

# A New Quadratic, Three-Level, DC/DC Converter Suitable for Fuel Cell Applications

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**Abstract**—This paper presents a new non-insulated quadratic three-level DC-DC boost converter. The quadratic feature is interesting for application where a wide voltage range is necessary. Since it is a current-source converter, its application in a fuel cell energy conversion system is interesting. Theoretical analysis for CCM of operation and experimental results are presented. A comparison between the two cascaded boost converter, the single switch quadratic boost converter and the proposed converter is made regarding commutated power. The efficiency of the proposed converter is higher than the others.

**Index Terms**—multilevel converters, quadratic converters, boost, fuel cells, current-source converter.

## I. INTRODUCTION

Fuel cell's steady-state and dynamic electrical characteristics are very peculiar when compared with other kinds of power sources. When designing converters for fuel cells, it is necessary to consider the fuel cell innate characteristics instead of considering it only as an ideal DC voltage source. Also, the complete system must be taken into account when choosing static converters for fuel cell applications.

Since fuel cells deliver energy at low voltages ( $\approx 1.17\text{V} @ 80^\circ\text{C}$ ), depending on the application they are usually stacked to reach useful voltages. Nowadays, in applications where the power is situated between 1kW and 10kW the range of the fuel cell output voltage is between 24V and 60V. These values are low when comparing with the necessary voltage at the inverter's input, when a DC/AC conversion is needed. This fact results in the necessity of another conversion stage between the fuel cell and the inverter, usually a step-up DC/DC converter. As a consequence the voltage gain of the DC/DC stage must be high enough to accommodate this difference. Then, cascaded converters or transformer isolation can be necessary, just to adapt the voltage difference.

Another problem is that, since fuel cell's voltage is low, the input current can be very high, even for low power (1kW to 10kW), making difficult to reach high efficiency in the DC/DC conversion stage.

Motivated by these facts, this paper proposes the topology of a quadratic, three-level, non-insulated DC/DC boost converter. Its characteristics suit the needs of applications where low input voltage and high voltage ratio are required, like in fuel cell systems. Since in fuel

cell applications large ripple current may bring additional problems [1], [2], this current-source converter is well adapted.

Previous works [3]–[6] presented wide range DC/DC converters, which could be suitable for this kind of application. In [5] a commutation cell for quadratic converters was presented, including some insulated topologies. Derived from the commutation cell presented by [5], the topology of the quadratic boost converter which uses only one active switch was presented in [6]. Several topologies have been presented in the last years regarding three-level converters, where the switch voltage is smaller than the input or output voltage. However, the three-level commutation cell presented here is mainly based on the work done by [7] and [8], which presents basic three-level converters, insulated and non-insulated versions, respectively.

In this paper, a comparison regarding installed semiconductor power is made between the proposed topology, two cascaded boost converters and a single switch quadratic boost converter. The procedure to generate the new topology is shown, where two other new, but less interesting boost converters are presented. The static gain, topological states and main waveforms are described theoretically for Continuous Conduction Mode (CCM) of operation of the most interesting presented topology. To validate the theoretical analyses, the proposed converter and the two boost cascaded converters were implemented and the efficiencies were compared. The experimental results are presented.

## II. TOPOLOGY CONCEPTION

The proposed converter topology was generated in the context of the application presented by [9], with the goal of improving the long-term UPS based on fuel cells. For the reader comfort, the UPS system is re-presented by Fig. 1, in which the DC/DC converter stage can be identified.

A good topology to be adopted in the DC/DC conversion stage of this application could be the conventional boost converter. However, for high static gains, the converter losses becomes important, reducing its efficiency, even so if the ideal static gain can reach high values. This technological limitation can be seen by considering the component losses in the static gain equations. In the mentioned application example, the voltage ratio between

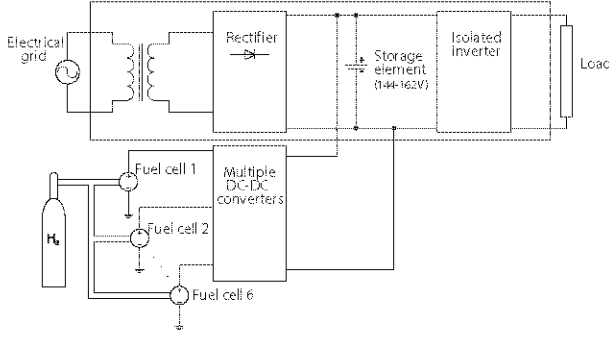


Fig. 1. Long-term uninterruptible power supply architecture.

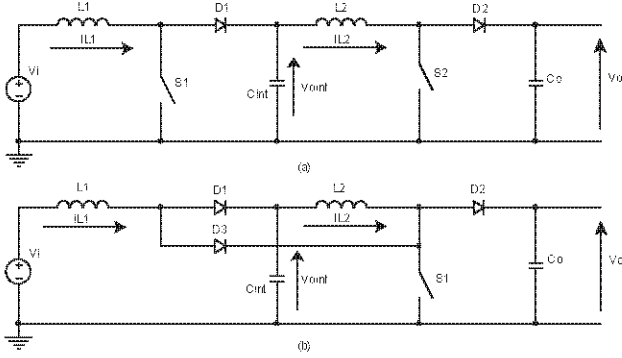


Fig. 2. (a) Two cascaded boost converters; (b) Single switch quadratic boost converter.

the input and output of the DC/DC stage is near 6. Other solutions to accommodate this voltage difference could be the use of quadratic, cascaded or insulated converters. Since this application did not require insulation, a non-insulated topology can be adopted.

An architecture where two boost converters are cascaded is shown by Fig. 2 (a). This solution fulfil the mentioned requirements. In another way, with one switch less but with one more diode, Fig. 2 (b) presents a quadratic boost converter [5], [6]. In this case only one active switch also means only one gate driver circuit, but also, only one degree of freedom regarding output voltage control.

When comparing both solutions in terms of installed (commutated) semiconductor power, which gives an image of the converter cost, it is possible to conclude that the total commutated power in the single switch converter is higher than in the two cascaded converters. Defining the commutated power [10] as presented by (1), it is possible to determine the total commutated power by using (2), where  $I_i$  and  $V_i$  are semiconductor's current and voltages. For the active switches, MOSFETs in this project, it is considered that the commutated power is the maximum voltage across the switch  $V_{S_i \max}$  times the RMS current  $I_{S_i \text{ rms}}$ , as shown by (3). While in case of diodes, it is considered that the commutated power is average current  $I_{D_i \text{ avg}}$  times maximum voltage  $V_{D_i \max}$ , as presented by (4).

$$Sc = I_i \cdot V_i \quad (1)$$

$$Sc_{tot} = \sum_{i=1}^k V_i \cdot I_i \quad (2)$$

$$Sc_{S_i} = I_{S_i \text{ rms}} \cdot V_{S_i \max} \quad (3)$$

$$Sc_{D_i} = I_{D_i \text{ avg}} \cdot V_{D_i \max} \quad (4)$$

Neglecting the inductor ripple current, since it should be low in fuel cell applications, it is possible to determine the semiconductors commutated power as presented from (5) to (9). Neglecting the efficiency, the total commutated power for the *two cascaded converters* (Fig. 2 (a)) is presented by (10), parameterized in function of the output power  $P_o$ .

$$\overline{Sc_{S_1}}(D) = \frac{Sc_{S_1}}{P_o} = \frac{\sqrt{D}}{(1-D) \cdot \eta_{tot}} \quad (5)$$

$$\eta_{tot} = \eta_1 \cdot \eta_2 \quad (6)$$

$$\overline{Sc_{S_2}}(D) = \frac{Sc_{S_2}}{P_o} = \frac{\sqrt{D}}{(1-D) \cdot \eta_2} \quad (7)$$

$$\overline{Sc_{D_1}}(D) = \frac{1}{\eta_2} \quad (8)$$

$$\overline{Sc_{D_2}}(D) = 1 \quad (9)$$

$$\overline{Sc_{tot}}(D) = \frac{2\sqrt{D}}{1-D} + 2 \quad (10)$$

where  $D$  is the switch duty cycle and  $\eta_{1,2,total}$  is the efficiency of the stage 1, 2 and total efficiency respectively. The commutated power is described by  $Sc$  for the switches  $S_1$  and  $S_2$  and for diodes  $D_1$  and  $D_2$ . The total commutated power is identified by the subscript *total* which is the sum of all semiconductor commutated powers. Over lined symbol means that the variable is parameterized in function of  $P_o$ .

Following the same methodology for the single switch boost converter, the switch's commutated power and additional diode's commutated power is presented by (13) and (14), respectively. The total commutated power, neglecting the converter's efficiency, is presented by (15).

$$I_{S_1 \text{ rms}} = (I_{L_{1 \text{ avg}}} + I_{L_{2 \text{ avg}}}) \cdot \sqrt{D} \quad (11)$$

$$V_{S_1 \max} = V_o \quad (12)$$

$$\overline{Sc_{S_1}}(D) = \frac{Sc_{S_1}}{P_o} = \frac{\sqrt{D}}{(1-D)^2} \left( \frac{\eta_2 + \eta_{tot}(1-D)}{\eta_{tot} \cdot \eta_2} \right) \quad (13)$$

$$\overline{Sc_{D_3}}(D) = \frac{D^2}{(1-D)^2 \cdot \eta_{tot}} \quad (14)$$

$$\overline{Sc_{btot}}(D) = 2 + \frac{D^2 + \sqrt{D}(2-D)}{(1-D)^2} \quad (15)$$

where  $I_{L_{1 \text{ avg}}}$  and  $I_{L_{2 \text{ avg}}}$  are the inductor average currents respectively. The commutated power by diode  $D_3$  is described by  $Sc_{D_3}$ . The total commutated power for the topology presented in Fig. 2 (b) is determined by  $\overline{Sc_{btot}}$ .

Considering that the duty cycle has the same value for all active switches, (10) and (15) can be rewritten as a function of the static gain, as presented by (18) and (19), respectively. These equations were obtained by substituting (17) into (10) and (15). From (5), (8) and (21) one can obtain the commutated power for the single stage converter (basic boost converter), as presented by (20) and (22).

$$Ge = \frac{1}{(1-D)^2} \quad (16)$$

$$D = 1 - \frac{1}{\sqrt{Ge}} \quad (17)$$

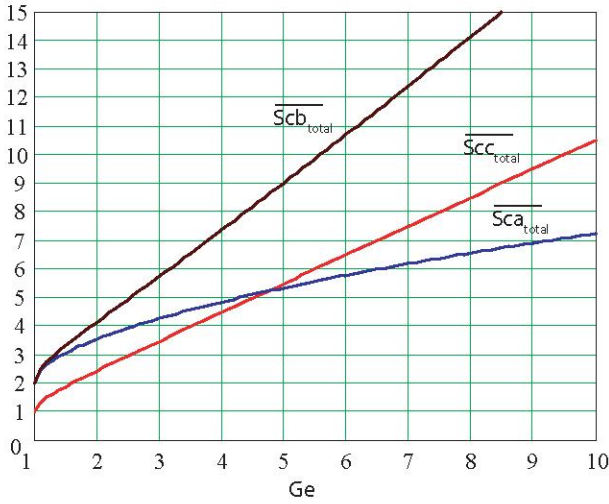


Fig. 3. Total commutated power.

$$Sca_{tot}(Ge) = 2\sqrt{Ge - \sqrt{Ge}} + 2 \quad (18)$$

$$Scb_{tot}(Ge) = 2 + (1 - \sqrt{Ge})^2 + \sqrt{Ge(\sqrt{Ge} + Ge - 1)} - 1 \quad (19)$$

$$Scc_{tot}(Ge) = \frac{\sqrt{D}}{(1-D)} + 1 \quad (20)$$

$$Ge = \frac{1}{1-D} \quad (21)$$

$$Scc_{tot}(Ge) = 1 + \sqrt{Ge^2 - Ge} \quad (22)$$

For an easy comparison, the total commutated power as a function of static gain  $Ge$  of the single stage boost converter (22), cascaded boost converters (18) and the single switch boost converter (19) are presented by Fig. 3, respectively. It is clear that the single switch converter has the higher commutated power. This can be explained by the following reasons. The voltage applied across diode  $D_3$  is the voltage difference between the output voltage and the intermediary voltage while its current is high, because it is related to the input current. But the major problem is related to the active switch, which is submitted to the output voltage and input current  $I_{L1}$  added of current  $I_{L2}$ , making the relation between the total commutated power and the converter's output power higher. As expected, for the basic boost converter the commutated power becomes ideally higher than the two cascaded converters, for static gains higher than 4.72.

By substituting switch  $S_1$  into Fig. 2 (b) by two switches and adding a clamping diode  $D_4$ , the converter presented by Fig. 4 (topology A) can be drawn. The addition of another switch and a clamping diode follows the strategy presented in [8] to obtain three level topologies based on the basic converters (buck, boost and buck-boost). However those topologies do not present the quadratic characteristic. Now, the applied voltage across each switch is lower than the converter output voltage. But the commutated problem still remain because the input current ( $I_{L1}$  current) is being commutated by  $S_2$  and  $S_1$ . Also, there are too many diodes. By changing the connection of diode  $D_3$  to the connection point between  $S_1$  and  $S_2$ , the

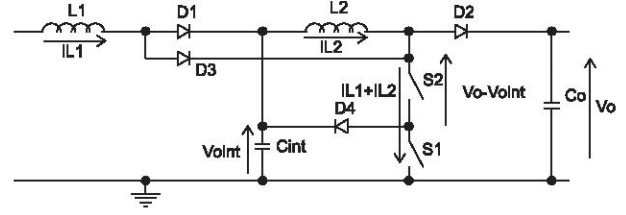


Fig. 4. Three-level quadratic boost converter, reducing the voltage across the switches - topology A.

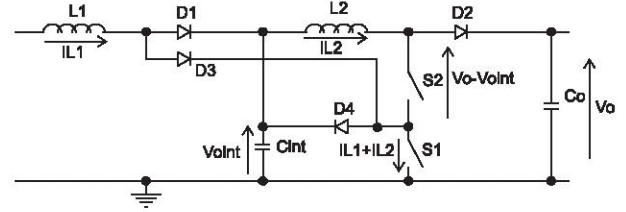


Fig. 5. Three-level quadratic boost converter, reducing the commutated power in  $S_2$  - topology B.

current that circulates in  $S_2$  is reduced. This converter is presented in Fig. 5 (topology B).

Now, for CCM in both inductors, two diodes can be removed from Fig. 5 resulting in the converter presented by Fig. 6 (topology C), which is the main contribution of this paper. The commutated power of this converter is lower than commutated power of the single switch quadratic converter, while keeping the quadratic characteristic. Also, the voltage across switch  $S_2$  is lower than the voltage across switch  $S_2$  of the two cascaded boost converters (Fig. 2 (a)). It means that in terms of voltage, the same switch capability can be used for  $S_1$  and  $S_2$ . The drawback is that the current in switch  $S_1$  is higher than the current in switch  $S_1$  of the two cascaded converters. But the total commutated power is the same, as presented by (26). The advantage of this converter is that two low voltage switches can be used, with low  $R_{DS(on)}$  resistance in case of MOSFET's semiconductors. This converter can also be interesting for input voltages higher than the fuel cell's voltage range or even for use in higher output voltages with IGBTs.

$$\overline{Scd}_{tot}(D) = 2 + \frac{2-D}{1-D} \cdot \frac{\lambda}{\lambda} \cdot \sqrt{D} \cdot \lambda + \frac{\lambda \cdot \sqrt{D^3}}{(1-D)} \quad (23)$$

$$\overline{Scd}_{tot}(D) = 2 + \frac{2\sqrt{D}}{1-D} \quad (24)$$

$$Ge \approx \frac{1}{(1-D)^2} \text{ for } \lambda \rightarrow 1 \quad (25)$$

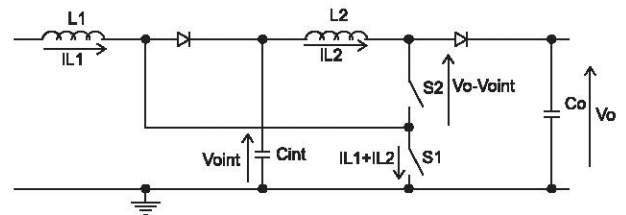


Fig. 6. Three-level quadratic boost converter, reducing the number of diodes - topology C.

$$S_{cd_{tot}}(Ge) = 2\sqrt{Ge - \sqrt{Ge} + 2} = \overline{S_{catot}} \quad (26)$$

### III. OPERATION PRINCIPLES

To explain the operation principles and analyze theoretically the proposed topology, the continuity of the current in both inductors must be taking into account. In this paper only the CCM of operation in both inductors will be considered. Future publications shall deal in detail with different modes of operation.

Another requirement for proper operation is that the conduction time of switch  $S_1$  must be smaller than switch  $S_2$  conduction time. Then the voltage applied to the switch will be lower than the output voltage, clamped by the intermediary voltage  $V_{oint}$ .

A non interesting topological state would occur if switch  $S_1$  is turned-on before switch  $S_2$ . The voltage applied across the switch  $S_2$  would be greater than  $V_{oint}$  and this converter loses its main advantage. The same undesired situation would happen if switch  $S_2$  is turned-off before  $S_1$ .

#### A. Topological states and main waveforms for CCM

A vertically centralized modulation strategy can be used to drive the switches, resulting in two degrees of freedom when controlling the output voltage. I means that there are two duty cycles for control purposes. To make the understanding easier, Fig. 8 shows the main waveforms obtained through simulation for this operation mode. In this figure the modulation scheme can be identified, including the switches' conduction times  $\Delta t_1$  and  $\Delta t_3$ . The voltage across the switches ( $V_{S_1}$  and  $V_{S_2}$ ) are also shown. As one can notice it is a half of the output voltage if  $V_{oint} \approx \frac{V_o}{2}$ .

#### B. Static gain for CCM in both inductors

By inspection of Fig. 8, the static gain of this converter can be obtained, which represents the output voltage variation as a function of the conduction time of each switch. The duty cycle  $D$  is defined as being switch  $S_2$  conduction time  $\Delta t_3$  divided by the switching period  $T$  as presented by (27). As stated before  $S_1$  conduction time  $\Delta t_1$  must be smaller than  $\Delta t_3$ . To respect this restriction, a reduction factor  $\lambda$  is applied as shown by (28). This new variable must be bigger than 0 and smaller than 1.

$$D = \frac{\Delta t_3}{T} \quad (27)$$

$$\Delta t_1 = \Delta t_3 \cdot \lambda \quad (28)$$

In steady state the average voltage across  $L_1$  is equal to zero. Then (29) can be written, where  $V_{oint}$  is the intermediary DC link voltage and  $V_i$  is the input voltage. The static gain between the intermediary DC link and the input voltage is determined by (31). To obtain the static gain for the second step-up voltage stage, the same procedure is taken. Considering steady state operation, the average voltage across  $L_2$  is equal to zero as presented by (32). The partial static gain is given by (34), where  $V_o$  is the output voltage.

By multiplying (31) by (34) the total static gain can be obtained as shown by (35). By applying the limit

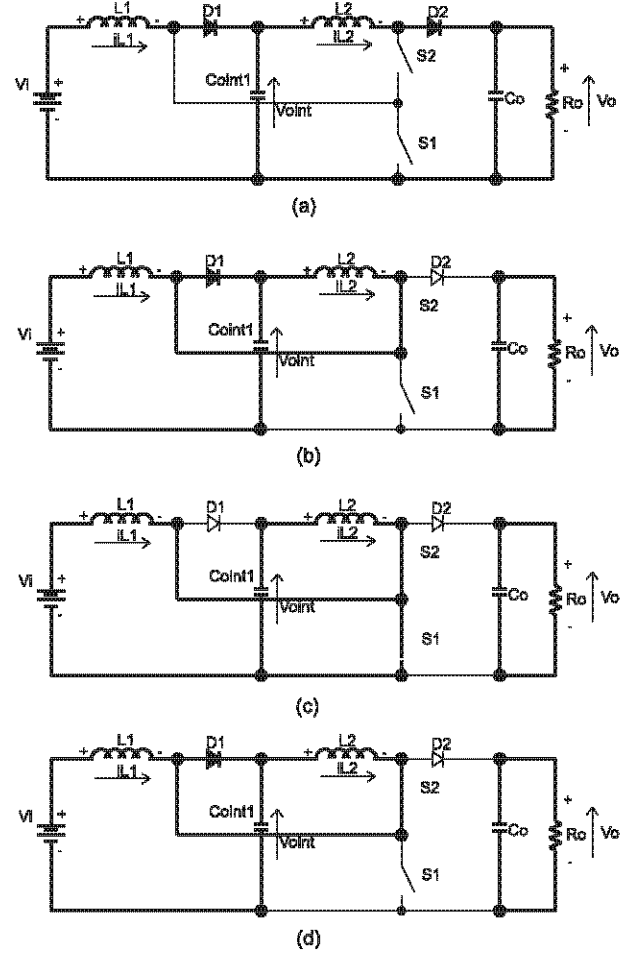


Fig. 7. Topological states of the proposed converter for CCM operation.

function in (35) with  $\lambda \rightarrow 1$ , (36) is obtained demonstrating the quadratic characteristic. That is why it is called here quadratic converter.

$$V_i \cdot \Delta t_3 \cdot \lambda = (V_{oint} - V_i) \cdot (T - \Delta t_3 + \Delta t_3 - \Delta t_1) \quad (29)$$

$$V_i(D \cdot \lambda) = (V_{oint} - V_i)(1 - D \cdot \lambda) \quad (30)$$

$$\frac{V_{oint}}{V_i} = \frac{1}{1 - D \cdot \lambda} \quad (31)$$

$$V_{oint} \cdot \Delta t_1 = (V_o - V_{oint}) \cdot (T - \Delta t_3) \quad (32)$$

$$V_{oint} \cdot D \cdot \lambda = (V_o - V_{oint}) \cdot (1 - D) \quad (33)$$

$$\frac{V_o}{V_{oint}} = \frac{D(\lambda - 1) + 1}{1 - D} \quad (34)$$

$$G_{tot_{ccm}} = \frac{V_{oint}}{V_i} \cdot \frac{V_o}{V_{oint}} = \frac{D(\lambda - 1) + 1}{(D \cdot \lambda - 1)(D - 1)} \quad (35)$$

$$\lim_{\lambda \rightarrow 1} (G_{tot_{ccm}}) = \frac{1}{(1 - D)^2} \quad (36)$$

It is interesting to notice in (31) and (34) that the static gains  $\frac{V_{oint}}{V_i}$  and  $\frac{V_o}{V_{oint}}$  are dependent of the conduction time of both switches differently of what happens when using cascaded boost converters. In other words, the output voltage is not only affected by the intermediary voltage and switch  $S_2$  duty cycle but also by switch  $S_1$  conduction time. The influence of  $S_1$  in the output voltage can be clearly visualized in the third topological state of Fig. 7. This fact shows the importance of obtaining models to control the respective converter, analysing what happens

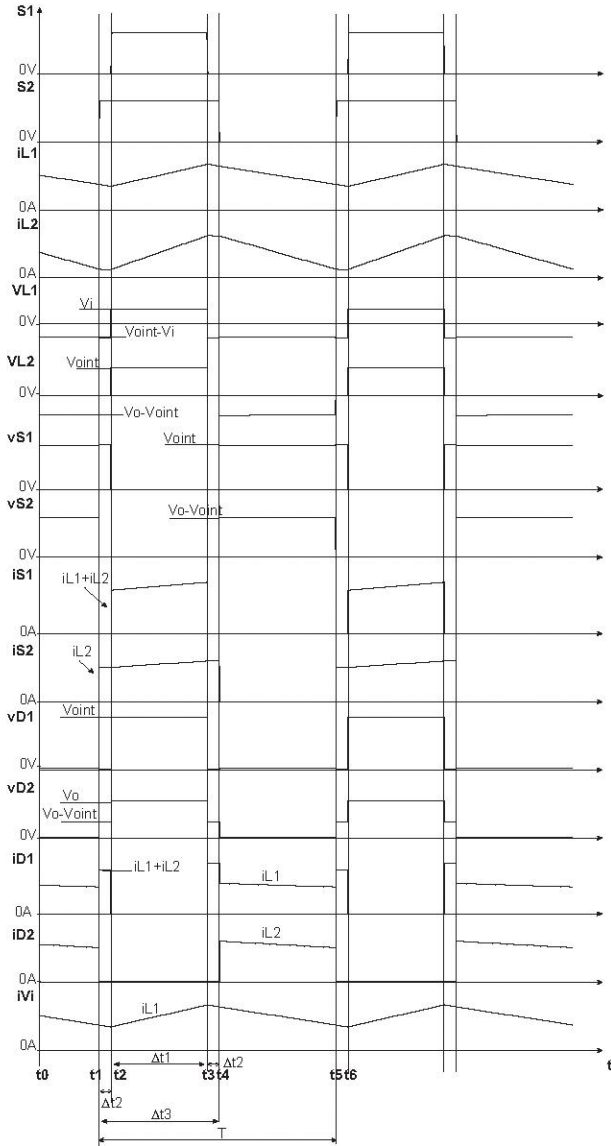


Fig. 8. Mainly waveforms for CCM operation in both inductors.

with the right-half-plane (RHP) zero that appears in the conventional boost converter. But this subject is out of the scope of this publication.

The total static gain as a function of the duty cycle with  $\lambda$  as a parameter is presented by Fig. 9. The same static gain is being presented by Fig. 10, but as a function of  $\lambda$  and with  $D$  as parameter. From both figures one can see that variations of the output voltage are less impacted by  $\lambda$  than by  $D$ .

#### IV. SIMULATION RESULTS

The Quadratic Three-Level (QTL) converter, the single switch boost converter and the two cascaded converters were simulated to investigate their devices stress. A summary of these results is presented on Table I, where Top1 is the proposed topology, Top2 is the two-cascaded converter and Top3 the single switch boost converter. One can see that the relation between the output power and the commutated power is worst for the single switch boost converter. The average current in  $S_1$  is higher for the

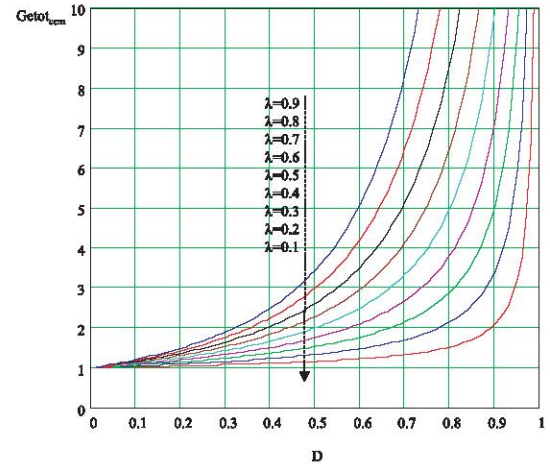


Fig. 9. CCM static gain as a function of  $D$  with  $\lambda$  as parameter.

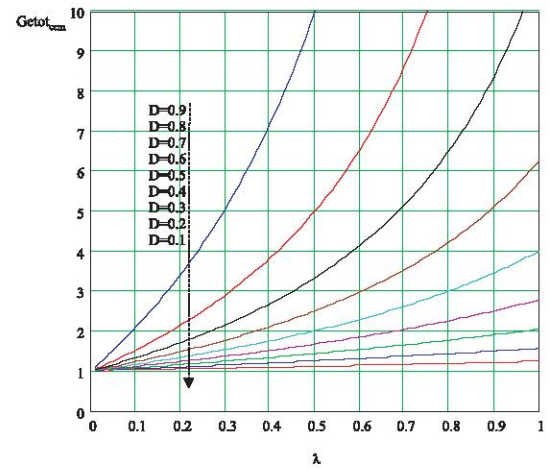


Fig. 10. CCM static gain as a function of  $\lambda$  with  $D$  as parameter.

TABLE I  
CONVERTERS' SIMULATION RESULTS. TOP1: PROPOSED CONVERTER (QTL); TOP2: TWO CASCADED BOOSTS; TOP3: SINGLE SWITCH QUADRATIC BOOST CONVERTER.

| Esforços/Topologia | Top1    | Top2     | Top3     |
|--------------------|---------|----------|----------|
| $IS1_{avg}$        | 15,18 A | 10,267 A | 15,28 A  |
| $IS2_{avg}$        | 5 A     | 5 A      | -        |
| $IS1_{rms}$        | 21,3 A  | 14,4 A   | 21,37 A  |
| $IS2_{rms}$        | 7,02 A  | 7,03 A   | -        |
| $VS1$              | 48,8 V  | 48,8 V   | 96,62 V  |
| $VS2$              | 48,8 V  | 97,8 V   | 96,62 V  |
| $ID1_{avg}$        | 9,8 A   | 9,8 A    | 9,8 A    |
| $ID2_{avg}$        | 4,82 A  | 4,82 A   | 4,82 A   |
| $ID3_{avg}$        | -       | -        | 10,257 A |
| $VD1$              | 48 V    | 48 V     | 48 V     |
| $VD2$              | 96 V    | 96 V     | 96 V     |
| $VD3$              | -       | -        | 48 V     |
| $S_{ctot}/Po$      | 4,63    | 4,63     | 6,98 V   |

In Fig. 11 simulation results for the QTL converter are showed. The output power is 500W, the input voltage is 25V, the intermediary voltage was set to 50V and the output voltage is 100V. Switching frequencies of both modulators are equal to 50 kHz. The chosen duty cycle was 0.55 and

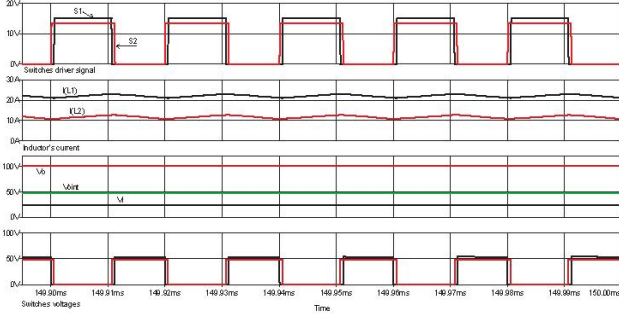


Fig. 11. QTL Simulation results operating in CCM.

parameter  $\lambda$  was set to 0.9.

It is important to mention that the voltages across the switches are perfectly clamped when considering this ideal circuit, so the concept of being a three-level converter is validated.

## V. EXPERIMENTAL RESULTS

The proposed converter has been implemented to validate its principle of operation for 25V input voltage and 100V output voltage. The maximum output power is 450W and the chosen switching frequency is 50 kHz. The value of  $\lambda$  is constant and near 0.9. This converter was implemented with the following semiconductors: two IRFB4710, MUR1520 and MUR820.

In Fig. 12 are presented the input current and the input voltage. Since the converter is operating in CCM, the ripple current is very small, what is interesting for fuel cell applications. If less ripple is required by the application, the input inductance could be increased, a capacitor could be added to the input (operating as a filter by considering the fuel cell impedance) or interleaved converters could be used. The output voltage and output current are being presented by Fig. 13. Note that the output voltage is around 100V.

The switches' voltages are being presented by Fig. 14. In this figure one can see that none of the switches are being submitted to the highest converter voltage, which is 100V. During the turn off commutation, an overvoltage occurs, which is justified by the utilization of a non appropriate layout design for this converter. After the turn-off transient it is possible to see that the switch's voltages are clamped, validating the proposal of this work.

### A. Efficiency

To compare the efficiency between the two cascaded converters and the proposed converter, both were tested at the same conditions. But the MOSFET of the second stage of the cascaded converter was substituted by a IREFP260N because of voltage requirements. The efficiency results are presented by Fig. 15, including its approximation by second order polynomial regression. Close to the nominal power the total efficiency is near 90 %. Some loss of energy occurred due to the use of shunt resistors (0.01 $\Omega$ ) used to measure the two inductors' current ( $\approx 0.96\%$ ). No efforts were done to improve the efficiency by using snubber or commutation techniques, since the applied

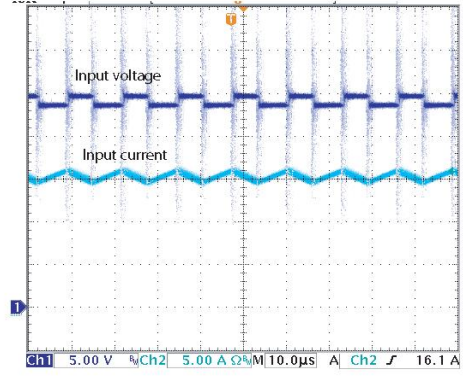


Fig. 12. Converter's input voltage (5V/div) and current (5A/div).

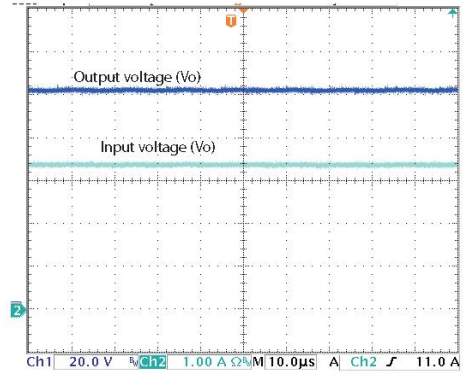


Fig. 13. Converter's output voltage (20V/div) and current (1A/div).

voltage is not so high. The efficiency of this converter, when compared with the two boost cascaded converters, is lightly higher. These results were obtained by using the same pcb and the same components, except switch for  $S_2$ . Also, the installed semiconductor power of the two cascaded boost converter was 1000VA, while the installed semiconductor power of the proposed converter was 750VA. I.e., for the same installed semiconductor power, the efficiency of the proposed converter could be even higher.

## VI. CONCLUSION

The integration of two boost cascaded converters is presented in this paper originating a new quadratic three-level

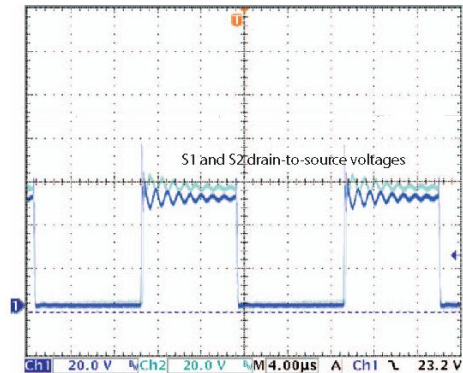


Fig. 14.  $S_1$  and  $S_2$  voltages, switching at 50kHz and 485W.

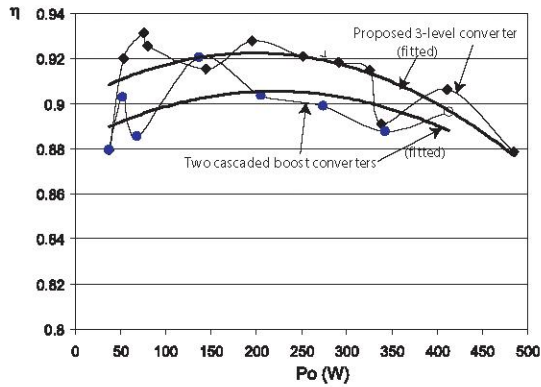


Fig. 15. Converter's efficiency comparison.

converter. The main advantage of the proposed topology, when compared with the single switch quadratic boost converter, is that the total installed semiconductor power is lower. When comparing the presented topology with two cascaded boost converters, the voltage across the switch  $S_2$  is lower in the proposed converter, while the current in switch  $S_1$  is higher, keeping the same semiconductor installed power.

The presented converter can be interesting for applications where a high voltage ratio is necessary, what can be the case of fuel cell applications, but only when transformer isolation is not required. This converter can be also interesting for higher power and higher output voltage. Next publications shall deal with the buck and buck-boost converters based on the same commutation cell, discontinuous conduction mode of operation and

modelling issues.

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