Buck-Boost DC-DC Converters for Fuel Cell Applications

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The use of fuel cells in DC microgrids has been receiving a lot of attention from researchers and industry since both technologies can deliver clean energy with little to no environmental impact. To effectively integrate fuel cells in DC microgrids, a power converter that can equate the fuel cell's voltage with the DC microgrid's reference voltage is required. Based on the typical output voltages of fuel cells, buck-boost topologies are commonly used in this type of application. This work compiles, compares and describes different DC-DC buck-boost topologies that have been introduced in the literature over the past few years.

fuel cell | DC microgrids | buck/boost converters | Ćuk-based converters | quadratic converters | fault-tolerant converters | efficiency

1. Introduction

The European Union has set an ambitious goal for 2050: aiming to become a carbon-neutral society, with a more competitive economy, whose growth is fully dissociated from resource use. Working towards this goal will inevitably change the EU's societal paradigm into a fairer and more prosperous one [1]. The short-term goal, set for 2030, is to reduce greenhouse gas emissions (GGE) by at least 55% [1]. Producing energy through renewable sources is envisioned as a promising way to accomplish this goal. Therefore, support for the adoption of renewable energy technologies is expected to grow exponentially [1].

Connecting different renewable energy sources on a single AC grid poses many technical and functional challenges since each source has a different voltage profile and requires different energy conversion stages [2]. A possible way to solve this issue is to use a microgrid, which is smaller, more efficient, and more reliable than a conventional AC grid [2]. This grid operates at a lower DC voltage level than the traditional AC grid and can easily incorporate various renewable sources, such as photovoltaic (PV) systems, wind turbines or fuel cells (FCs), as well as different energy storage systems, such as batteries, supercapacitors, flywheels and hydrogen storage systems [2]. Furthermore, DC microgrids can either work independently of the main grid, in is-landed mode or connected to it, in grid-connected mode [2].

Nowadays, DC microgrid applications mostly rely on PV technologies. Nevertheless, the use of FCs in microgrids has been studied and researched thoroughly by industry and scholars alike [2]. Unlike other renewable sources, FCs do not depend on external factors such as the wind or the sun. FCs also have a substantially higher power/volume ratio than other renewable sources [3].

Figure 1 depicts an example of a DC microgrid which integrates renewable energy generation supported through FCs, PV panels, and wind turbines.

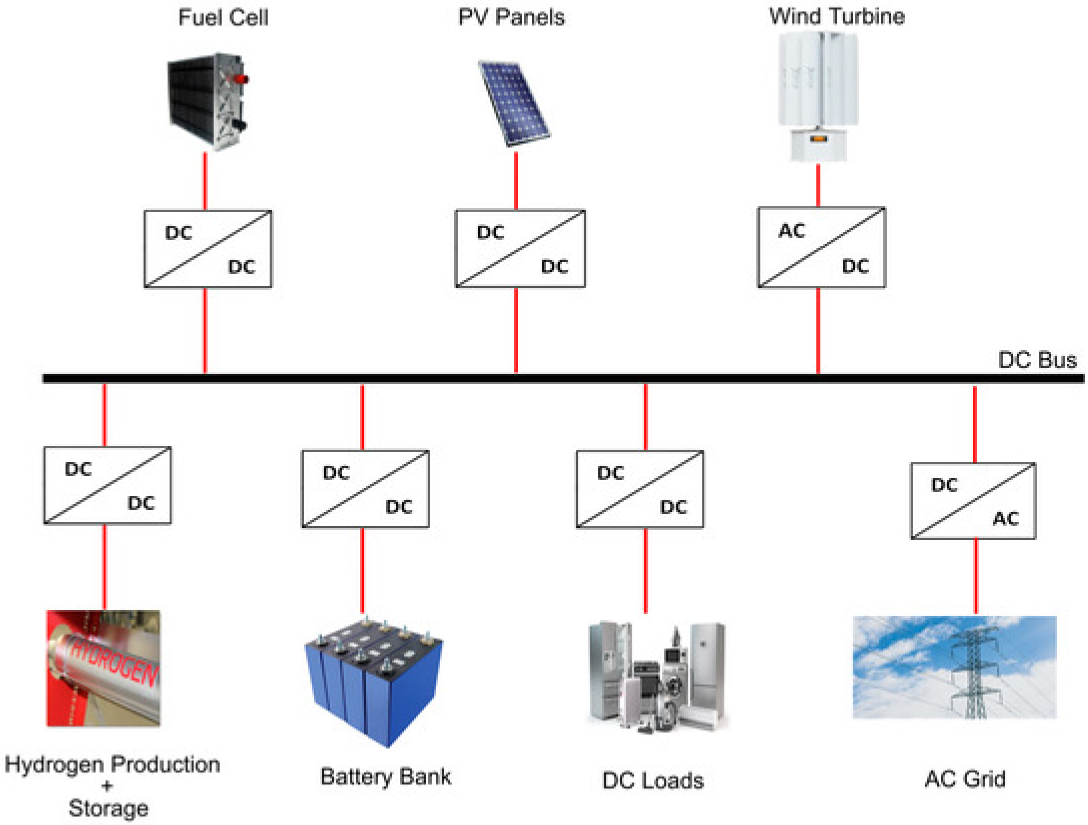


Figure 1. Example of a DC microgrid's structure.

The safe and efficient connection of the voltage characteristic of the FC and the reference voltage of its application requires the integration of power electronic converters between the FC and the DC microgrid. Different nominal voltages have been provided by FC manufacturers over the past years, with manufacturers aiming to offer even higher voltage levels as the technology progresses [4]. Therefore, when designing a power converter for FC applications in DC microgrids, buck-boost topologies, which can provide lower, equal or higher output voltage levels, are necessary [4]. Buck-boost topologies enable three distinctive operation modes in a single converter: the buck-mode, which happens when the input voltage is higher than the output voltage; the boost-mode, also known as the set-up mode, which occurs when the output voltage is higher than the input voltage; and the third mode, which happens when the input voltage is very similar to the output voltage, hence referred to as the buck-boost mode. Over the years, FCs were mostly employed on electric vehicles. As a result, there is a variety of work concerning FC systems applied to e-mobility solutions [5],[6],[7],[8],[9],[10]. On the other hand, there is a lack of research concerning buck-boost topologies for FC applications in DC microgrids.

Despite all of the benefits associated with adopting power converters, their switching nature introduces ripple, which might affect the FC performance, and thus, the system's efficiency [11]. The ripple is mostly noted on the current, generating unwanted effects, such as fuel waste and higher losses, low reactant concentration, accelerated electrode ageing and decreased FC durability [4],[11].

2. Coupling Behavior between FCs and DC-DC Converters

The interaction between buck, boost, and buck-boost converters and FCs were analysed in [11]. The root causes of oscillations in the current and voltage of the FCs and possible mitigation solutions are presented [11]. For the boost converter, the analysis was performed under three different scenarios. All scenarios started with the same load resistance. The first scenario kept the load resistance constant; for scenario number two, a load step was performed, with the resistance being reduced; as for scenario number three, a load step was introduced, with the resistance being increased [11]. Both scenarios one and two showed no significant impact on the oscillation of the FC output. In turn, and due to the low FC output current for scenario three, the same voltage oscillation can no longer be neglected [11]. Therefore, for low current densities on the FC, the boost converter negatively affects the voltage oscillation [11]. The occurrence of these phenomena can be reduced if a capacitor is introduced in between the FC and the boost converter or if the converter switching frequency is increased. This latter option increases the switching losses on the converter [11]. To evaluate the buck converter, two scenarios were considered. For the first scenario, the FC was operated close to the maximum point with a constant duty cycle equal to one [11]. In the second scenario, a load step was introduced such that the FC could operate at a lower power rating [11]. The results showed that for scenario one, no oscillation in the FC voltage was observed since the converter switch was always on, while for scenario two, large oscillations in both FC current and voltage were observed [18].11 Such large oscillations increase fuel consumption and FC temperature. These consequences were not considered in this study. The oscillations can be mitigated if the converter switching frequency is increased or if the FC CDL is increased [11]. This latter technique is implemented by introducing a large capacitor in between the FC and the converter [11].

The coupling behaviour between the FC and the buck converter can be used to estimate the FC parameters, such as the exchange current and the transfer coefficient, by measuring the average inductor current and the amplitude of the FC voltage oscillation. These variables are then considered as inputs for a mathematical model, derived in [11]. Finally, the coupling behaviour between the FC and the buck-boost converter was analysed. The results showed that, due to the presence of a switch in series with the FC output, the buck-boost converter also introduces large oscillations in the FC variables [11].

The literature shows that the current ripple can have a negative effect on the efficiency and overall lifetime of the FC [12]. Therefore, it is necessary to choose a power converter topology capable of eliminating such negative effects by limiting the converter input current ripple, the cost and the number of components, while preserving high efficiency. The next section describes different buck-boost topologies that are suitable for FC applications in DC microgrids, with a focus on the main merits and demerits of each one.

3. Buck-Boost Topologies

The previous section presented the coupling behaviour between the three most basic DC-DC power converter topologies. As mentioned, the buck-boost topology introduces large oscillations in FC voltage and current that ultimately lead to fuel waste and decrease efficiency. It has a very reduced number of components, and the output voltage polarity opposes the input one [13],[14]. To solve the oscillation problem, a plethora of different buck-boost topologies have been proposed over the past few years. Although these topologies can be categorised according to the number of power switches, some authors also categorise buck-boost converters as current- or voltage-source converters.

A continuous input-current buck-boost (CIbB) DC-DC converter for proton-exchange membrane (PEM) FC applications, which is based on the conventional single-switch buck-boost converter, was introduced in [4]. The converter possesses a capacitor connected between the positive terminal of the input voltage source and the negative terminal of the load [4].

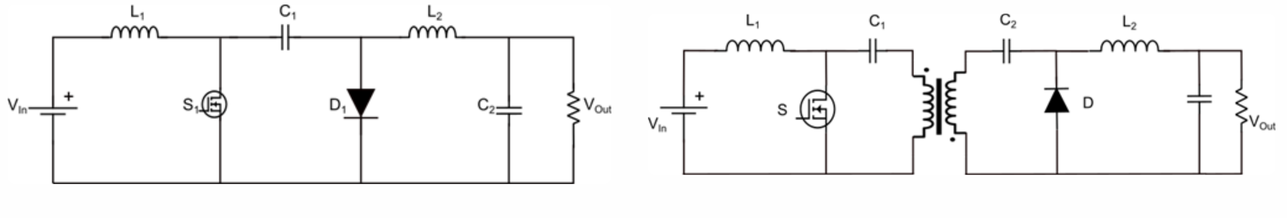
3.1. Ćuk-Based Converters

The Ćuk converter, represented in **Figure 2**a, is another common buck-boost converter. This converter is used in many different applications, ranging from renewable energies [15],[16] to power factor correction [17]. The main merits of this converter are its low output voltage ripple and non-pulsating input and output currents [18]. In contrast, the inverted polarity on the output side is the main drawback. In addition, and due to the presence of just one power switch, this converter shows high component stresses and low conversion efficiency [19].

The problem of inverse polarity at the converter output can be overcome by means of an isolation transformer [20]. This converter is referred to as an isolated Ćuk converter and has the same advantages as its predecessor. In addition, it also provides electrical isolation between the input and output, as shown in **Figure 2**b. Despite the interesting benefits of the isolated Ćuk converter, some drawbacks should be considered. One drawback is the presence of a transformer, which introduces undesired parasitic losses and limits the available duty cycle range, in both modes of operation (buck or boost). The ratio between the output voltage and the input voltage is equal to the inverse of the transformer ratio times the ratio between the power switch in the ON state over the OFF state [21]. Hence, to have equal voltage gain for both buck and boost modes, the ideal transformer turns ratio must be equal to one.

To assess the reliability of power electronics converters, a previous study reported on the results of a questionnaire survey which was conducted to determine the main elements of a power converter that are prone to failure in industrial applications [35]. Different semiconductor manufacturers from the aerospace, automation sector and utility power sectors were asked to answer the questionnaire. Questions ranged from power device operating conditions to failure counteraction and costs. The results showed that, within all elements of a power converter, semiconductors, such as IGBTs and MOSFETS, represented 31% of all failures. In contrast, capacitors represented less than 20% of failures, while gate drivers corresponded to 15% of failures [35]. This study clearly shows the importance of semiconductor failures in power converter functions.

Although most studies emphasise aspects like reduced components stress, control, and efficiency optimisation, very few fault mitigation strategies have been presented so far. Although it has not been thoroughly addressed, support for the adoption of the interleaving technique to build a fault-tolerant converter structure has been gaining ... allel while ... educe the ... ring extra ... [4]. was ... current is



(**a**) (**b**)

shifted in each arm, the total current ripple is cancelled, which means that smaller inductors can be used to obtain the desired current ripple [4]. Another topology with a fault tolerance mechanism (FTbbB) is presented in [36]. The authors proposed a fault-tolerant two-stage buck/buck-boost converter with tolerance against open-circuit switch failure that uses redundancy acquired through a synchronous switch for the power switches. The redundant circuit is composed of a single switch and two diodes, hence keeping the number of redundant switches to a bare minimum [36]. The converter is represented in **Figure 5**a.

More recently, a buck-boost topology (4PIBb) was presented in [37]. This topology uses a four-arm interleaved boost converter with changed load connection. In practice, this means that the load is connected between the cathode of the output diode and the input capacitor, resulting in an inverted output voltage. This configuration, represented in **Figure 5**b, allows for both continuous input and output currents and enables operation in both buck and boost modes, which the traditional boost converter cannot provide.

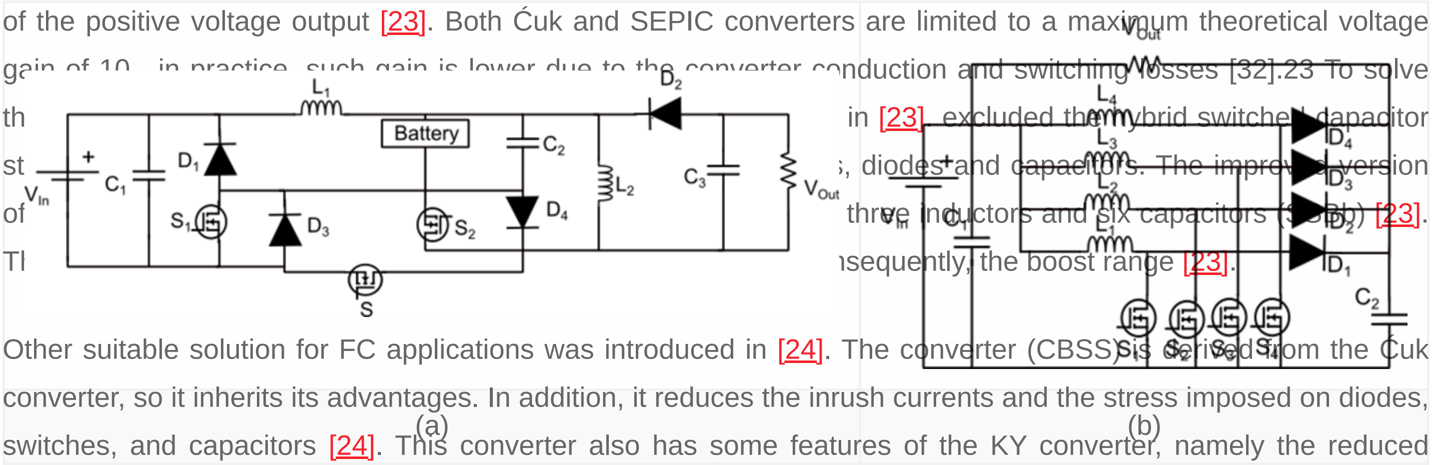


Figure 5. Fault-tolerant buck/buck-boost converter (FTbbB) (**a**). Four-phase interleaved buck-boost converter (4PIBb) (**b**).

Table 1 presents a compilation of the main characteristics of each converter such as the number of components, current profile, gain and reported efficiency.

Table 1. Comparison between the state-of-the-art converter topologies suitable for FC applications.

From the table, it is noticeable that the total number of components is generally lower for the Ćuk-based converters. This is because these converters only rely on a single switch. Another notable aspect of the Ćuk-based converters is the relation between the total number of components and the output voltage polarity. Converters such as SSBb, TSSBb, and NISBb possess a positive output polarity, which means that they have a higher number of components when compared to converters such as CBB and ĆSC. This translates into a higher efficiency because the stress on the power switch and diodes is lower. In addition, the required inductors and capacitors have lower values than that of other converters. Regarding the quadratic converters, all of them have the same number of components, except for the SSQBB. They are mostly used in applications where the voltage levels between input and output are very different. The reported efficiency varies between 60% and

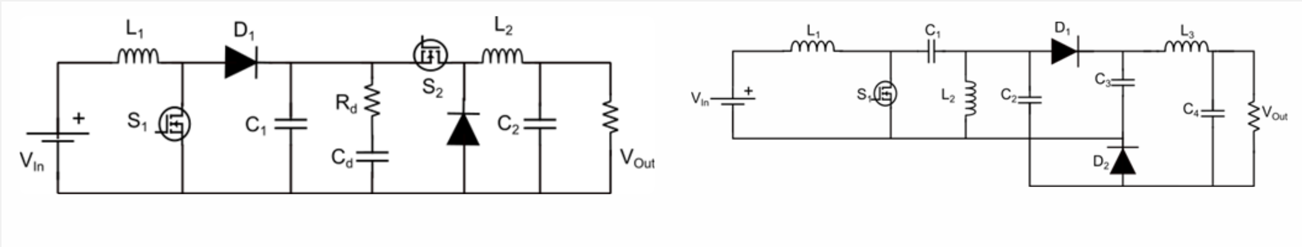
Figure 2. Ćuk converter (**a**). Isolated Ćuk converter (**b**).

The electrical isolation between the input and output, provided by the isolation transformer, provides the converter with extra security in case of a fault. Like the isolated Ćuk converter, push-pull converters can also be used as buck-boost converters. This converter is based on the forward converter; however, it possesses an extra power switch and a different connection to the intermedium transformer. The additional power switch allows the current to flow continuously through the primary winding of the transformer, as long as the power switches have opposing switching signals [22]. The continuous flowing of current through the primary input of the transformer increases its efficiency and, consequently, the overall converter efficiency.

Another Ćuk-based converter was introduced in [23]. This converter not only exhibits similarities with the Ćuk converter, since both have a single power switch but also possesses similarities with the SEPIC converter, because of the positive voltage output [23]. Both Ćuk and SEPIC converters are limited to a maximum theoretical voltage gain of 10 , in practice, such gain is lower due to the converter conduction and switching losses [32].23 To solve th ... in [23], excluded the hybrid switched capacitor st ... , diodes and capacitors. The improved version of ... three inductors and six capacitors (SSBb) [23]. Th ... nsequently, the boost range [23].

Other suitable solution for FC applications was introduced in [24]. The converter (CBSS) is derived from the Ćuk converter, so it inherits its advantages. In addition, it reduces the inrush currents and the stress imposed on diodes, switches, and capacitors [24]. This converter also has some features of the KY converter, namely the reduced voltage stress on the components. During the OFF state of the power switch, two more modes are added, so the stress on the components is reduced [24]. The voltage gain is two times the one of the Ćuk converter, so there is an increase in the boost range [24]. Despite the considerable advantages of this converter, there are some drawbacks to consider. One of them is the reverse polarity of the output voltage. This feature, inherited from the Ćuk converter, imposes higher voltages across the intermediate capacitors, which increases the risk of short-circuit failure.

A converter suitable for FC applications in DC microgrids was first introduced in [26]. This converter (TSBb), presented in [25], suppresses the effect of the RHP zero by using magnetic coupling inductors and damping networks. The authors were able to mitigate the effect of the RHP through capacitors and magnetic coupling between the input and output inductors. They were also able to increase the control dynamics of the converter using the damping network, constituted by a capacitor in series with a resistor, which increases the bandwidth of the proposed converter [26]. The configuration of the converter is based on cascaded between the boost and buck converter, producing a double-switch converter with low components stress and high efficiency, as depicted in **Figure 3**e.



(**a**) (**b**)

Figure 3. Two-switch boost-buck converter (TSBb) (**a**). Novel high-gain single-switch DC-DC buck-boost converter with continuous input and output power (NISBb) (**b**).

A more recent Ćuk-based topology (NISBb) was presented in [27]. This converter uses only a single power switch with lower stress, four diodes, four capacitors and three inductors. Unlike its predecessor, this converter has the same output polarity as the input, and the disposition of the capacitors provides a significantly higher voltage gain when compared to the Ćuk converter.

All in all, Ćuk-based converters are very suitable for FC applications in DC microgrids. Most of the presented converters possess both continuous input and output currents, which helps reduce the negative impact of the current ripple in the FC and allows for enhanced and more accurate current control. The continuity of the input current is possible due to the presence of an inductor in series with the input, meaning that at least one zero will be present in the RHP.

3.2. Quadratic Converters

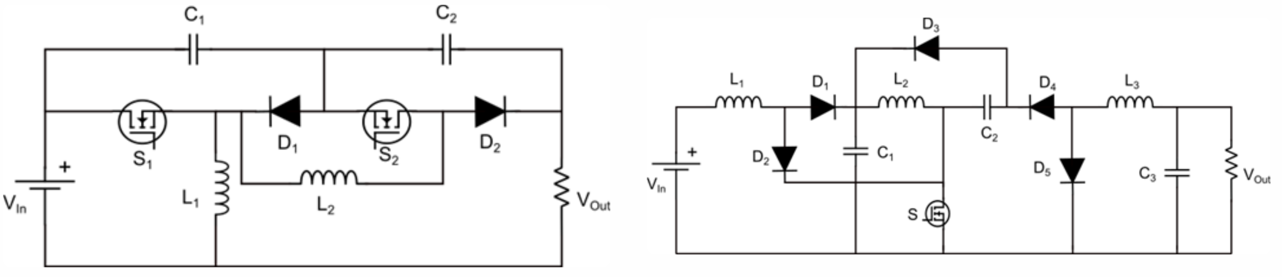
The voltage gain of any DC-DC converter is an important factor when choosing the correct topology for a specific application. For applications whose input and output voltage levels are significantly different, the use of isolation transformers, which provide safe integration between input and output, is an interesting solution. Another possible solution consists of the use of quadratic converters. These converters have a quadratic gain, which means that they are suitable for applications whose input and output voltage levels are very different [28][29]. Several high-gain boost DC-DC converters have been presented in the literature. These converters provide a wide input voltage range and have therefore become crucial for FC applications in electric vehicles [30],[31],[32]. In [28], a quadratic buck-boost converter with positive polarity at the output voltage and continuous input current (QBBPO) is presented. Both power switches of the converter have the same switching signal, whose duty cycle is the nominal duty cycle of the converter [28]. This converter resembles a cascaded configuration of two traditional single-switch buck-boost converters. To solve the input current continuity problem that is characteristic of the original converter, a group of two capacitors is inserted in parallel in between the input and output. The effective converter operation is strongly dependent on the correct behaviour of the two capacitors that filter the input and output currents. The converter is illustrated in **Figure 4**a.

structure by introducing redundancy to enable fault-tolerant operations. Although some findings addressing this topic were published in [38], the occurrence of faults or how the converter can adapt itself to such faults was not considered.

4. Conclusions

Choosing the right power converter topology for FC systems is a key aspect of the design process because it affects the efficiency and reliability of the overall system. This paper presents a state-of-the-art analysis of different buck-boost topologies which are suitable for FC applications in DC microgrids that have been introduced over the past few years. Intensive research aimed at increasing the efficiency and reliability of both FCs and DC microgrids means that they may provide a safe and clean way for the EU to achieve its goals by 2050. Throughout the paper, the impact of the current ripple was analysed and different topologies were presented and described. Some considerations, such as application, ripple, number of components, voltage level, voltage gain, robustness, cost and efficiency, must be accounted for when choosing the converter. In general, single-switch converters will have low efficiency and a low number of components, and consequently a reduced cost. Converters such as the Ćuk or the continuous input current buck-boost may be considered for applications where both volume and cost are important factors. Their main drawback is the inverting voltage polarity, which can cause installation problems and undesirable consequences if the components fail. On the other hand, converters with more than one switch tend to have higher efficiency, but this comes at the expense of a higher number of components and a higher cost. Nevertheless, when considering the entire system, the additional components are responsible for at least a third of the overall efficiency. Some suggestions for future work, especially related to the control approach and fault-tolerance, such as using the interleaved technique, MPC methods or both, were also presented.

The converter proposed in [29] is a combination of three basic converters: boost, buck-boost and buck converters (SSQBB). Along with the quadratic gain, this converter also has continuous currents at both input and output and possesses a single power switch. Thus, following the cascade sequence, the output voltage of the boost stage is the input of the buck-boost stage, and the output voltage of the buck-boost stage is the input voltage of the buck stage,as shown in **Figure 4**b.



(**a**) (**b**)

Figure 4. Quadratic buck-boost converter with positive output voltage and continuous input currents (QBBPO) (**a**). Single-switch quadratic buck-boost with both input and output current continuous converter (SSQBB) (**b**).

Both converters possess the same voltage gain; however, the total number of components is quite different. The QBBPO obtains quadratic gain characteristics without the use of transformers or coupled inductors; rather, it employs the same duty cycle on the power switches. On the contrary, the SSQBB converter uses just one power switch and two storage elements that transfer and store the energy to reach the quadratic voltage gain.

To solve the problem of pulsating currents, a semi-quadratic converter with positive voltage output (SQBuBoC) was introduced in [33]. It consists of two power switches that are operated simultaneously (as is the converter in [28], two inductors, two diodes and two capacitors. It has a continuous input current, a wide output voltage range and non-inverting voltage polarity [33]. The low voltage stress across the power switches also improves the converter's efficiency [33]. Despite the positive features of the presented converter, some considerations should be made regarding the output current.

A similar converter (NOBB) was introduced in [34]. Both power switches have the same duty cycle, so a semi-quadratic gain is obtained [34]. The input current ripple of this converter is slightly larger in comparison to other semi-quadratic converters because the inductor is not directly placed in series with the input voltage source. Changing the position of the input inductor would improve the filtering capacity of the input current.

3.3. Fault-Tolerant DC-DC Converters