Ren, 2008; Methekar, Patwardhan, Gudi, & Prasad, 2010; Bizon, 2010a).

On the other hand, on vehicle applications appear high energy demands in a short time that will cause high current slopes and obviously voltage drops, which is recognized as fuel starvation phenomenon. Consequently, it is necessary to add Energy Storage Devices (ESD) on vehicles supplied by PEMFC stack (Thounthong, & Davat, 2007; Lukic, Cao, Bansal, Rodriguez, & Emadi, 2008; Kim, & Peng, 2007). Sometime, the proper ESD's, with short time response, are used as Power Dynamic Compensators (PDC). Usually batteries and ultracapacitors are used as ESD's and PDC's, respectively. Such devices are required to absorb the energy from the regenerative braking, to compensate the fast power demand, reducing the fuel cell starvation phenomenon. During these sharp power profiles, and fuel cell start-ups and shutdowns, respectively, the power interface control forces batteries and ultacapacitors stacks to supply such peaks, improving PEMFC dynamic performance and transient response (Tang, Yuan, Pan, Li, Chen, & Li, 2010). For above considerations, it is obviously that hybrid and fuel cell technologies need to be merged in Hybrid Power Sources (HPS). Usually, a HPS combines two or more energy sources and ESD's that work together to deliver power (to DC load or into AC grid by the inverter system) or store energy in order to act as a single power delivery unit. Consequently, the challenge for power management control in HPS is to enhance the performance of all technologies working together and to minimize fuel consumption while reducing system degradation (Rodatz, Paganelli, Sciarretta, & Guzzella, 2005). The power/current slopes are given experimentally for different PEMFC stacks, depending on their power (about 10 A/s per each kW power) (Thounthong, Davat, Raël, & Sethakul, 2009; Corbo, Corcione, Migliardini, & Veneri, 2009; Thounthong, Chunkag, Sethakul, Sikkabut, Pierfederici, & Davat, 2010). So, many recent works have already reported the HPS structures of type FC/ultracapacitor (Uzunoglu, & Alam, 2006), FC/battery (Xu, Li, Hua, Li, & Ouyang, 2009) and FC/ultracapacitor/battery (Thounthong, Raël, & Davat, 2009; Bizon, Lefter, & Oproescu, 2007) for vehicle applications.

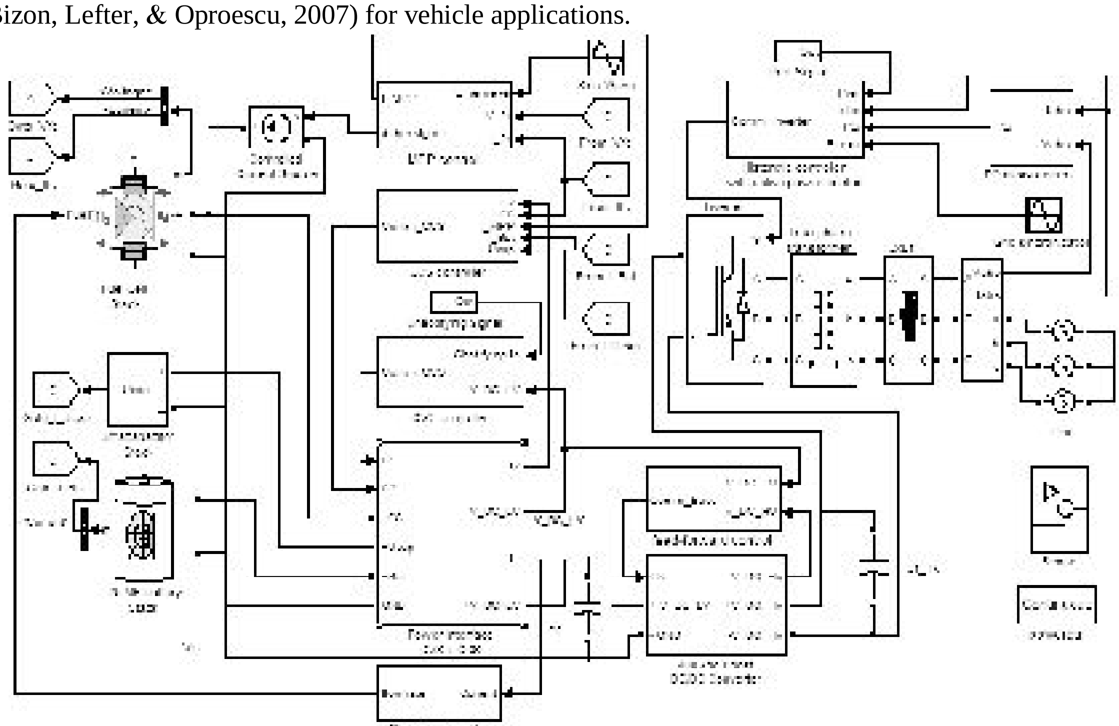

Figure 1. A typical EGS topology

Usually, 100Hz fuel cell current ripple and other LF harmonics appear in operation of grid inverter system and HF harmonics are generated by PWM switching control of DC-DC converter. Figure 2 shows how appears the LF current ripple in the inverter system and then this is back propagated to the PEMFC stack. In an EGS without ESD, first power conversion stage is a DC-DC converter (figure 2). To obtain the AC output voltage from the high voltage (HV) on HV DC bus, the second power conversion stage is a DC-AC converter. Both converters form an inverter system used in figure 2 as a grid EGS. In grid EGS the HV DC bus value, V_{HVbus}, is in range of 350V to 450V (usually around 400 V). Using, for example, a 26V/1.2kW fuel cell stack (figure 2), the DC fuel cell output voltage (which is also low voltage (LV), V_{LVbus}, on LV DC bus for EGS without power interface) is in the 25V ÷ 35V range, depending by load current. For EGS structure without power interface, input current of the DC-DC converter is the current demand from fuel cell stack. For a 230 V AC grid voltage, the boost controller maintains the HV DC voltage at the rated value of 400 V.

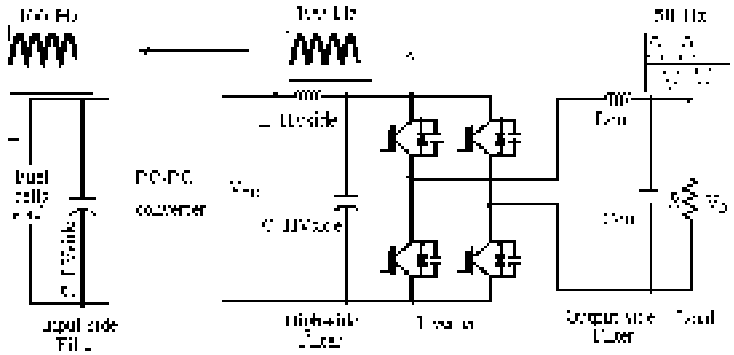

Figure 2. Back propagation of current ripple in the fuel cell inverter system

Fuel cell current ripple must be mitigated by passive filtering on HV DC and LV DC buses and by an adequate active control at different energy conversion stages. Typical structure of the basic EGS is presented in figure 3. A possible structure for a low power AC load and a power demand relatively constant it is possible to use a EGS without ESD's (see figure 4, where the fuell cells stack supply directly the inverter system) or with minimum size of the ESD capacity (Bizon, 2007). In order to increase the inverter efficiency the number for stages of energy conversion should be minimized (Raducu, & Bizon, 2007; see figure 5).

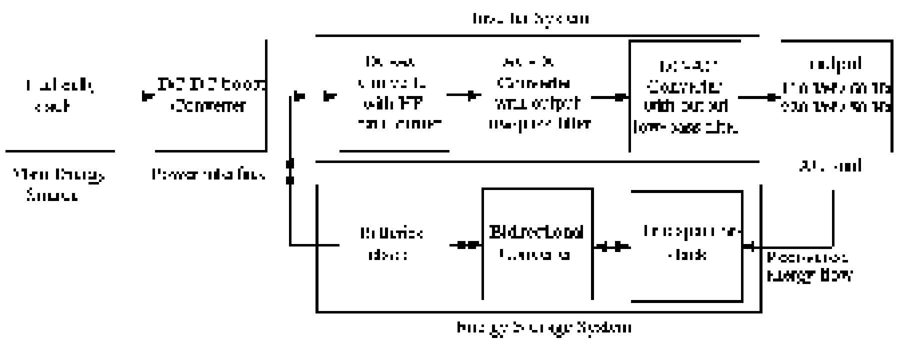

Figure 3. Basic EGS topology with the inverter system powered by a fuel cell HPS

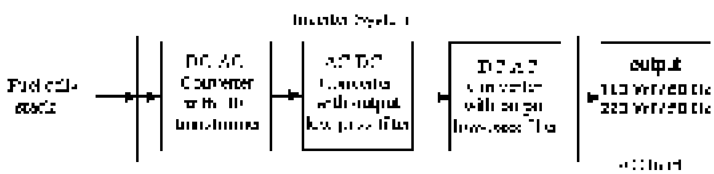

Figure 4. Inverter system powered directly from the fuel cell stack

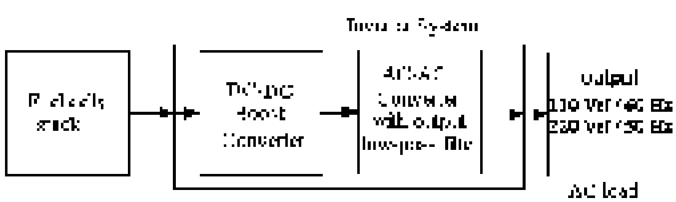

Figure 5. Two-stage inverter system powered directly from the fuel cell stack

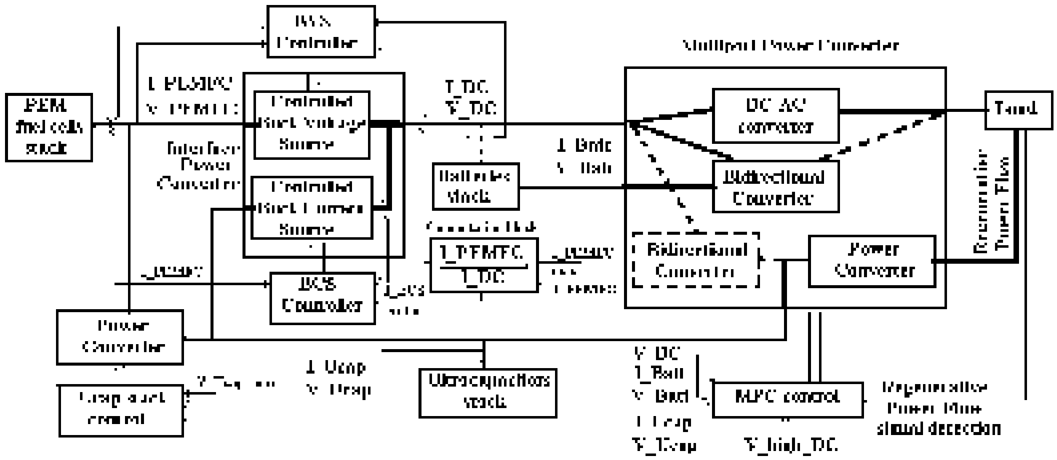

Figure 6. Multiport EGS topology with power interface for ripple mitigation

A multiport EGS topology (see figure 6) with power interface for ripple mitigation was proposed and analyzed in references (Bizon, & Oproescu, 2009; Bizon, & Oproescu, 2010; Bizon, 2008; Bizon, Raducu, & Oproescu, 2008). Figure 7 shows a HPS topology with MPP tracking control that assure a low current ripple by PEMFC stack operation near to MPP using an appropriate control of the power interface (Bizon, 2010c).

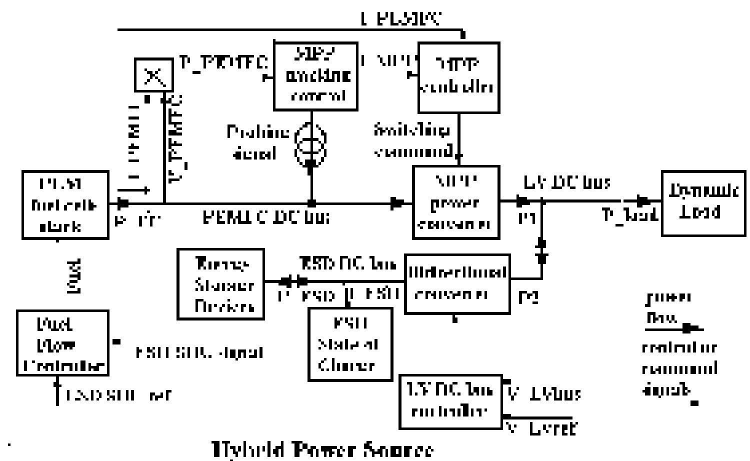

Figure 7. Hybrid power source topology with MPP tracking control

In this chapter, the modelling analysis will be focused on designing and operating of the fuel cell HPS with passive/active ripple mitigation techniques. The remainder of the chapter is organized as follows. Section 2 presents the basic EGS topology and modelling methodology of the EGS blocks for correct evaluation of ripple in back propagation on different DC buses. Two PEMFC models, which use to model the PEMFC dynamic a transfer function and an electrical circuit, respectively, are compared in ripple mitigation simulations. The mitigation performances of passive filters connected on LV DC bus and HV DC bus are analyzed in Section 3 in order to obtain a referential for other architectural and control solutions for ripple mitigation that are presented in next sections. Experiments performed have validated the design of PEMFC models presented in Section 2. Some aspects of the appropriate control performed to a boost power interface used in fuel cell inverter system are shown in Section 4. The implemented inverter system and the obtained results when is powered by a 12V/2kW fuel cell stack are presented in Section 5. Section 6 shown some representative simulation results and analyze the mitigation performances for an active control of bi-buck interface and last section concludes the chapter.

FUEL CELL EGS SYSTEM MODELLING FOR RIPPLE EVALUATION

The fuel cell EGS topology, which will be used to analyze the back propagation of inverter current ripple towards the PEMFC stack and to estimate the filtering effect, is show in figure 8 (Oproescu, Bizon, & Sofron, 2009; Oproescu, Bizon, & Sofron, 2009). The current ripple will be mesured by Ripple Factor (RF):

$$RF_I = \frac{I_{Max} - I_{Min}}{I_{(AV)}} \quad (1)$$

where I_{Max}, I_{Min}, and $I_{(AV)}$ are maximum, minimum and average value of the fuel cell current.

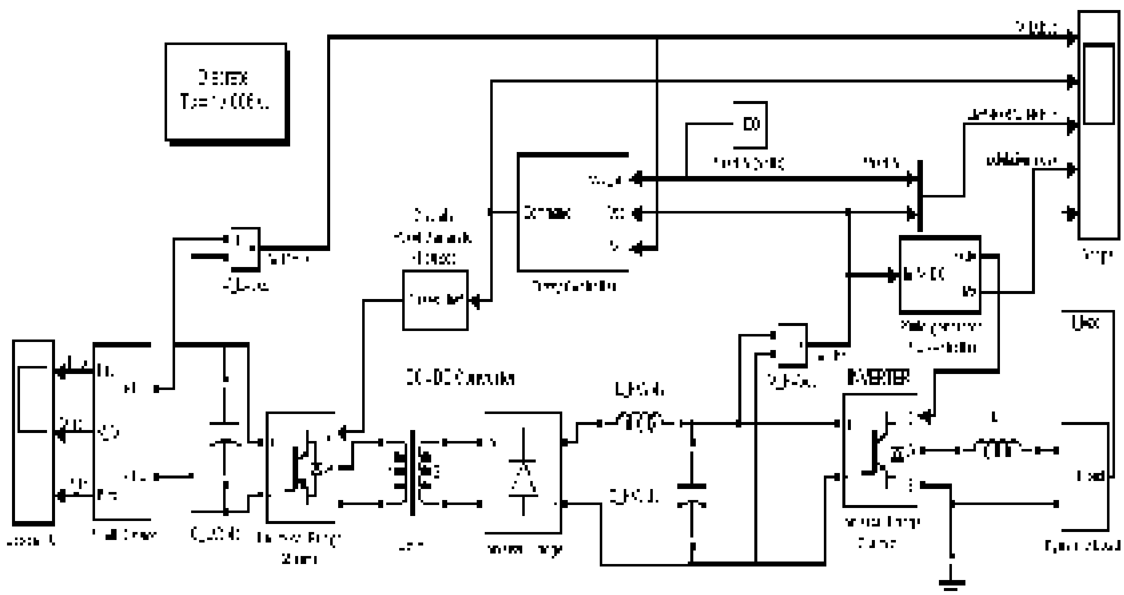

Figure 8. Matlab-Simulink diagram of the analyzed EGS

EGS Modelling to Evaluate the Current Ripple

In this section an analysis of current ripple back propagation for a mono-phase full-bridge inverter system is made using the EGS topology show in figure 8. The current ripple harmonics on LV DC bus are shown in order to estimate the current ripple on LV DC bus by modelling the DC-DC converter. The ripple model of DC-DC converter is presented in second subsection.

Power Spectrum of the Inverter System

The command of a mono-phase full-bridge inverter system can be easy make using a full-wave switching signal, but the output voltage can't be controlled in this case. A linear control of the output voltage level by index modulation can be made using a "pure" sine PWM switching signal. Output voltage and current of the inverter are shown in figure 9 and 10, respectively, for a given index modulation.

Obviously, the fundamental harmonic for output signals is at 50Hz grid frequency. The output current harmonics are at odd multiples of the grid frequency. The output voltage spectrum includes high components, which depend by the used carrier frequency. Input voltage and current for the same inverter are signals on HV DC bus and it are shown in figure 11 and 12, respectively. As has been stated before, the fundamental harmonic for input signals is of twice of grid frequency.

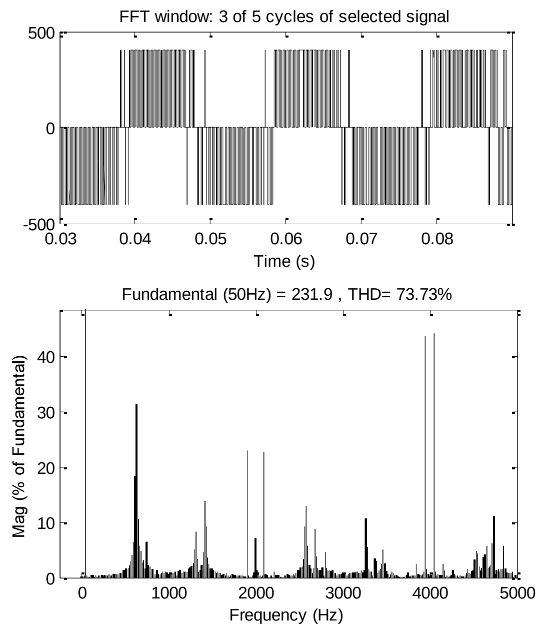

Figure 9. Output voltage of the inverter with pure sine PWM command: signal in time (top) and associate power spectrum (bottom)

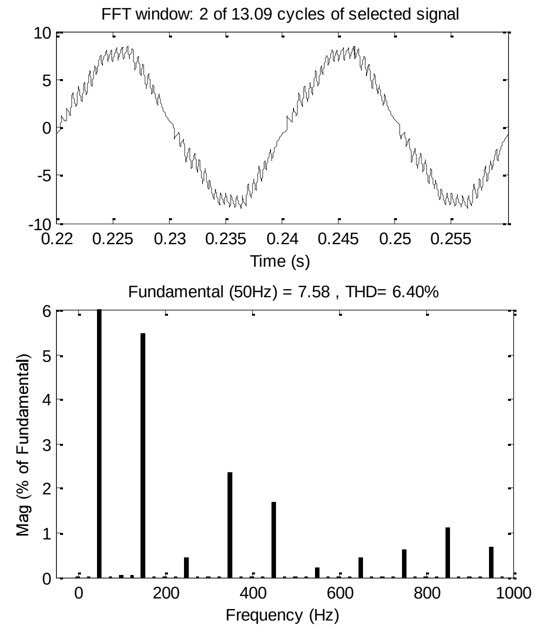

Figure 10. Output current of the inverter with pure sine PWM command: signal in time (top) and associate power spectrum (bottom)

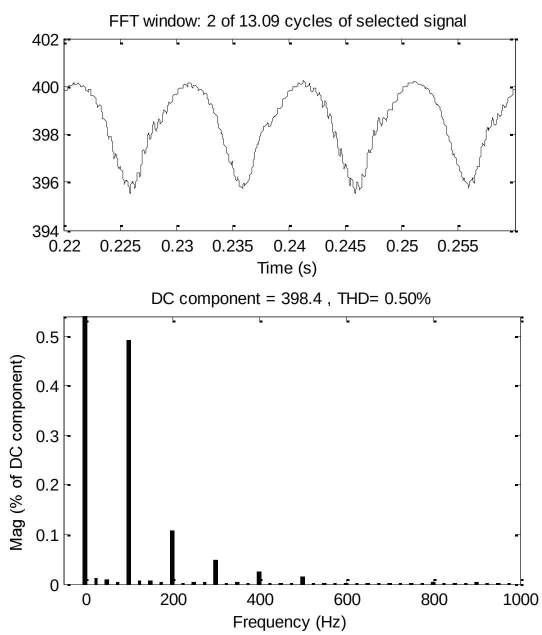

Figure 11. Input voltage of the inverter with pure sine PWM command: signal in time (top) and associate power spectrum (bottom)

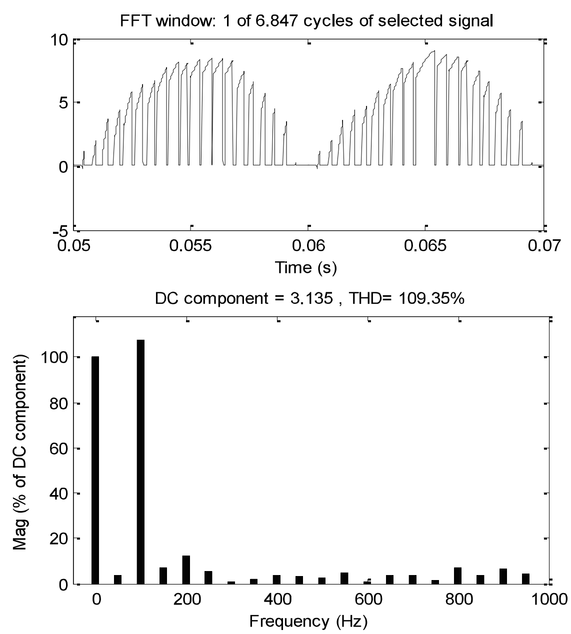

Figure 12. Input current of the inverter with pure sine PWM command: signal in time (top) and associate power spectrum (bottom)

A way to mitigate some harmonics is to use the phase shift command, also named as modified sine PWM command because of the shape of output voltage (figure 13). Output voltage and input current of the inverter with modified sine PWM command are shown in figure 13 and 14, respectively, for a $\pi/6$ phase shift angle.

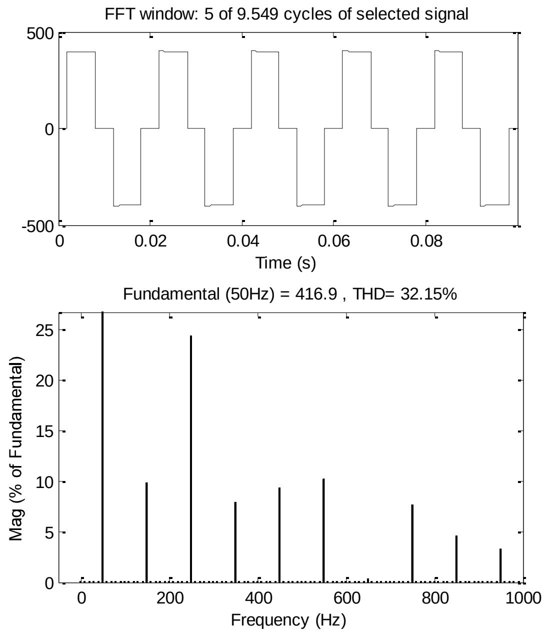

Figure 13. Output voltage of the inverter with modified sine PWM command: signal in time (top) and associate power spectrum (bottom)

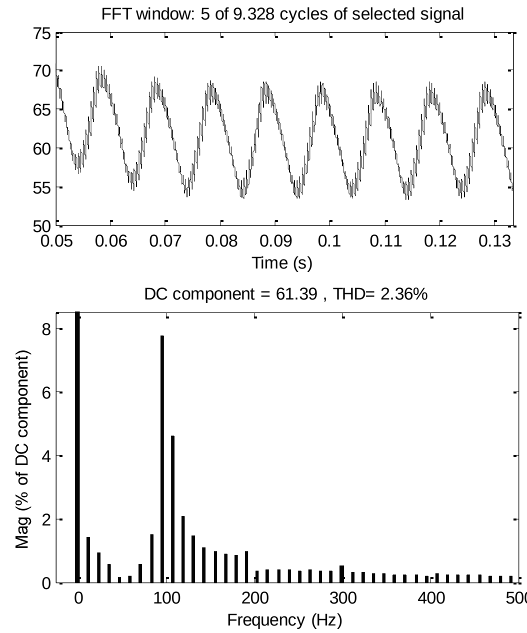

Figure 14. Input current of the inverter with modified sine PWM command: signal in time (top) and associate power spectrum (bottom)

The current harmonics level is clearly dependent by filtering capacitance value on LV-side and HV-side and the harmonics number is given by the used switching techniques: full-wave rectangular command, phase shift command or pure sine PWM command, respectively.

The current slopes for PEMFC stacks must be limited at about 10 A/s per each kW power. So, the EGS behavior under dynamic load must be analyzed. Voltage shapes on HV DC bus and LV DC bus are shown in figure 15 for a pulse load. The effect of high power demand at PEMFC stack is shown in figure 16.

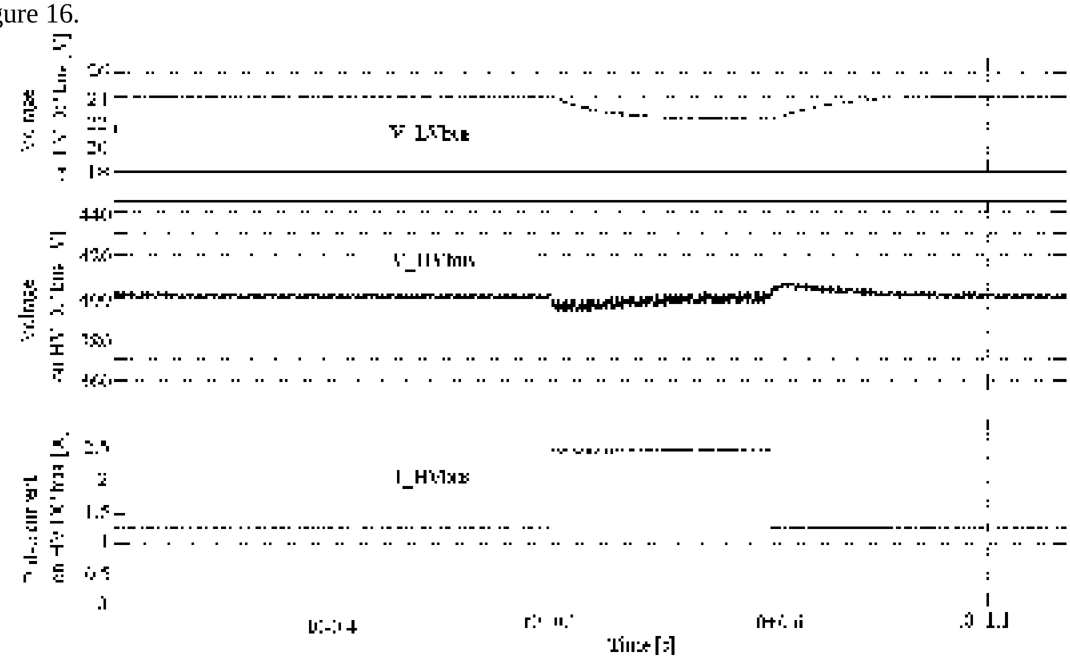

Figure 15. The effect of the current pulse, I_HVbus (bottom), on HV DC voltage, V_HVbus (middle), and LV DC voltage, V_LVbus (top)

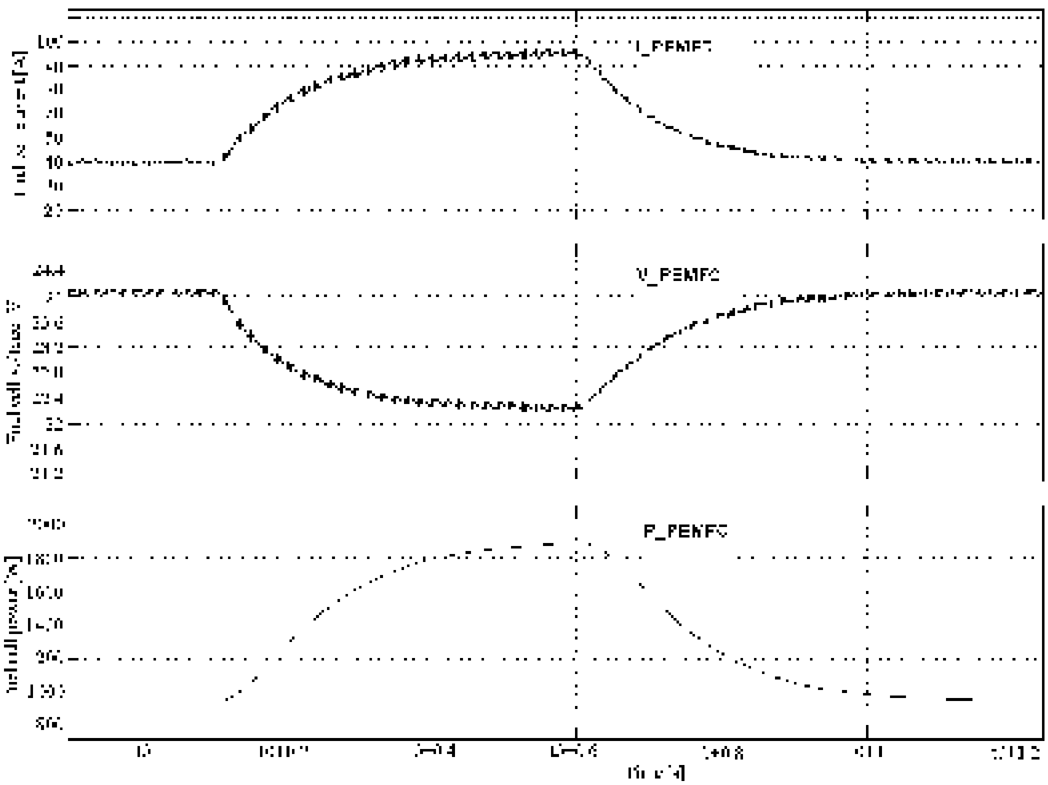

Figure 16. PEMFC stack behaviour under load pulse: power, P_PEMFC (bottom), voltage, V_ PEMFC (middle), and LV DC voltage, I_ PEMFC (top)

Analyzing figure 16 (where PEMFC current slope exceeding 50 A/s per each kW power), we can conclude that high load pulse (which might lead to a variation from rated load to double of its - which is close of maximum of PEMFC power delivery) can cause sharp current variations that exceed acceptable limits, if are not used appropriate pasive/active filters on DC buses.

Considering the inverter current ripple level that appear on HV DC bus, an AC model of the DC-DC converter is needed to evaluate the currrent ripple that propagates back on LV DC bus by DC-DC converter. A simple model of DC-DC converter for current ripple evaluation is developed in next section.

Modelling of DC-DC Converter for Back Propagation Evaluation of the Inverter Current Ripple

Starting from the mono-phase full bridge DC-DC converter shown in figure 17, the generic DC-DC converter topology, with passive filters at its ports of input and output, is shows in figure 18.a. The current ripple model for the DC-DC converter that will be used in the simulation are shown in figures 18.b and 18.c for case with galvanic isolation made by HF transformer and case without galvanic isolation, respectively.

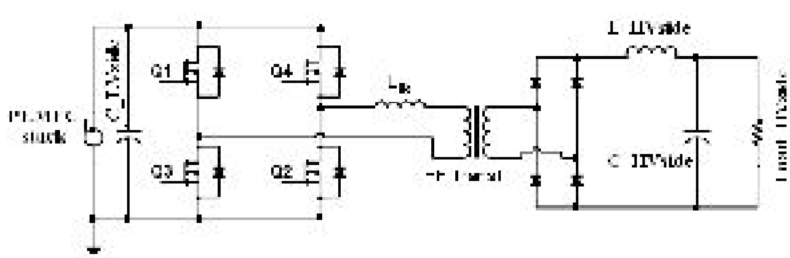

Figure 17. Mono-phase full bridge DC-DC converter topology