State-of-the-Art of DC-DC Converters for Fuel Cell Vehicles

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***Abstract*—In the last few years, fuel cells have gained more interest as a clean source of energy. Fuel cells are current intensive sources, they produce electricity directly from hydrogen and oxygen at low voltage. In fuel cells vehicles (FCV), the main DC-DC converter between the FC and DC bus is a key issue. This converter should be designed and operated with high voltage ratio, high efficiency and high compactness keeping low cost. The purpose of this paper is to present the different topologies of DC-DC converters isolated and nonisolated suitable for FCV, their advantages and disadvantages. Finally the paper gives some guidelines to help the designer to choose among the most suitable converter topologies in term of compactness, efficiency and cost.**

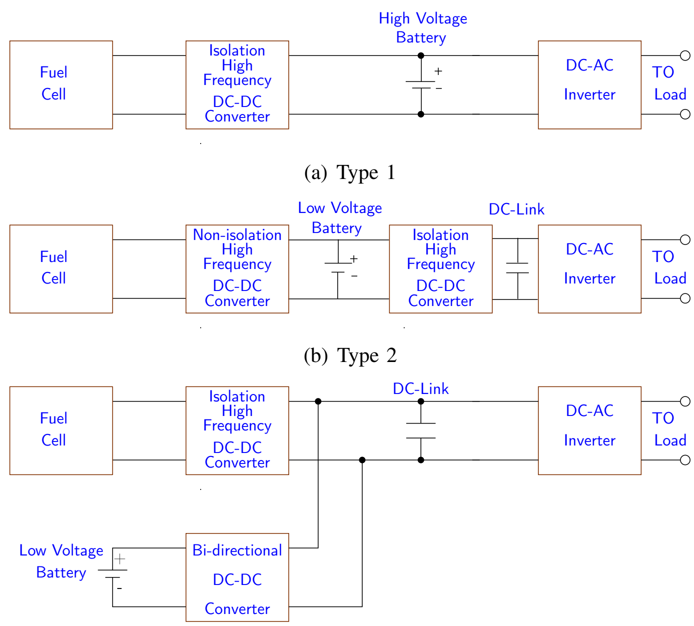
I. Introduction

Fuel cell systems are current intensive sources, so that their output voltage must be increased to approximately a few hundred volts to be suitable for vehicles powertrains. This is performed by a DC-DC converter. In addition, in a system, peaking power sources (PPS), such as batteries and super capacitors are needed for the power peans or to recover energy during braking phases. In this case, a bidirectional DC-DC converter is necessary to manage the PPS. Although there are several combinations of DC-DC converters, bidirectional DC-DC converters and DC-AC inverters, they can be grouped into three categories, as shown in Figure 1 [1]–[3].

The PPS can be connected in parallel to the DC-bus capacitor through bidirectional converter for maximum fuel cell utilization and a better batteries power management. However, using a bidirectional DC-DC converter leads to an increase of the system cost and overall, it decreases the system efficiency. Finally, depending on the applications, a good configuration of these three types can be choosen. The purpose of this paper is to present the different topologies of DC-DC converters isolated and nonisolated suitable for FCV, their advantages and disadvantages. Finally the paper gives some guidelines to help the designer to choose among the most suitable topologies in term of compactness, efficiency and cost.

II. DC-DC power converters

DC-DC converters are used in several applications including power supplies for personal computers, office equipment, telecommunications equipment, laptops and DC motor drives [4]. In terms of power conversion, the above mentioned power converters play an important role in power systems



(a) Type 1

(b) Type 2

(c) Type 3

Figure 1. Basic configurations of PCS for FC

using a fuel cell. The input of these converters is an unregulated DC voltage, the output is a regulated DC voltage having a magnitude (and possibly polarity) differing from the input voltage. The main characteristics required by these converters are [5]:

1) High efficiency;
2) High power density;
3) Small size and low weight;
4) Electric isolation to prevent electric leakage and/or electric shock;
5) Low electromagnetic interference (EMI);
6) Reduced ripple current to avoid damaging of fuel cell for example;
7) Low cost;
8) If possible, soft switching to reduce the volume of passive associated components.

Many topologies of DC-DC converter are suitable.they can increase or decrease the magnitude of DC voltage and/or invert its polarity [6]–[8]. These topologies are divided into two categories isolated and nonisoltated.

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A. Nonisolated DC-DC Converters

Figure 2 shows several nonisolated topologies of DC-DC commonly used converters. The first topology is the buck converter, its output voltage is smaller than its input voltage. Its conversion ratio is:

$$M(D) = D \tag{1}$$

where D is the duty cycle. In a similar topology known as the boost converter, the position of the switch and the inductor is interchangeable. The converter produces an output voltage bigger than its input voltage, its conversion ratio is:

$$M(D) = \frac{1}{1-D} \tag{2}$$

The third converter is the buck-boost converter that inverts the polarity of the input voltage, it can increase or decrease the output volatage, it depends on the value of D. The conversion ratio is:

$$M(D) = \frac{-D}{1-D} \tag{3}$$

The Cuk converter, contains an inductor in series with the input and the output, its conversion ratio is identical to that of buck-boost converter. It inverts also the polarity of the input voltage and can increase or decrease its input voltage in according to the value of the duty cycle.

The voltage of a fuel cell is normaly a low quite and it must be boosted to achieve several hundreds of volts on the DC-bus. To this end, boost DC-DC converters are needed. Among the most important required characteristics is the current ripples reduction to avoid a lifetime reduction of the fuel cell. The following equation gives current ripples of basic DC-DC boost converter [9]:

$$\Delta I = \frac{V_i \cdot D}{2 \cdot f \cdot L} \tag{4}$$

where V_i is the input voltage, D the duty cycle, f the switching frequency and L the inductance value.

From this equation it can be seen that small current ripples requier large value inductance, and consequently a large inductor volume, making the total volume of the conventional boost converter quite large. Another parameter that plays an important role in the current ripples is the switching frequency. However, it cannot increased because the switching losses which are propotional with the switching frequency have to be minimized. The advantages and the drawbacks of basic boost converters are presented in the Table I.

Advantages	Drawbacks
Simple converter	Low efficiency for high conversion ratio
Low cost	Low voltage-gain
Simple control	Volume of passive components (low compactness)

Table I
ADVANTAGES AND DRAWBACKS OF BASIC BOOST CONVERTERS

To improve voltage gain, compactness, and efficiency of basic boost converter, several topologies based on the basic

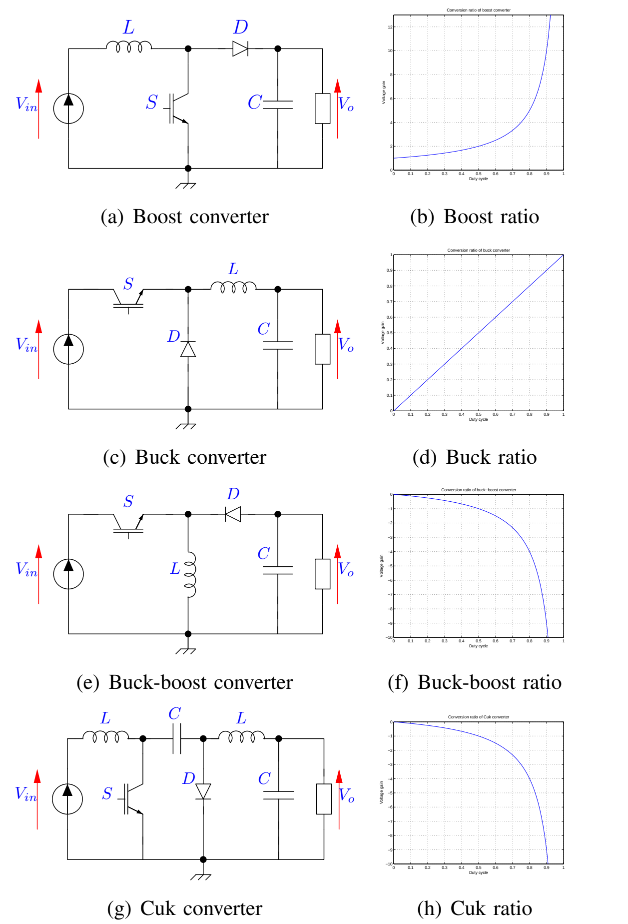
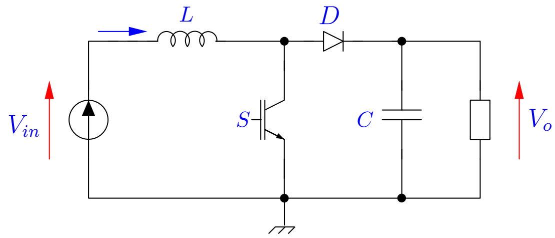


Figure 2. Basic nonisolated DC-DC converters and their conversion ratio

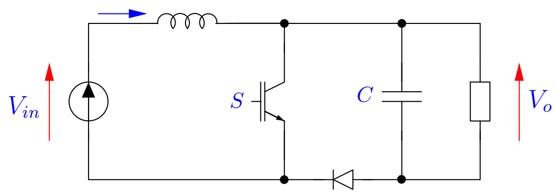
configurations of it are proposed. Figure 3 shows the basic configurations of conventional boost converter.

When the converter connexions are explored to achieve high conversion ratio, floating topologies have many apportunities. The topologies based on the topology of the basic boost converter shown in Figure 3 have several advantages, including inteleaving and higher voltage-gain of the entire converter. On the other hand, the concept of interleaving at the input provides an improved performance agiannst high curren ripples flowing from the source (fuel cell) [10], [11]. To this end, these topologies are found to be suitable for fuel cell applications. The first topology is the floating-dual-boost converter (FDB), the floating and non-floating version are powered from the same source resulting a floating converter as shown Figure 4.

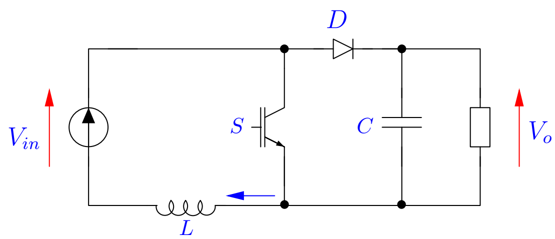
The concept of interleaving is guaranteed by the parallel connection of the floating and non-floating version at the input and by the phase shifted control of the two switches ($S1$,$S2$). Many different topologies can be derived from the converter FDB. Figure 5 and Figure 6 present two topologies [9], the first converter is floating double-interleaved dual boost (FDIDB), and the second is floating double boost double stage boost (FDBDSB). The series connection of the floating and non-floating version at the output allows a high voltage-gain, and



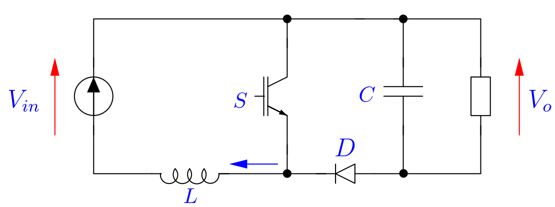
(a) Non-floating boost



(b) Floating boost (FB) and inductor placed on the positive rail



(c) Floating boost (FB) and inductor placed on the negative rail



(d) Floating boost (FB) and inductor placed on the negative rail

Figure 3. Basic boost converters

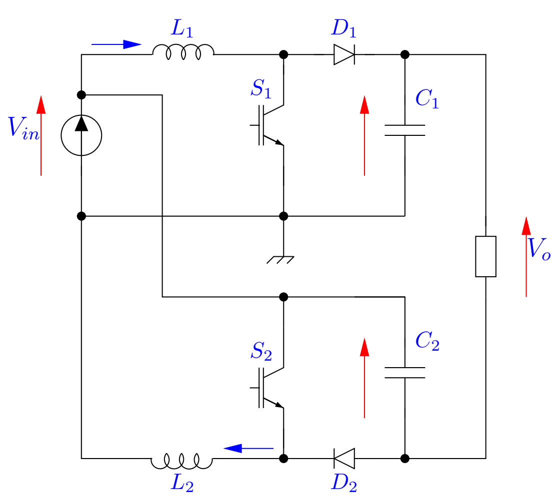


Figure 4. Floating dual boost converter (FDB)

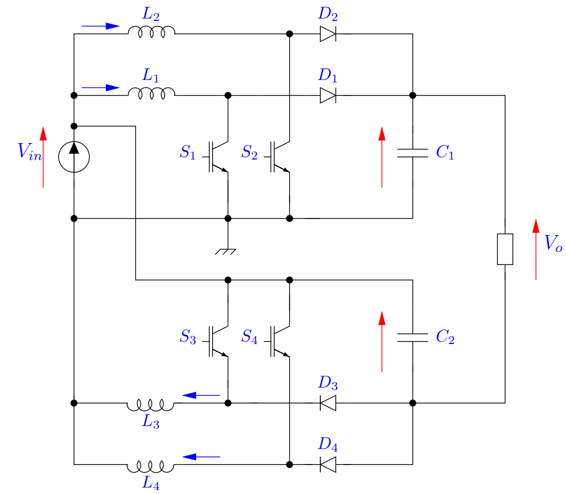


Figure 5. Floating double-interleaved dual boost converter (FDIDB)

reduced output voltage ripple. The voltage-gain of the FDIDB topology is:

$$\frac{V_o}{V_{in}} = \frac{1+D}{1-D} \tag{5}$$

where D is the duty cycle of all switches.

For the FDBDSB topology the voltage-gain is:

$$\frac{V_o}{V_{in}} = \frac{2}{(1-D_1)\cdot(1-D_2)} - 1 \tag{6}$$

where D_1,D_2 are the duty cycle of the first and second stage respectively.

Both topologies use the concept of interleaving, which reduces the rippl of the input current, and consequently the volume of associated inductors. The advantage of the FDIDB topology over the FDBDSB topology is that the current through the inductor of floating and non-floating version is the input current divided by four. This means that there is less voltage drop on the resistance of the inductors, and therefore a higher efficiency. It is possible to improve the efficiency of the FDBDSB topology by using the concept of interleaving for the first stage, but it increases the number of components, and therefore increase the cost and complexity of the entire topology.

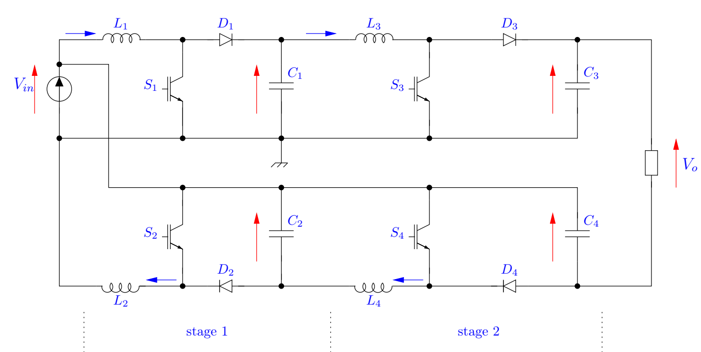


Figure 6. Floating double boost double stage boost converter (FDBDSB)

For high power applications, a single converter requires several devices in parallel to handle high currents. To this end, it is desirable to have several phases to reduce either voltage or current stress, and thus better efficiency. Figure 7 shows a DC-DC bi-directional converter [12], [13]. Three independent inductors and three legs of switches can be controlled with 120 degree phase shift from each other. The current ripples total after interleaving will be minimized.

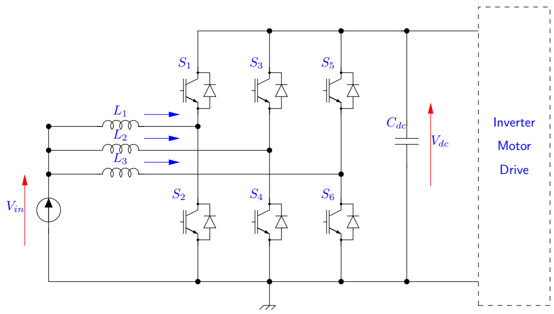


Figure 7. Three-phase bi-dirctional DC-DC converter

With the concept of interleaving total current ripples are sufficiently low to allow a significant reduction in the volume of passive components, and as the volume of the converter is determined by the volume of passive components, there will be a significant reduction in the volume converter, and consequently higher compactness. The relationship between the volume of the inductor and the number of phases is given in the following equation [14]:

$$\text{InductorVolume}_{\text{total}} = \left(\frac{I}{N}\right)^2 \cdot L \cdot N \qquad (7)$$

where I is the current throught the inductor, N the number of phases and L the inductance value.
From this equation, the volume of the inductor is found to be reduced by a factor of $1/N$.

B. Isolated DC-DC Converter

In most applications it is desired to use a transformer into the converter, to obtain DC isolation between the converter input and output. On the other hand, the volume and weight of a transformer vary inversely with the operating frequency, and therefore the use of a transformer into the converter can provide significant improvements. Since the transformer operates at the converter switching frequency of tens or hundreds of kilohertz. These high frequencies lead to dramatic reductions in transformer size. When a large step-up or step-down conversion ratio is required, the use of a transformer can allow better converter optimization. By an appropriate choice of the transformer turns ratio, the current or voltage stresses imposed on the transistors and diodes can be minimized, leading to an improved efficiency and lower cost.

There are many kind of circuit configurations for isolated DC-DC converters. Figure 8 [15] shows two basic configurations of isolated DC-DC converter. The inductor that serves as a current source can be placed on both low or high voltage sides. Placing the inductor at the low voltage side requires a large current carrying magnetic component. Placing the inductor at the high voltage side, requires high voltage semi-conductor device because the voltage stress on the semiconductor is the voltage drop across the inductor plus the high voltage side. It is also possible to embed the inductor in the leakage inductor of the transformer.

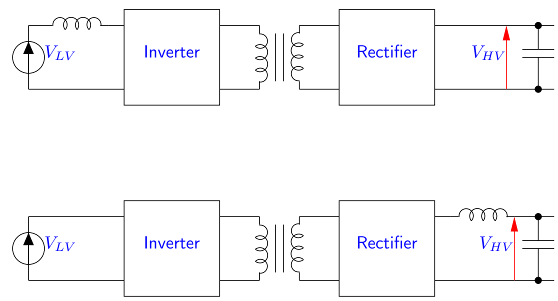


Figure 8. Basic isolated DC-DC converter configurations

Each inverter may be a voltage source converter that has a capacitor in parallel on the DC bus, or a current source converter that has an inductor in series on the DC bus. In practical applications, the topologies of voltage source and current source are combined for high efficiency and high performance [1]. Figure 9 shows the first topology of nonisolated DC-DC converter known as the full-bridge converter.

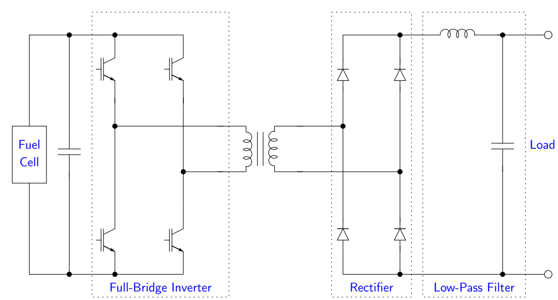


Figure 9. Isolated full-bridge converter

The main advantages of this topology are the following:

1) The most popular circuit for high power applications;
2) Reasonable device voltage ratings;

On the other side, this converter has the following drawbacks:

1) High conduction losses;
2) High number of components;
3) Current mode control is requiered to avoid the transformer saturation;
4) Low efficiency;

To reduce the conduction losses, Figure 10 presents another topology derived from the previous topology known as the series-resonant full-bridge converter. The main advantage of this converter over the previous converter is that, there is no transformer saturation problem. On the other hand, the switching frequency can be increased. The volume of the passive associated components to be reduced.

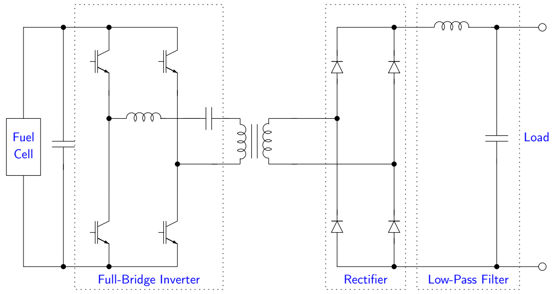


Figure 10. Isolated series-resonant full-bridge converter

To reduce the number of components, Figure 11 presents another topology known as the half-bridge converter. This converter has low voltage device compared to the previous topology. The main drawbacks of this converter is that, the device handles twice the current compared to the previous topology. In addition, there is an unbalance problem due to split capacitors.

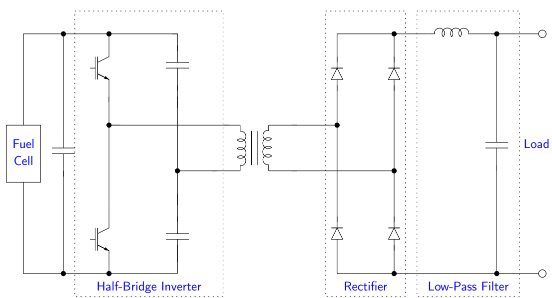


Figure 11. Isolated half-bridge converter

One of the topology suitable for the fuel cell applications is the push-pull converter given in Figure 12. This converter is suitable for low-voltage low-power applications. Its main drawback is that the device handles twice the input voltage. To this end, a high voltage device (MOSFET or IGBT) is needed. In this case, there will be high conduction losses due to high conduction voltage drop, and consequently, low efficiency. Another drawback is the center-tapped transformer, because it is difficult to make low-voltage high-current terminations.

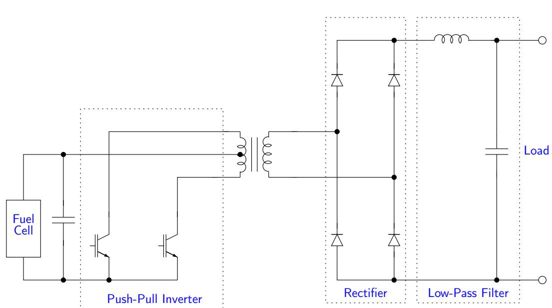


Figure 12. Isolated push-pull converter

To reduce the voltage and current ripples, passive components (inductors and capacitors) are requiered. The volume of these components is a big challenge. To decrease this volume and at the same time to keep the current and voltage ripples as small as possible (to increase the lifetime of the fuel cell), the concept of using multiple phases in parallel is recommended. Figure 13 shows the most advantageous topology for high-power converters with current intensive sources. This converter is known as the V_6 converter [16]. The advantages of this topology are the following:

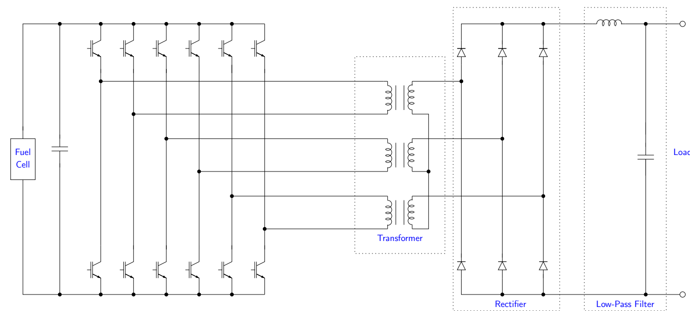


Figure 13. Isolated V_6 converter

1) The connexion Δ/Y doubles the ouput voltage without increasing transformer's turns-ratio, that allows reduction of the associated leakage inductance;
2) Reducing of the root mean square (RMS) current per phase, thus reducing the I^2R conduction losses;
3) Elimination of the DC link inductor current ripples, therby reducing its size and cost;
4) Secondary voltage overshoot reduction, thus cost and size reduction with elimination of voltage clamping circuit;
5) Significant EMI reduction, allowing the EMI filter cost to be reduced;
6) Soft switching over a wide load range;
7) High efficiency;
8) Input side high-frequency current ripples elimination, consequently cost and size reduction of high-frequency capacitor;

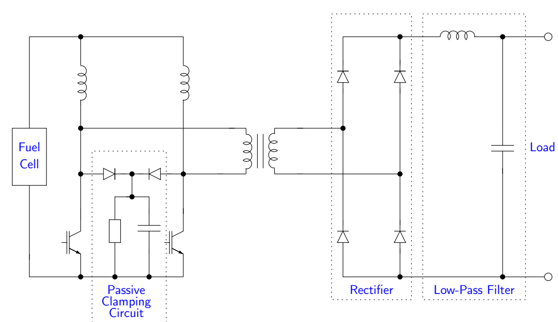


Figure 14. Isolated L-type converter

The second group of isolated DC-DC converters is current source converters that have an inductor in series with the DC bus. Figure 14 shows current source L-type converter [15]. Its main advantage is the volume inductor reduction as well as the possibility to eliminate the current ripples. To reduce the device voltage stress due to the discharge of inductors in the switches during the commutation, the use of passive clamping circuit is unavoidable. This increases the complexity as well as additional losses. On the other hand the design of the converter shows that the volume of the inductor remains dominant and the converter's efficiency is not satisfactory [17], [18]. To reduce the number of inductors, Figure 15 shows another topology known as the full-bridge current source converter. Like as the previous converter, the use of voltage clamping is also requiered to avoid excessive voltage stress across the switches during the commutation. Otherwise, the previous converter, the voltage clamping is an active clamping circuit.

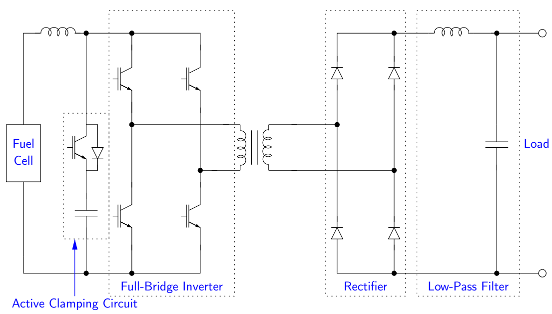


Figure 15. Isolated full-bridge current source converter

III. HOW TO CHOOSE THE RIGHT TOPOLOGY FOR A GIVEN APPLICATION?

To make a choice of a topology among the topologies previously presented, the criteria described in this article have to be considered. On the other side, for a given application, the choice will be guided by the criteria of particular application. In our case, the application is an electric vehicle using a fuel cell system. To this end, the topology must be able to operate with a low voltage-high current source with high voltage and current ripples. Moreover, in an electric vehicle, volume, weight and cost of the converter are very important criteria. Indeed, it is a big challenge to design a converter with high efficiency, high performance, high compactness and low cost. Considering this challenge, we will choose the topology according to some criteria that are given in Table II.

Criteria	**Topology**
Volume and cost	Isolated full-bridge and push-pull converter
Reduced current ripple	Floating double-interleaved dual boost (FDIDB) and floating double boost double stage boost (FDBDSB) converter
High efficiency and reduced current ripple	Isolated V_6 converter

Table II
CRITERIA AND CORRESPONDING TOPOLOGY

IV. CONCLUSION

In this paper different topologies of isolated and nonisolated DC-DC converters suitable for fuel cell applications have been presented. Their advantages and drawbacks have been given. The different criteria and their associated topologies have been also presented. Finally this paper gives somes guidelines to help the designer to choose the suitable converter topologies in terms of compactness, efficiency and cost for a particular application.

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