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A Review of Non-Isolated Bidirectional DC-DC Converters for Energy Storage Systems

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Abstract— There is a growing interest in bidirectional dc-dc converters for interface battery with energy source and load. This paper provides a comprehensive review of non-isolated bidirectional dc-dc converter topologies. The classification and description of each type presented is based on the features and applications. This review paper is intended as a convenient reference to future non-isolated converter users. The most promising converters in terms of their simplicity, flexibility, and high efficiency are singled out.

Keywords— *dc-dc converter; bidirectional converter; buck-boost converter; non-isolated.*

I. INTRODUCTION

Sources of electric energy for industry, agriculture, civilian or military use differ in their purposes, appliance and supplied system types. Autonomous generation systems, sources based on solar and wind energy, are commonly used to supply various appliances, facilities, systems, and provide for heating, illumination, and other purposes in almost all spheres. Almost all of these systems use super-capacitors, accumulators (batteries) or different energy buffers for stable operation under all possible conditions and requirements.

For the reason above and due to the growing needs in systems with the ability of bidirectional energy transmission between two dc buses, Bidirectional Dc-dc Converters (BDCs) have received increased attention. Apart from their traditional application in energy storage and dc motor drives, BDCs have become a promising option for many applications, such as portable devices, spacecraft power systems, Uninterruptible Power Supplies (UPS), electric vehicles [1], fuel cells and renewable energy systems [2], [3].

In the electric vehicle application (Fig. 1a), an auxiliary energy storage battery absorbs the energy fed back by the electric machine during deceleration of the motors. In addition, BDC is also required for the power supply from auxiliary battery to boost the high-voltage bus during motor startup or acceleration when a large amount of power is required [1], [4]-[7]. Moreover, BDCs can also be used in industrial equipment. Such equipment started and stopped very frequently, so energy can be recuperated without being wasted.

Recently, clean energy resources such as solar photovoltaic technologies and wind turbines have been widely exploited for developing renewable power generation systems. However, fluctuations of power generation due to changes in weather conditions and occasional massive needs in output power makes Renewable Energy Sources (RES) inapplicable for self-

contained operation as the single power source. The typical solution to this problem is the use of energy storage devices in conjunction with the RES to compensate this variability and obtain a stable and smooth power flow to the load. The most applicable and cost-effective energy storage devices in the medium-power range are lithium-ion or other types of batteries and super-capacitors. A renewable power system with BDC is shown in Fig. 1b. BDCs maintain a stable load bus voltage and make full usage of the solar array, wind turbine, fuel cell and the storage battery in all operating modes [7]-[13].

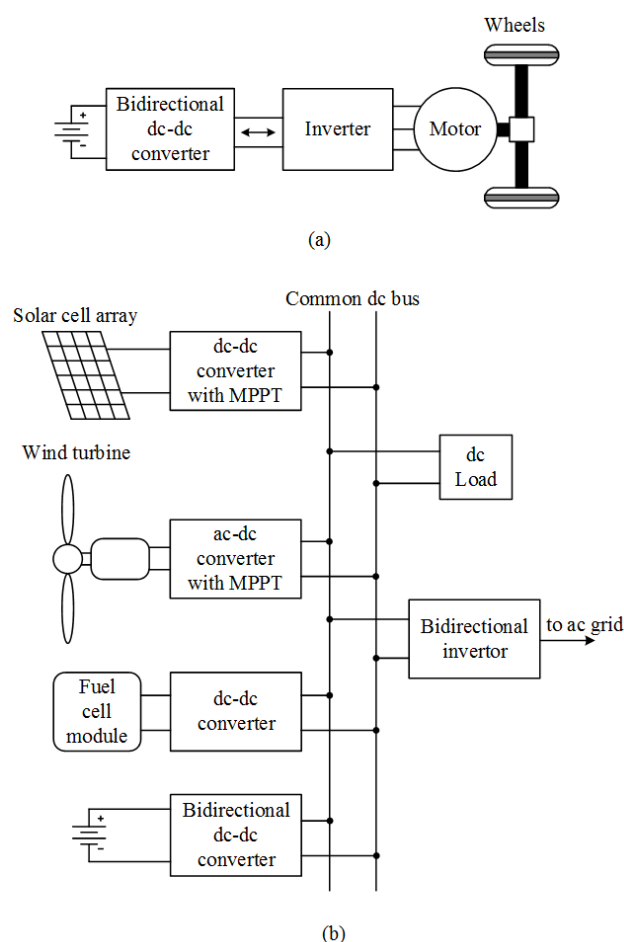


Fig. 1. Bidirectional dc-dc converter in an electric vehicle application (a) and in a renewable energy system (b).

This paper proposes a general classification of Non-Isolated BDCs (NBDC) with a brief discussion of particular qualities of each class.

II. BIDIRECTIONAL DC-DC CONVERTERS

Most of the existing BDCs are characterized by a current fed or voltage fed on one side [14]-[18]. Based on the placement of an auxiliary energy storage, BDCs can be categorized into buck and boost type. In the buck type, energy storage is placed on the high voltage side and in the boost type on the low voltage side.

To realize the double power flow in BDCs, the switch cell should carry the current in both directions. It is usually implemented with a unidirectional semiconductor power switch such as power MOSFET or IGBT in parallel with a diode (or body diode) because the double sided current flow power switch is not available.

Depending on the application, different dc-dc converters are used to modulate the input voltage. Generally, there are two basic types of BDCs, which are non-isolated and isolated (Fig. 2).

This paper will focus on the non-isolated converters. In the transformerless non-isolated power conversion systems, the boost type and the buck type dc-dc converters are commonly chosen. The high frequency transformer based system is a reasonable solution to obtain isolation between the source and the load side. Isolation is mandatory when the very high step-up or step-down ratio is required. But to improve the efficiency, size, weight and cost, the non-isolated type is much more attractive. Thus, in the high power or spacecraft power system applications [17]-[23] where weight and size are the main concern, the transformerless type is more preferable.

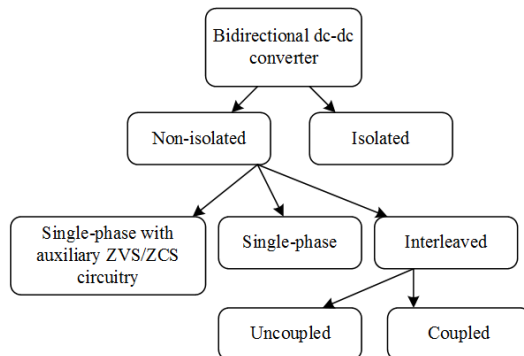


Fig.2. Simplified classification of the bidirectional dc-dc power converters.

As it can be seen from Fig. 2, the main types of non-isolated converters are single-phase, single-phase with ZVS/ZCS circuitry and interleaved converters. Note that it is not only the second type that exploits the benefits of soft-switching or resonant techniques to increase the switching frequency and achieve lower size and weight. Instead of auxiliary circuitry, single-phase and interleaved converters use different frequency modulation and switching techniques, e.g. parasitic elements of the devices as resonant elements, e.g. output capacitance of MOSFET.

The continuity of the current in the battery is also an important classification criterion. It influences the battery lifetime. Thus, it is possible to select the prior solution suitable for specific tasks. Topologies with continuous current from the battery are shown with background highlighted in Fig. 3.

III. OVERVIEW OF THE BASIC NON-ISOLATED DC-DC CONVERTERS

This section focuses on the performance analysis of different non-isolated dc-dc converters. Figs. 3, 4 and 5 show the basic circuits for each type of the dc-dc converters covered in this paper.

A. Single-phase NBDCs

The common non-isolated half-bridge BDC topology, shown in Fig. 3a is basically a combination of a step-up converter together with a step-down converter connected in anti-parallel [24], [25]. It can operate in either synchronous buck or boost mode to transfer power in both directions. The bidirectional operation of the circuit can be explained in two modes as follows. During the forward step-down operation, T_1 is operated with the required duty cycle and the switch T_2 is always off while its body diode is conducting. Similarly, in the backward step-up operations, T_2 is operated and T_1 is always off.

The second bidirectional topology [24] can be obtained from the simple inverting buck-boost topology by replacing diode with second switch T_2 (Fig. 3b). The principal of operation is similar to a flyback converter but with single inductor instead of a transformer. During the forward operation mode, T_1 is switching at the required duty cycle while switch T_2 is kept close all the time. Same, during the backward operation mode, switch T_2 is conducting at the required duty cycle while switch T_1 is always off. Comparing with the first converter circuit, wherein the output voltage can be $0-V_{in}$ in buck mode and $V_{bat}-\infty$ (ideal converter), the voltage in bidirectional inverting buck-boost converter can be $0-\infty$ in both directions (ideal converter). Note that output voltage has opposite polarity than input, which is a burden in many applications. This problem can be resolved by adding more switches to this configuration, as shown in Fig. 3c.

The third topology (Fig. 3c) can be obtained by cascading the buck converter with the boost converter [26]-[29]. This topology operates in all quadrants (4 quadrant converter). It means that it is capable of step-down and step-up operations in both directions. Cascading buck-boost BDC is the most flexible topology. But it has several drawbacks: increasing the number of power switches and, as a consequence, a more complex control system and control algorithms and higher turn-on losses caused by reverse recovery problem of transistors body diodes.

The bidirectional Cuk converter structure [26], [30], [31] shown in Fig. 3d is derived from the conventional unidirectional Cuk converter by replacing the main diode by MOSFET. It has an advantage of low ripple in the input and the output currents, therefore, the bidirectional Cuk converter is a proper choice for applications like battery equalization [32], ultracapacitor-battery interface circuits [33], and bidirectional converter to manage the power flow and maintain energy storage device's health. Inductors L_1 and L_2 can be coupled for decreasing ripple of input and output currents. Due to the fact, that Cuk converter essentially is series-connected boost and buck topologies with the energy storage capacitor C , the output voltage can be either higher or lower than the input in both

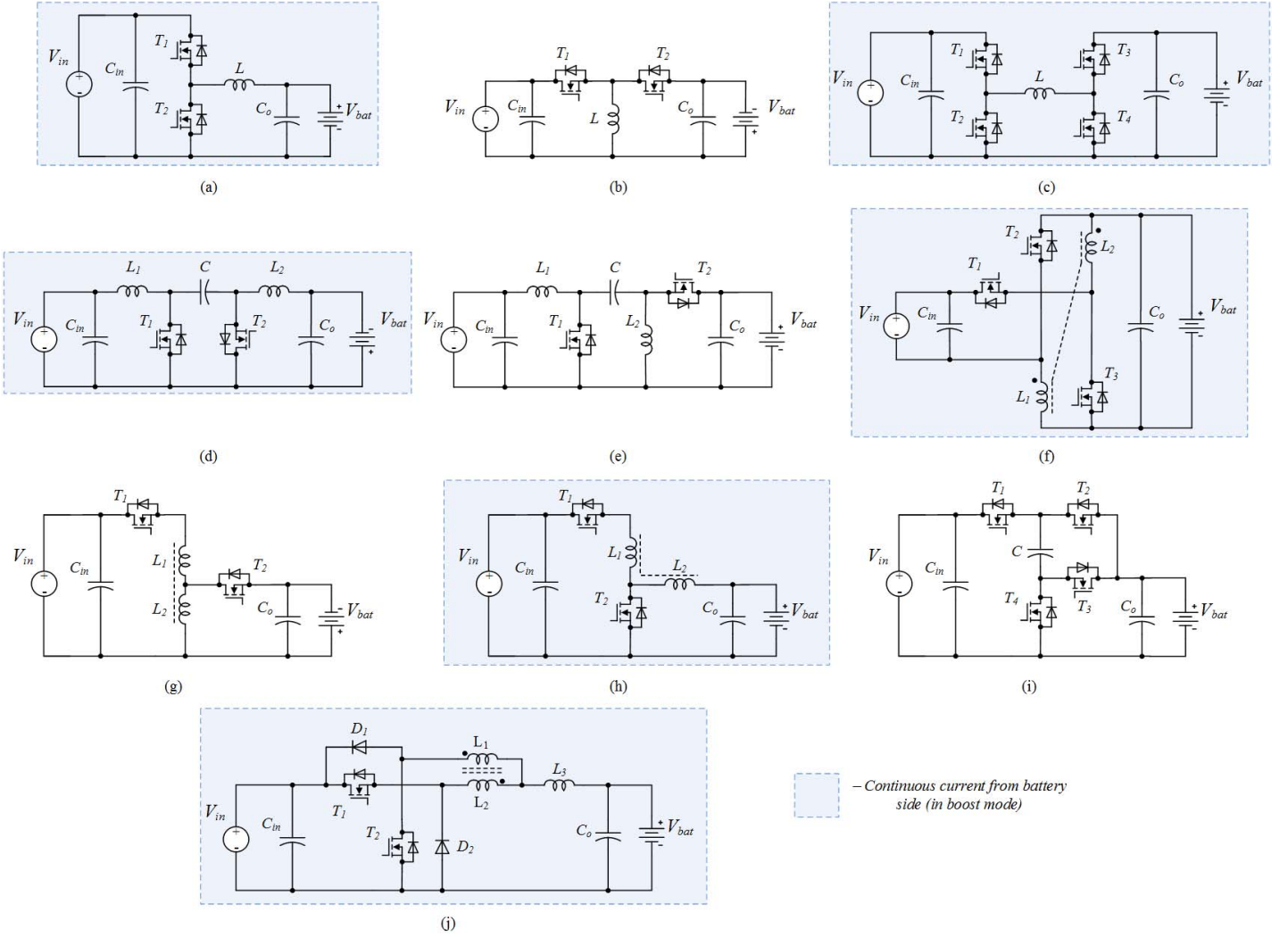


Fig. 3. Basic types of single-phase NBDCs.

directions. In the forward mode of operation, T_1 is controlled and T_2 is off and the body diode of T_2 operates as the main diode. Similarly, in the backward mode of operation, T_2 is controlled and T_1 is off and the body diode of T_1 operates as the main diode.

The basic schematic circuit of a bidirectional SEPIC/Zeta dc-dc converter shown in Fig. 3e operates as a conventional SEPIC converter for the forward power flow, and like a Zeta converter for the backward power flow [34]-[36]. It is basically the rearrangement of Cuk converter. SEPIC/Zeta converter can also have either higher or lower output voltage in both directions, but the polarity of dc buses is the same. During the forward power flow, the SEPIC converter acts as a buck converter, T_1 is acting as a power switch and T_2 is off during this charging period. The backward power flow is considered as the Zeta mode of operation, the converter acting as a boost. T_2 is acting as power a switch and T_1 is off during this discharge period. Inductors L_1 and L_2 can be coupled to reduce output voltage ripple and voltage stress on switches.

A modified BDC [37]-[39] is shown in Fig. 3f. This converter employs a coupled inductor with the same winding

turns in the primary and secondary sides. The proposed converter has the following advantages over the conventional half-bridge bidirectional converter: higher step-up and step-down gains, lower average value of the switching current under the same electric specification. In the step-up mode, PWM technique is used to control switches T_2 and T_3 simultaneously. Switch T_1 is a synchronous rectifier. In the step-down mode, the PWM technique is used to control switch T_1 , while switches T_2 and T_3 are the synchronous rectifiers.

Figs. 3g and 3h show a BDC with tapped inductor [40]-[43]. The traditional converter topologies (Figs. 3b and 3a) are extended by an additional inductor which is magnetically coupled with the original inductor. Due to the magnetic coupling, both windings are on the same core and therefore no additional magnetic part is necessary. In constant to the conventional topologies, the use of a tapped inductor leads to a higher step-up ratio, thus avoiding the extreme duty cycle of the active switch and the high peak currents in the active and passive switches. Also, lower step-down ratio is achieved. Note that the polarity of dc bus voltages is reversed with respect to a common ground (same as in Fig. 3b), which is a burden in many applications.

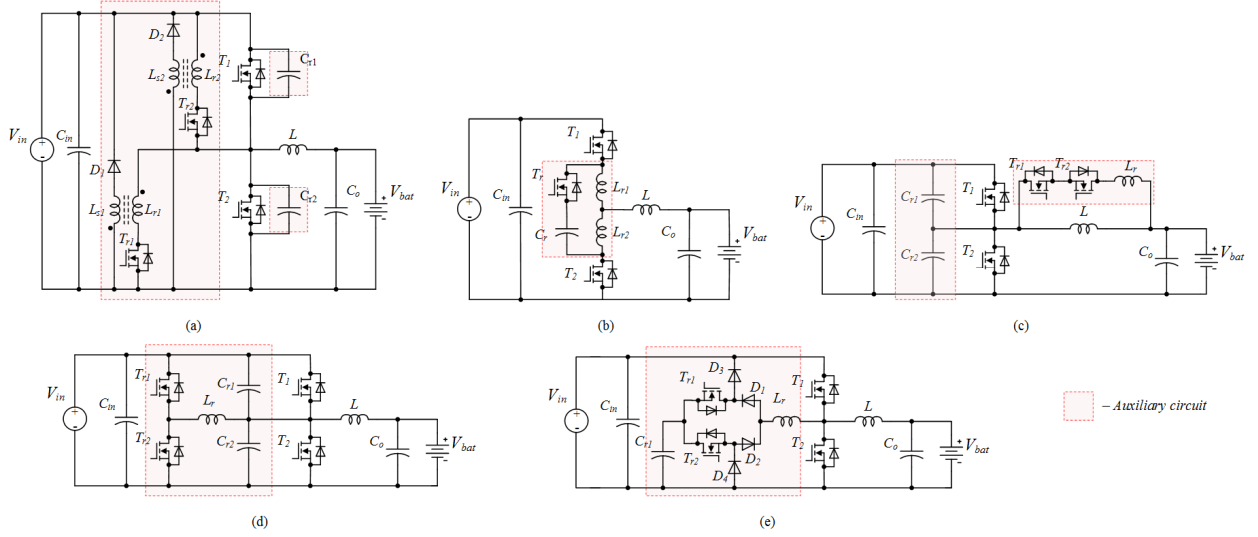


Fig. 4. Basic types of half-bridge single-phase NBDCs with auxiliary circuit

The Switched Capacitor (SC) BDC [44]-[46] shown in Fig. 3i. Is mostly used when it is required to realize the dc-dc converter by Integrated Circuit (IC) technology. As no magnetic devices are required in those converters, possibilities of IC fabrication are promising. Starting from the idea of using basic SC cells in filter design [47], many techniques of operating the switches and switching pattern have been proposed for power conversion. Each capacitor in the converter is basically passing through a charging phase from the supply and/or another capacitor. However, SC converters are characterized by weak regulation capability, their voltage conversion ratio is determined by the circuit topology, high ripple of input current that produces Electromagnetic Interference (EMI). Most of those problems can be solved by adding a current control scheme and a voltage control scheme, which will adjust the charging trajectory of the capacitor. However, the result increased converter complexity and cost.

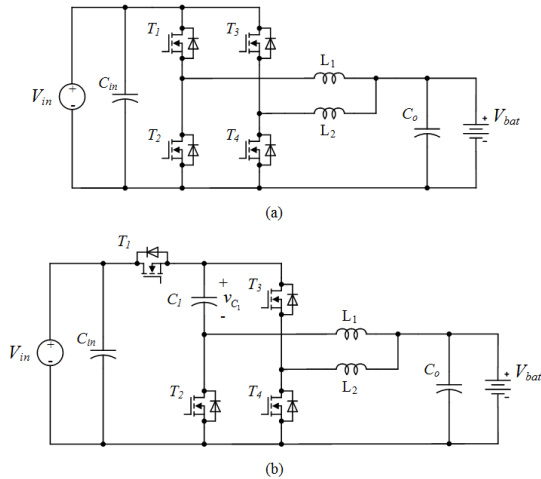


Fig. 5. Basic interleaved NBDCs.

Non-isolated BDC with Negative-Coupled Inductor (NCI) [48] is shown in Fig. 3j. Splitting the switch branch into two power flow paths prevents the freewheeling current from flowing through the body diode of the MOSFETs. Thus, reverse-recovery problem of MOSFET's body diode is alleviated. During the forward step-down operation mode, T_1 is controlled with the required duty cycle, T_2 is off and D_1 operates as the main diode. Similarly, in the backward step-up mode, T_2 is controlled with the required duty cycle, T_1 is off and D_2 operates as the main diode.

B. Single-phase with auxiliary ZVS/ZCS circuitry

In all converters, high efficiency, reliability and simple control technique are the key criteria. Because of the limited efficiency of hard-switching converters, soft-switching techniques are gaining popularity and are applied to the non-isolated BDCs [49]-[52]. Soft-switching technique enables high efficiency by reducing switching losses and miniaturization and light weight. However, it makes schematics more complex, more difficult to control and tune. Fig. 4 shows the basic types of half-bridge single-phase bidirectional converters with auxiliary ZVS/ZCS circuits [53]-[57]. Other types of converters, such as the Cuk converter [31], the SEPIC/Zeta converter [20], [36] and the switched capacitor converter [46], could also have resonant circuits and active clamps.

C. Interleaved converters

In recent years, it has been found that an interleaving concept or in more general terms, synchronizing paralleling power stages with relative phase shift ($360^\circ/n$) is applicable.

TABLE I. CHARACTERISTICS COMPARISON OF NBDCs

Topology	Basic criteria's					
	Voltage conversion ratio V_{bat}/V_{in} (buck mode)	Voltage conversion ratio V_{in}/V_{bat} (boost mode)	Output current ripple (buck mode)	Number of switches	Number of passive components	Magnetic required
Half bridge (Fig. 3a)	D	$\frac{1}{1-D}$	$\frac{V_{bat}(1-D)}{Lf_{sw}}$	2	3	Single inductor
Inverting bidirectional (Fig. 3b)	$-\frac{D}{1-D}$	$-\frac{D}{1-D}$	$-\frac{V_{bat}(1-D)}{Lf_{sw}}$	2	3	Single inductor
Cascaded bidirectional (Fig. 3c)	D	$\frac{1}{1-D}$	$\frac{V_{bat}(1-D)}{Lf_{sw}}$	4	3	Single inductor
Cuk (Fig. 3d)	$-\frac{D}{1-D}$	$-\frac{D}{1-D}$	$-\frac{V_{in}D}{L_2f_{sw}}$	2	5	Coupled or two inductors
SEPIC/Zeta (Fig. 3e)	$\frac{D}{1-D}$	$\frac{D}{1-D}$	$\frac{V_{in}D}{L_1f_{sw}}$	2	5	Coupled or two inductors
Modified BDC with coupled inductors (Fig. 3f)	$\frac{D}{2-D}$	$\frac{1+D}{1-D}$	$\frac{V_oD}{(1+k)Lf_{sw}}$	3	4	Coupled inductors
Tapped inductor (Fig. 3h)	$\frac{D}{D+n(1-D)}$, $n=1+\frac{N_{in}}{N_{bat}}$	$\frac{1-D+nD}{1-D}$	$\frac{n^2V_{bat}(1-D)}{Lf_{sw}}$	2	3	Single tapped inductor
Switched capacitor (Fig. 3i)	0.5	2	$Cf_{sw}(V_{in}-V_{bat})$	4	3	No
Interleaved (Fig. 5a)	D	$\frac{1}{1-D}$	$\frac{V_{bat}(1-2D)}{Lf_{sw}}$	2N	2+N	N inductors with or without coupling
Interleaved with charge pump (Fig. 5b)	$\frac{D}{2}$	$\frac{2}{1-D}$	$\frac{2V_{bat}(0.5-D)}{Lf_{sw}}$	2N	2N+1	N inductors with or without coupling

The best-known application is for powering microprocessors, commonly referred to as Voltage Regulator Modules (VRMs) [58], [59]. However, the interleaving technique is also well suitable for bidirectional converters. Power converter paralleling architecture gives several advantages: current splitting (I_o/n), current ripple cancelation, higher efficiency, better thermal performance, and high power density. One of the most interesting benefits of the interleaved structures is the provision of high efficiency in a wide power range (from few a percent of a converter's nominal power to its nominal power). Also, by splitting the current into several paths, conduction (I^2R) losses can be reduced.

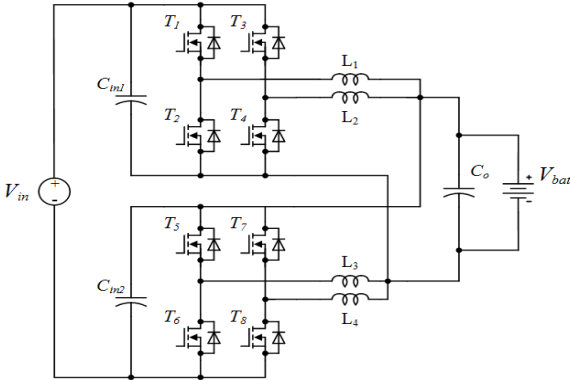


Fig. 6. Floating interleaved NBDC.

Fig. 5 shows basic two-phase interleaved topologies. Interleaving half bridge topology (Fig. 5a) is the most common choice [18], [60]-[62]. Fig. 5b shows the two-phase charge pump topology, which has higher conversion ratio than the conventional converter [63]-[65]. Also, to gain a higher conversion ratio, a floating interleaved BDC can be applied [66]. It is composed of a double non-floating (positive branch) and a double floating (negative branch) as shown in Fig. 6.

This configuration enables high voltage gain, high efficiency, and low input current ripple, with reduced inductor and capacitor volumes, making it more cost-effective than conventional BDCs. Power inductors of an interleaved converter can be coupled direct or inverse. Inverse coupling reduces phase current ripple and increases transient response [67], [68]. The number of phases can be any from 2-4 to 16 [69] or even 36 [70].

IV. CONCLUSION

BDCs are gaining interest because of popularity of renewable energy sources and electric vehicles. They provide power exchanges between the dc bus and energy storage system. Despite the variety of the schemes, NBDCs can be divided into several basic families. Two main families are isolated and non-isolated converters. This paper focuses on the non-isolated type. An overview and key operating features of each NBDC topology were provided. The advantages and

disadvantages of each configuration were underlined. Comparison of the basic reviewed bidirectional converter topologies is summarized in Table I. Resulting from the analysis presented, the half-bridge topology and its interleaving variations with coupled inductors are the most promising, high-efficient and robust solutions for future research.

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