Low Frequency Ripple Mitigation of the Fuel Cell Inverter System using a Controlled Buck Current Source – Part II: Nonlinear Control

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Abstract: This paper analyzes the possibility of using a nonlinear controller to mitigate the current ripple of an inverter system powered by a Polymer Electrolyte Membrane Fuel Cell (PEMFC) stack. Hybrid and fuel cell technologies need to be merged in Hybrid Power Sources (HPS) to assure high performance regarding the PEMFC energy efficiency and PEMFC life cycle. The nonlinear controller is designed based on inverse gain that gives a constant answer for all levels of current ripple. Its advantages will be showed in comparison with hysteretic current control technique (that was shown in part I). Finally, a fuzzy logic controller is proposed to design the nonlinear control law.

Keywords: Fuel cell, inverter system, current ripple, ripples mitigation control, energy efficiency, nonlinear control.

1. Introduction

Some typical structures of the fuel cell inverter systems are presented in [1]. In order to increase the inverter’s efficiency it should minimize the stages of energy conversion [2,3]. A possible structure is presented in figure 1, where the fuel cell stack was directly connected to DC-DC-AC inverter system (the system of energy storage is not shown). The Polymer Electrolyte Membrane Fuel Cell (PEMFC) represents the main energy source in fuel cell Energy Generation System (EGS) and in vehicle applications because of its features: small size, the ease of construction, fast start-up and low operating temperature.

The inverter current ripple that is back propagated to the PEMFC stack represents the main factor for low performances regarding the PEMFC energy efficiency [4,5] and
The main problem appears at dynamic low frequency (LF), so the LF PEMFC current ripple that cause hysteretic losses and subsequently more fuel consumption must be mitigated under the reliability limits [8]. Because the LF inverter current ripple reduces with more than 10% the maximum output power, new restrictions of the fuel cell current ripple on different frequencies bands are specified as Ripple Factor (RF):

\[
RF_f = \frac{I_{\text{Max}} - I_{\text{Min}}}{I_{\text{AV}}}
\]

where \(I_{\text{Max}}, I_{\text{Min}}, \text{ and } I_{\text{AV}}\) are maximum, minimum and average value of the fuel cell current, respectively. The LF RF must be up to 5% from 10% to 100% load, not to exceed 0.5 A for lighter loads.

![Fig. 1. Back propagation of current ripple in the fuel cell inverter system](image)

Fuel cell current ripple may be mitigated by passive filtering on high-voltage (HV) and low-voltage (LV) DC buses or by an adequate active control that operates at different energy conversion stages. Because passive filters are bulky at high power of load, the second method is usually used [9,10,11].

A multi-port EGS topology (see figure 2) with power interface for ripple mitigation served the purpose and has been analyzed in [12,13,14].

![Fig. 2. Multi-port EGS topology with power interface for ripple mitigation](image)
In this chapter, the modeling analysis will be focused on the designing and operation of the fuel cell HPS with active ripple mitigation based on nonlinear control. A new and efficient topology is proposed to obtain both performances in energy conversion and ripple mitigation. This topology uses an inverter system directly powered from the appropriate fuel cell stack and a controlled buck current source as low power source that is working in parallel with the main power source. A FC/battery HPS structure is considered in this paper and the control goal is to mitigate the inverter current ripple as much as possible by using an active nonlinear control. Some power spectrums of LF ripple, which result in EGS using three-phase inverter, were shown in part I of this paper. In part II – section 2, the power spectrums of LF ripple that result in EGS using mono-phase inverter are analyzed.

2. Current ripple in mono-phase EGS

In this section an analysis of current ripple that is back propagation in a mono-phase full-bridge inverter system is made using the EGS topology shown in figure 3 [11]. The current ripple harmonics on HV DC bus are shown in order to estimate the current ripple on LV DC bus by modeling the mitigation in DC-DC converter. Different control techniques of mono-phase full-bridge inverter system are considered.

Fig. 3. Matlab-Simulink diagram of the analyzed mono-phase EGS

The command of a mono-phase full-bridge inverter system can be easily made using a full-wave switching signal, but the output voltage can not 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. Obviously, the fundamental harmonic of the output signals is at a grid frequency (50Hz). The output current harmonics are at odd multiples of the grid frequency. The output voltage spectrum includes high components, which depend on the
used carrier frequency. The fundamental harmonic for input signals is twice as the grid frequency. Obviously, the level of current harmonics is dependent by the filtering capacitance value that is used respectively on LV-side and on HV-side. Also, the harmonics number is given by the used switching techniques: full-wave rectangular command, phase shift command or pure sine PWM command, respectively [15,16]. So, the fundamental harmonics of LF ripple current are situated at the double or the triple of the grid frequency for the AC grid connected inverter of mono-phase or three-phase type, respectively. The significant LF harmonics are situated in LF frequency band from 100 Hz to 600 Hz. The LF spectral distribution of ripple harmonics and its levels for the DC input inverter current were showed in part I of this paper and those were considered in the designing of the equivalent load for inverter system (figure 4). It can be observed that equivalent load for the inverter system was implemented by a Controlled Current Source (CCS), which simulates a superposition of three rectified sine waves with set levels, having the frequency of 50 Hz, 150 Hz and 300 Hz. The set levels are 30 A, 5 A and 5 A, respectively. The low-pass filter is used for mitigation of HF current ripple (L_f=200 µH and C_f =5000 µF). The DC reference current, i_{ref}, has been chosen to be 240 A in correlation with Maximum Power Point (MPP) of used PEMFC stack (figure 5) that is powered to the maximum fuel flow rate of 1400 lpm (litre per minute).

The EGS architecture with current ripple mitigation control is shown in figure 6 and the structure of CCS controller with hysteretic control law is shown in figure 7.

The remainder of the paper is organized as follows. In section 3 are presented some features of the CCS hysteretic controller concerning mitigation performance of the inverter current ripple. The CCS nonlinear controller is designed based of these results. The EGS architecture shown in figure 16, which uses the proposed CCS nonlinear controller for the current ripple mitigation, is analyzed in section 4.

**Fig. 4.** Equivalent load current (top) and its power spectrum (bottom)

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**Fig. 5.** PEMFC parameters

- **Fuel cell nominal parameters:**
  - Stack Power: 50000 W
  - Nominal current: 1200 A
  - Nominal voltage: 1.53 V
  - Maximum voltage: 2.05 V
  - Maximum current: 1200 A
  - Maximum power: 180 kW
  - Current efficiency: 60%
  - Nominal pressure: 5 bars
  - Operating temperature: 80°C
  - Fuel: Hydrogen
  - Fuel cell efficiency: 55% in 100°C
  - Fuel cell efficiency: 45% in 80°C
  - Fuel cell efficiency: 35% in 60°C
  - Fuel cell efficiency: 25% in 40°C
  - Fuel cell efficiency: 15% in 20°C
  - Fuel cell efficiency: 5% in 0°C

- **Fuel cell stack parameters:**
  - Nominal power: 50 kW
  - Nominal voltage: 850 V
  - Nominal current: 60 A
  - Nominal efficiency: 75%
  - Nominal efficiency: 70%
  - Nominal efficiency: 65%
  - Nominal efficiency: 60%
  - Nominal efficiency: 55%
  - Nominal efficiency: 50%
  - Nominal efficiency: 45%
  - Nominal efficiency: 40%
  - Nominal efficiency: 35%
  - Nominal efficiency: 30%
  - Nominal efficiency: 25%
  - Nominal efficiency: 20%
  - Nominal efficiency: 15%
  - Nominal efficiency: 10%
  - Nominal efficiency: 5%
  - Nominal efficiency: 0%

- **Fuel cell characteristic parameters:**
  - Fuel cell efficiency: 55% in 100°C
  - Fuel cell efficiency: 45% in 80°C
  - Fuel cell efficiency: 35% in 60°C
  - Fuel cell efficiency: 25% in 40°C
  - Fuel cell efficiency: 15% in 20°C
  - Fuel cell efficiency: 5% in 0°C

- **Fuel cell stack characteristic parameters:**
  - Nominal power: 50 kW
  - Nominal voltage: 850 V
  - Nominal current: 60 A
  - Nominal efficiency: 75%
  - Nominal efficiency: 70%
  - Nominal efficiency: 65%
  - Nominal efficiency: 60%
  - Nominal efficiency: 55%
  - Nominal efficiency: 50%
  - Nominal efficiency: 45%
  - Nominal efficiency: 40%
  - Nominal efficiency: 35%
  - Nominal efficiency: 30%
  - Nominal efficiency: 25%
  - Nominal efficiency: 20%
  - Nominal efficiency: 15%
  - Nominal efficiency: 10%
  - Nominal efficiency: 5%
  - Nominal efficiency: 0%
Simulation results are shown in this section using a piecewise linear (PWL) implementation for the nonlinear gain used in the control loop, too. The possibility to design the PWL nonlinear law by a fuzzy logic controller is shown in section 6. Last section concludes the paper.

3. The necessity of a nonlinear gain in control loop and its design

Fuel cell current ripple vs. G\textsubscript{Ifc} gain is shown in figure 8.a. It can be observed that mitigation of fuel cell current ripple is significantly for G\textsubscript{Ifc} gain up to 40 and much smaller for G\textsubscript{Ifc} over to 40. The ripple mitigation ratio, RM, is measured as ratio of equivalent load current ripple to fuel cell current ripple, RM=\Delta I\textsubscript{load}/\Delta I\textsubscript{FC}. RM is shown in figure 8.b. Both characteristics show that G\textsubscript{Ifc} gain must be nonlinear. Ripple mitigation ratio(RM) vs. fuel cell current ripple is shown in figure 9.a (marker ■) considering G\textsubscript{Ifc} gain in the extended range up to 200. Ripple mitigation ratio can be almost constant for different load current ripple (or fuel cell current ripple) levels if the nonlinear gain (G\textsubscript{Ifc}) is defined symmetrically about the dashed vertical axis.
a) Fuel cell current ripple vs. $G_{fc}$ gain  

b) Ripple mitigation ratio vs. $G_{fc}$ gain  

Fig. 8. Performance characteristics of fuel cell EGS architecture with current ripple mitigation control that uses an equivalent load for inverter system

The nonlinear gain is implemented by a piecewise linear (PWL) function using a look-up table (figure 18.b):

$X = [0, 2.5, 3.5, 4, 4.49, 4.5]$;

$Y = [10, 20, 40, 100, 200, 200]$.

The proposed CCS controller that uses a PWL nonlinear gain is shown in figure 10.

a) Ripple mitigation ratio vs. fuel cell current ripple  

b) PWL nonlinear gain  

Fig. 9. Nonlinear gain of CCS controller

Fig. 10. The CCS nonlinear controller structure
The control gain has a nonlinear part (PWL nonlinear gain) and a linear part ($G_{lc}$). The last part increases the mitigation performance by choosing a value in range 1 to 10. A higher value than 10 increases the switching frequency over to 50 kHz, as shown in next section. So, the set value is 10.

4. **Simulation results using a PWL nonlinear gain in control loop**

Some simulation results are presented in figure 11 for the fuel cell EGS architecture using the CCS nonlinear controller.

![Fig. 11. Simulation results for fuel cell EGS architecture with nonlinear CCS controller](image)

**a)** Fuel cell current ripple (top) and its LF power spectrum (bottom)

**b)** Buck CCS current ripple (top) and its LF power spectrum (bottom)

**c)** Zoom of buck CCS current ripple (top) and its HF power spectrum (bottom)
d) Mean value of buck CCS current ripple (top) and its LF power spectrum (bottom)

Fig. 11. Simulation results for fuel cell EGS architecture with nonlinear CCS controller (continued)

The 100 Hz harmonic level of fuel cell current (plot a), buck CCS current (plot b) and load current (plot e) are of 0.032 A, 7.357 A and 7.397 A, respectively. The ripple mitigation ratio is about 7.397/0.032≈231, and it is better than the result obtained by using a constant gain (see figure 8.b). Comparing the LF power spectrums of buck CCS current (plot b and d) and load current (plot e), it can be observed that are almost the same. The mean value of buck CCS current (plot d) is obtained using a 1 ms moving-window. The HF power spectrum of the buck CCS current is shown in plot c. It is obviously that is unpractical to use the unprocessed buck CCS current as one input of Fuzzy Logic Controller (FLC) that will be designed in the next section, so a 1 ms moving-window means filter will be used for the signal processing of both FLC inputs. In this case the same delay will appear on both input variables.

5. A point of view concerning the designing of nonlinear law by a fuzzy logic controller

If the used constant gain is $G_{Ifc}=10$ and the $Xg$ vector is the scaled X vector by this $G_{Ifc}$ gain of 10, then the nonlinear gain that includes this constant gain may be implemented by the following PWL function:

$Xg = [0, 0.25, 0.35, 0.4, 0.449, 0.45];$

$Y = [10, 20, 40, 100, 200, 200].$

The memberships functions for the fuel cell current ripple (fc), the ripple mitigation ratio (rm) and the command signal (com) are shown in figure 12, plot a, b and c, respectively. Five membership’s functions are defined for both input variables in correlation with PWL vectors (Xg, Y). They are named as VS=Very Small, S=Small,
M=Medium, B=Big and VB=Very Big. For output variable are uniformly defined five membership’s functions in range 0 to 1, too. They are named as VS=Very Small, S=Small, M=Medium, B=Big and VB=Very Big. The base rules are shown in table 1 and also in figure 12.d.

The Mamdani implication and center of gravity defuzzification method are used. The resulting control surface and projections contour for different command signal levels are shown in figure 12, plot e and f, respectively.

TABLE 1. FLC rules base

<table>
<thead>
<tr>
<th>Command signal</th>
<th>Fuel cell current ripple [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VSfc</td>
</tr>
<tr>
<td>VSrm</td>
<td>Mcom</td>
</tr>
<tr>
<td>Mrm</td>
<td>VBcom</td>
</tr>
<tr>
<td>Brm</td>
<td>VBcom</td>
</tr>
<tr>
<td>VBrm</td>
<td>VBcom</td>
</tr>
</tbody>
</table>

![a) Fuel cell current ripple memberships](image1)

![b) Ripple mitigation ratio memberships](image2)

![c) Command signal memberships](image3)

![d) FLC rules base](image4)

Fig. 12. Designing of FLC and its characteristics
It can be observed that projection contour for command signal level of 0.7 is similar with the shape of the PWL nonlinear gain that include the constant gain, $G_{il}=10$. So, the hysteresis levels can be chosen around this value. These results confirm the design made for nonlinear controller in the above section.

The structure of the CCS controller using the above FLC design is shown in figure 13. The switching command is obtained by using a hysteretic law for the relay block.
The simulation results of ripple mitigation are almost the same with those obtained using the nonlinear controller. If the moving-window of the mean filter is larger than 1 ms, then the delays in the processing of input variable can influence the mitigation performance the CCS controller that uses a FLC.

6. Conclusion

In this paper the designing of a nonlinear controller is presented step by step. Two ways to design of the nonlinear control law are proposed. First is based on simulation trials to draw the characteristic of ripple mitigation ratio vs. fuel cell current ripple. By symmetry is designed the nonlinear control law. The second is based on FLC control surface that is projected for 0.7 – cut as contour in plane of the input variables (ripple mitigation ratio vs. fuel cell current ripple). The advantages of nonlinear controller are shown by computing the ripple mitigation (RM) ratio using the simulation. Lower values of RM ratio are obtained for each significant harmonics from the power spectrum of the inverter current ripple by designing of the FLC. The nonlinear controller keeps all control performances of the FLC.

REFERENCES


