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A NOVEL FUEL-CELL DC-AC POWER CONDITIONER TO BACK-UP CRITICAL LOADS

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ABSTRACT

In this paper a novel dc-ac power conditioning converter along with a fuel-cell module are proposed as back-up power source. The proposed approach consists of a typical single phase full-bridge SPWM inverter. The main contribution of this novel approach is realized with an integrated arrangement of a single boost-cell connected on both half-bridge legs of a typical full-bridge inverter topology. Each boost-cell helps on boosting a back-up dc input voltage in order to provide an ac output voltage (120 VRMS) to a critical load. An experimental lab prototype which includes two boost-cells for each one of the half-bridge legs is proposed and experimental results show the feasibility of the proposed approach. A commercial fuel-cell module will provide the back-up power source from a +48V (dc), 2.5 kW to the single phase full-bridge SPWM inverter. Analysis and design is discussed briefly and a design example illustrates the main parameters of the dc-ac approach.

Keywords: fuel-cell, single-stage, boost-inverter, critical loads

1. INTRODUCTION

Critical loads like computing servers, medical and critical equipment are sometimes required to be backed-up by some type of emergency power conditioning equipment under undesirable power disturbances. The use of clean and renewable energy sources like Fuel Cells is becoming nowadays mandatory at some applications, thanks to their benefits compared to traditional technologies that hurt the environment. Fuel Cell technology permits to deliver high quality energy for as long as being fed with hydrogen, making them highly suitable for sustaining critical loads such as medical gear, computing servers or industrial equipment for very long time. The energy provided from the Fuel Cell is on a dc level, and therefore it needs to be power conditioned to ac level. Typically, two or more conversion stages (boosting and inversion) are required to achieve the desired ac output [1]-[3]. A critical problem is that cascading power conditioning stages leads to an important overall efficiency reduction in the system. For this reason, single-stage topologies are preferred [4]-[6]. In this paper, a novel single-stage Integrated dc-ac Back-up Fuel Cell Single-phase Converter (IBFCSC) is presented. The converter steps-up the Fuel Cell voltage (+48 V) to a range of 200 V – 300 V and then makes the inversion process to get 60 Hz single phase ac (120 V_{RMS}). The proposed converter has the advantage of being an efficient and yet very simple circuit, because it's based on a typical full bridge topology with boosting capabilities [7]-[9]. This characteristic allows the use of common control techniques such as bipolar or unipolar SPWM (Sinusoidal Pulse Width Modulation).

2. PROPOSED INTEGRATED DC-AC BACK-UP FUEL CELL SINGLE-PHASE CONVERTER

The proposed converter topology consist of a common full-bridge single-phase voltage source inverter (VSI), with an added arrangement of two "boosting cells" stacked in series on each switching leg. The dc input voltage is increased and held for every commutation cycle. This way, the output voltage at load is the sum of the source dc voltage, plus the lifted voltage of each boosting cell's capacitors. If more voltage gain is needed, then more cells are added in the same way. Every boosting cell charges the inductor in parallel and delivers the stored energy in the capacitor, in series with the dc voltage source (Fuel Cell). To reduce the high frequency input current ripple, an LC filter was added at the Fuel Cell dc-bus voltage. The schematic diagram of the proposed novel converter is shown in Fig. 1.

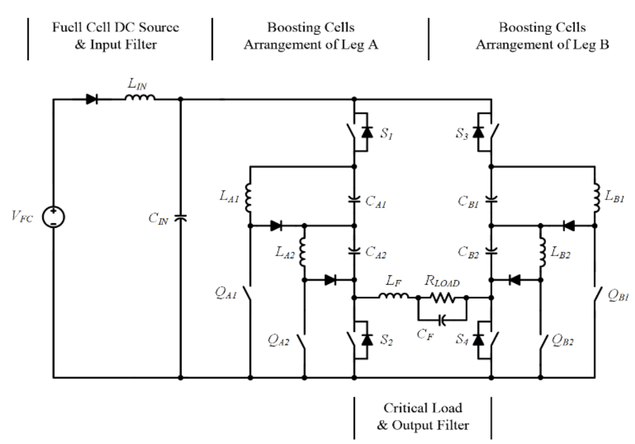

Fig. 1 Schematic diagram of the proposed Integrated DC-AC Back-up Fuel Cell Single-phase Converter.

3. PRINCIPLE OF OPERATION

In this section, it is explained the operation principle of the proposed Integrated DC-AC Back-up Fuel Cell Single-phase Converter (IBFCSC). For each commutation cycle, voltage from Fuel Cell is lifted to a range between 200 V is explained the operation principle of the proposed Integrated dc-ac Back-up Fuel Cell Single-phase Converter (IBFCSC). For each commutation cycle, voltage from Fuel Cell is lifted to 200 V – 300 V range through "boosting cells". Because the boosting cells are based on a Buck-Boost converter, such cells consist of an arrangement of an inductor, a capacitor, a diode and a grounding switch as shown in Fig. 2. In this converter, there are two boosting cells stacked in series for each main switching leg. The grounding switches of each boosting cell, operate simultaneously with the main upper switch of the same leg: S1 for leg A and S3 for leg B. When switches S1 and S4 are in on-state, the inductor on each cell at leg A draws a high current, while the parallel capacitor stores its reflected voltage on the next time lapse (off-state). Because of the series arrangement, the next cell receives the energy previously stored, boosting even more the voltage available to the load. Similar operation occurs when switches S2 and S3 are in on-state, at leg B. The control implemented on the IBFCSC is based on a unipolar SPWM scheme. To ensure that a value of 0 V is repeatedly achieved on every commutation cycle, the unipolar scheme was implemented with a control logic shown in Fig. 3 (Modified Unipolar SPWM).

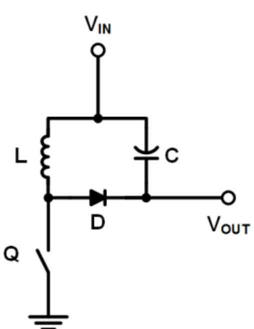

Fig. 2 Boosting cell arrangement.

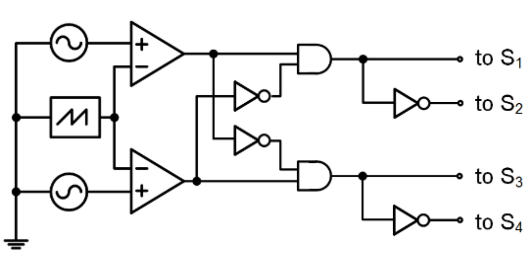

Fig. 3 Control logic to implement a modified unipolar SPWM scheme.

4. ANALYSIS AND DESIGN

On every commutation cycle, each cell's inductor generates a voltage that it's reflected on the parallel capacitor, defined as follows:

$$V_C = V_L = L\frac{di_L}{dt} \quad (1)$$

where V_C represents the parallel capacitor voltage, V_L the inductor voltage, L the inductance value (H) and i_L the inductor current. The intermediate diode, allows energy flow to the next boosting cell, adding more voltage to the load. This way, when the main switches are not generating 0 V across the load, the total voltage lift is:

$$V_T = V_{FC} + V_{C1} + V_{C2} \quad (2)$$

where V_T represents the total voltage lift, V_{FC} the source voltage from Fuel Cell, V_{C1} the capacitor voltage of first boosting cell and V_{C2} the capacitor voltage of second boosting cell. The output voltage is a function of the total voltage lift and the modulation index for a single phase full bridge inverter [11], according to the following expression:

$$V_O = \frac{V_T * m_a}{\sqrt{2}} \quad (3)$$

where m_a is the modulation index and V_O the RMS output voltage.

5. DESIGN EXAMPLE

In this section, a design example is illustrated to compute the main component values. A simulation is conducted and results are presented in the following section. Since the topology it's symmetrical, leg A and leg B have the same components and values. The parameters used are shown in Table 1. Ideal components and analysis on steady state were considered.

Table 1 Design example parameter values.

Parameter	Value	Parameter	Value
$V_{FC,nom}$	+48 V	$C_{A,2} = C_{B,2}$	2,400 µF
L_{in}	30 mH	L_f	600 µH
C_{in}	3,300 µF	C_f	220 µF
$L_{A,1} = L_{B,1}$	450 µH	R_{Load}	32 Ω
$L_{A,2} = L_{B,2}$	450 µH	f_S	30 kHz
$C_{A,1} = C_{B,1}$	13,600 µF	m_a	0.68

6. SIMULATION RESULTS

In this section some simulation results are presented to validate the proposed approach. As can be seen from Fig. 4(a), input current ripple can be as high as 8.5 % from the steady state average input current I_D. A main objective of this converter will be reducing as much as possible the input current ripple which is drawn from the Fuel Cell module. In Fig. 4(b) the voltage across capacitors stored on the pair of

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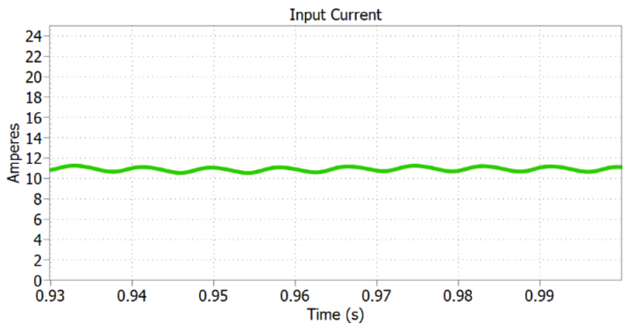
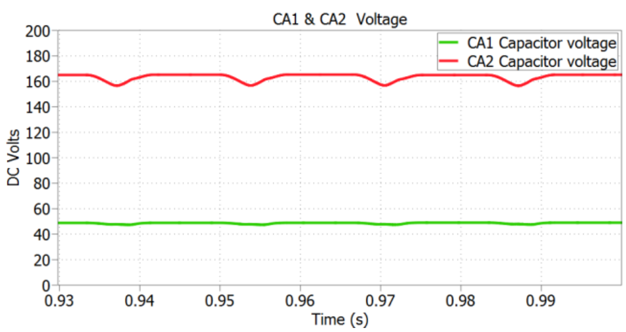
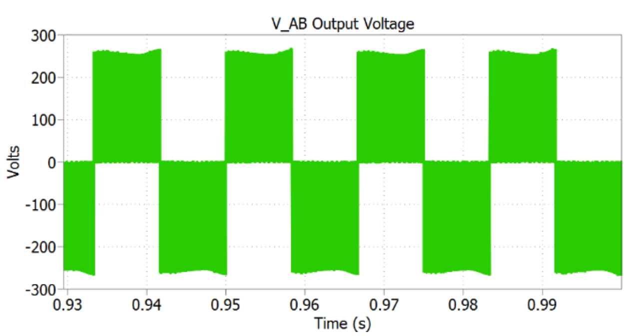
boosting cells of each main switching leg is shown. Pre-filtered ac output voltage waveform can be seen in Fig. 4(c) with a maximum voltage amplitude of 265 V, which matches equation (2). A filtered output voltage obtained from simulation is shown in Fig. 4(d), matching equation (3). From the simulations results, THD was evaluated and computed as 1.8%. In Table 2, steady state values obtained from simulation results are presented. Also, parasitic losses were considered during simulation.



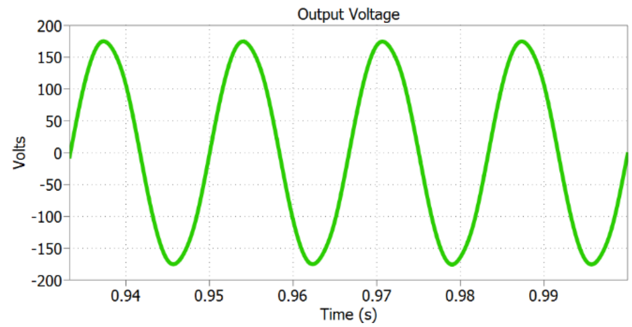
(a)



(b)



(c)



(d)

Fig. 4 Simulation results of the proposed IBFCSC; a) input current, b) voltage stored on C_{A1} & C_{A2}, c) pre-filtered output voltage, & d) 60 Hz sinusoidal output voltage.

7. EXPERIMENTAL RESULTS

Experimental results were conducted on a lab prototype to verify its capability of boosting and inverting the dc source level voltage from a Fuel Cell module. Since the prototype is still in development stage, input and output LC filters are not considered in this section. On early tests, the prototype did not behave as expected. For unknown reasons, only upper boosting cells of each main switching leg were triggered, leading to C_{A2} & C_{B2} not storing any voltage. Several tests were made to explain this unwanted behavior: from verifying any signal and discrete component one by one, to replacing switches and capacitors with different values. On Fig. 5 and Fig. 6, SPWM signals that trigger the boosting cell switches are displayed. As can be seen, there is no error on amplitude or phase, as expected.

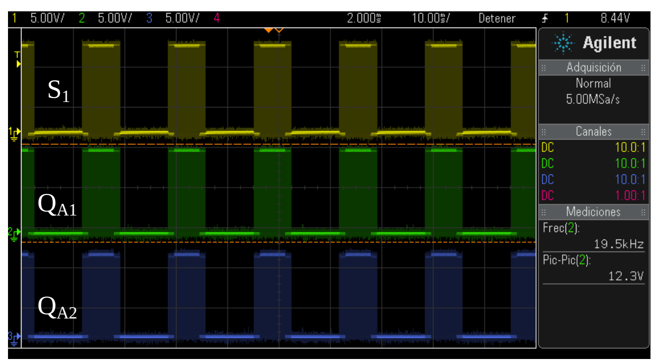


Fig. 5 SPWM triggering signals on leg A (S_1, Q_{A1} and Q_{A2})

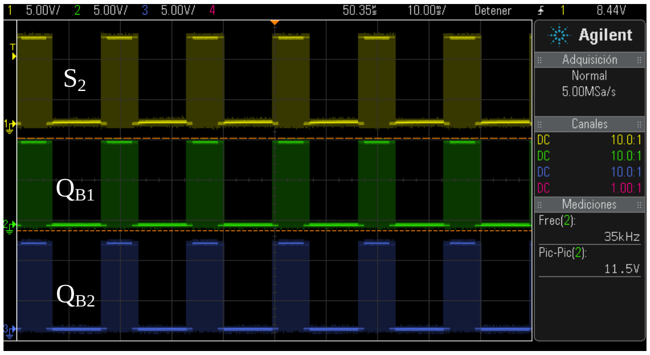


Fig. 6 SPWM triggering signals on leg B (S_2, Q_{B1} and Q_{B2})

Taking in account this situation, the following parameters were applied to the preliminary prototype: Input voltage of 5 V_{DC}, ma = 0.6, f_S = 30 kHz, and only one of two boosting cell grounding switches per leg was triggered (Q_{A1} & Q_{B1}). On Fig. 7, a test was conducted to discard unwanted voltage drain on capacitors C_{A1} and C_{B1}, as they deliver energy in series to faulty boosting cells. As it is displayed, these capacitors stored energy on any conmutation cycle.

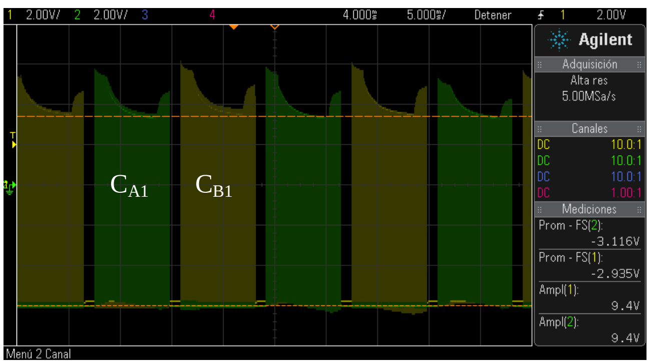


Fig. 7 Voltage measured respect to ground on C_{A1} and C_{B1}

Unfiltered output voltage is shown on Fig. 8. The output voltage is 23.8 Vpp, with a 60 Hz fundamental frequency. Since only one grounding switch per leg is triggered, only the first boosting cell per leg is activated. Fig. 9 shows the voltage across capacitor C_{A1} (same as C_{B1}) with a maximum value of 6.9 Volts. This correlates with equation (2), partially confirming the desired behavior of boosting and inversion capabilities on a single stage.

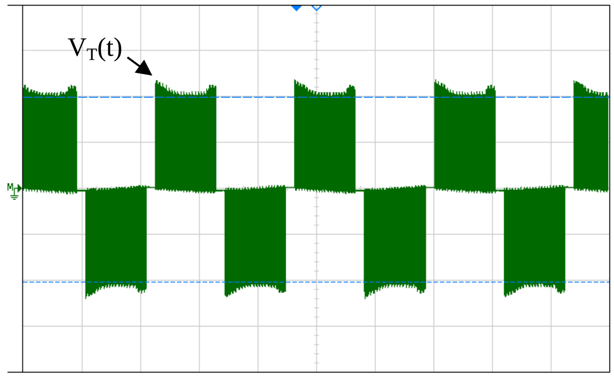


Fig. 8 Unfiltered output voltage from 5 VDC input voltage. Resolution: 5 V/div, 5 ms/div.

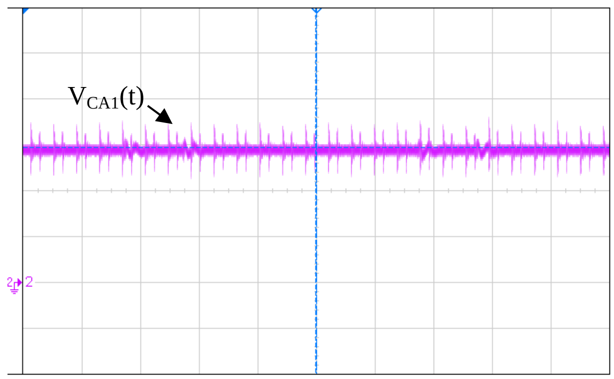


Fig. 9 Voltage on C_{A1}. Resolution: 2 V/div, 10 us/div.

8. CONCLUSIONS

In this paper, a novel Integrated DC-AC Back-up Fuel Cell Single-phase Converter (IBFCSC) has been proposed, analyzed and discussed. The principle of operation has been briefly presented with the boosting cell arrangement. A design example of the proposed topology illustrated the key equations and component values obtained from analysis. Simulation results have been extensively conducted and shown the feasibility of the proposed IBFCSC approach to convert a FC-bus voltage to an output ac voltage to supply a critical load. An early prototype was built and partially confirmed the desired behavior of boosting and inverting the Fuel Cell dc voltage on a single stage, all while it is driven by a simple commutation scheme (Modified Unipolar SPWM). In the final paper, new experimental results from an improved prototype are going to be presented, to validate the operation of the proposed power converter.

9. REFERENCES

[1] A. Vazquez-Blanco, C. Aguilar-Castillo, F. Canales-Abarca, and J. Arau-Roffiel, "Two-stage and integrated fuel cell power conditioner: Performance comparison," in *Proc. Appl. Power Electron*. Conf., Feb. 15–19, 2009, pp. 452–458.

[2] C. Pan and C. Lai, "A high-efficiency high step-up converter with low switch voltage stress for fuel-cell system applications" *IEEE Trans. on Ind. Electron.*, vol. 57, no. 6, pp. 1998 – 2006, June 2010.

[3] Z. Wang et al., "Design of a two-stage fuel cell based single-phase utility-interactive inverter," *2007 IEEE Power Electronics Specialists Conference*, Orlando, FL, 2007, pp. 1227-1231.

[4] Y. Li, S. Jiang, J. G. Cintron-Rivera and F. Z. Peng, "Modeling and Control of Quasi-Z-Source Inverter for Distributed Generation Applications," in *IEEE Tran. on Ind. Electron.*, vol. 60, no. 4, pp. 1532-1541, April 2013.

[5] M. Jang, M. Ciobotaru and V. G. Agelidis, "A single-stage fuel cell energy system based on a buck–boost inverter with a backup energy storage unit," *IEEE Trans. on Power Electron.*, vol. 27, no. 6, pp. 2825 – 2834, June 2012.

[6] G. K. Andersen, C. Klumpner, S. B. Kjaer and F. Blaabjerg, "A new green power inverter for fuel cells," *2002 IEEE 33rd Annual IEEE Power Electronics Specialists Conference. Proceedings*, 2002, vol. 2, pp. 727-733.

[7] Y. Li, S. Jiang, J. G. Cintron-Rivera and F. Z. Peng, "Modeling and Control of Quasi-Z-Source Inverter for Distributed Generation Applications," in *IEEE Trans. on Ind. Electron.*, vol. 60, no. 4, pp. 1532-1541, April 2013.

[8] C. Wang, "A novel single-stage full-bridge buck–boost inverter," *IEEE Trans. on Power Electron*., vol. 19, no. 1, pp. 150 - 159, Jan. 2004.

[9] G. L. Piazza and I. Barbi, "New step-up/step-down DC–AC converter", *IEEE Trans. on Power Electron.*, vol. 29, no. 9, pp. 4512 - 4520, Sep. 2014.

[10] C. Aguilar et al., "Integrated DC–AC converter as power conditioner for fuel cell based system ", *IEEE Latin America Transactions*, vol. 14, no. 5, pp. 2107 – 2113, May 2016.

[11] N. Mohan et al., *Power Electronics: Converters, Applications and Design*. 2nd ed. Wiley, 1995.

[12] Simulation Software for Power Electronics, PLECS, PLEXIM. Available [online]: http://www.plexim.com