Non-Isolated High Voltage Gain Bidirectional DC-DC Converters: A Review

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Abstract—**Battery storage systems have been developed for various applications, from power generation in wind and solar power plants to electric vehicles. Bidirectional DC-DC converters (BDCs) are key elements in battery storage systems as they allow power flow in two directions when operating in charging and discharging modes. BDCs are effective solutions to provide an appropriate output voltage in low-voltage battery storage systems. Generally, there are two major types of BDCs, isolated and non-isolated structures. Non-isolated BDCs have lower volume, weight, and power losses, and thus, are suitable where a compact structure is needed, and galvanic isolation is not mandatory. In this paper, a comprehensive review of recent non-isolated high voltage gain BDCs is conducted. Based on structures and components of BDCs, there are four types of methods to increase the voltage gain in these converters: capacitor-base, inductor-base, combined capacitor and inductor-base, and mixed structures-based methods. In this paper, the operational principle of each type of methods is examined in detail and their advantages and disadvantages are compared. The future research directions in this area are also recommended.**

Index Terms— **Battery storage, bidirectional DC-DC converters, cascaded converters, high voltage gain, interleaved converters, renewable energy sources, soft switching, switched capacitors, switched inductors.**

I. Introduction

Bidirectional DC-DC converters (BDCs) play a crucial role in modern energy systems by managing power flow in two directions, which is one fundamental requirement for battery energy storage systems (BESSs), essential when combined with intermittent renewable energy sources, such as wind and solar power [1]. By storing excess energy during periods of high generation/low demand and releasing it during periods of low generation/peak demand, BESSs ensure an uninterrupted and reliable energy supply. BDCs also play an essential role in electric vehicle (EV) chargers, on-board battery chargers, vehicle-to-grid (V2G), and grid-to-vehicle (G2V) systems for bidirectional energy transfer between EVs and the grid [2].

Generally, BDCs can be divided into two categories, isolated and non-isolated structures. Due to safety considerations, it is necessary to use a separate ground for the input and the output of a converter in some applications, where using an isolated BDC is mandatory. For isolated BDCs, a high voltage gain can be obtained by increasing the turn ratio of an isolated transformer. However, this isolated transformer can lead to the increased weight, size, cost, and electromagnetic interference (EMI) in the converter [3]. On the other hand, non-isolated BDCs have simpler designs, operations, and control systems than isolated BDCs, where isolation is not necessary [4].

The conventional bidirectional buck/boost DC-DC converter (BBBC) is comprised of two power switches and one inductor, and is one of the most popular converters due to its simple structure. However, the main disadvantages of this converter are high voltage stresses on its switches and its limited voltage gain. Therefore, high-rate switches with a high drain-source on-resistance ($R_{DS(on)}$) should be used, causing high losses in this converter. Theoretically, this converter can provide a high voltage gain at extreme duty cycles, but can also cause instability control, high voltage stresses on switches, and increased power losses due to high losses in switches [5].

To overcome limitations of conventional BDCs, many studies have been conducted to introduce advanced topologies that provide a high voltage gain in both power flow directions. In this paper, the power flowing from the low voltage (LV) side to the high voltage (HV) side is named the forward mode, and the opposite power flow is named the backward mode. This study aims to comprehensively review and categorize various methodologies utilized in the literature to enhance voltage gains in non-isolated BDCs. A comparative analysis of each methodology is conducted to demonstrate its effectiveness.

II. High Voltage Gain Techniques

Voltage regulation is the main feature of power converters. A higher voltage gain can achieve the desired output voltage using a smaller turn-on time of the converter's main switch(s), reducing both conduction losses of switches and voltage stresses on switches. Much research on non-isolated BDCs has been conducted in the literature to achieve high voltage gains.

As shown in Fig. 1, there are four main categories of high voltage gain techniques for BDCs: capacitor-based, Inductor/magnetic-based, the combination of capacitor and inductor-based, and mixed structures-based techniques.

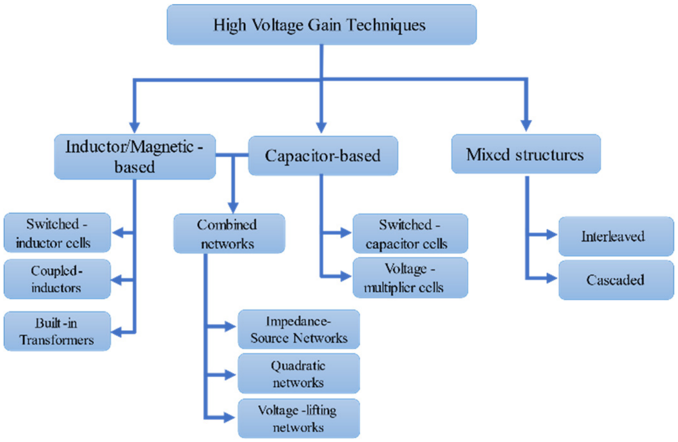

Fig. 1. Categorization of high voltage gain techniques for non-isolated BDCs.

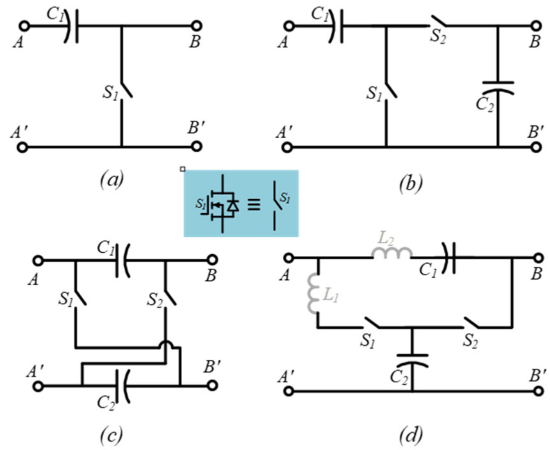

Fig. 2. Fundamental bidirectional SC cells: (a) Villard circuit, (b) Greinacher circuit, (c) A-SC, (d) modified A-SC.

A. Capacitor-based techniques

In capacitor-based BDC techniques, a specific configuration consisting of semiconductors and capacitors is used to form a cell, which can increase the voltage gain of a converter. They can be divided into switched-capacitor (SC) cells and voltage multiplier (VM) cells.

1) Switched-Capacitor cells

Switched-capacitor cells are mainly comprised of switches and capacitors, and their operational principle is based on the capacitive energy transfer. In the forward mode, capacitors in the cell are charged in parallel or charged separately by a different path, and discharged in series to the load; similarly, in the backward mode, capacitors in the cell are charged in series to the HV side, and discharged in parallel or discharged separately by a different path. Typically, power switches operate in the forward mode, and their antiparallel diodes conduct during the backward mode. These cells are usually placed in the middle of the circuit to improve the voltage gain and reduce voltage stresses on the main switch(es).

There is a vast variety of unidirectional SC structures in the literature, and some of them are developed for use in BDCs, as shown in Fig. 2. The basic SC configuration is illustrated in Fig. 2(a), known as “a Villard circuit”, and comprises one capacitor and one switch. In this circuit, by closing the switch, C_1 is charged by the LV circuit, and is discharged in series to the HV circuit when the switch is turned off. Since this structure suffers from high voltage ripples on the HV side, a modified cell was introduced by Greinacher (G-SC), as shown in Fig. 2(b), which has one more capacitor and switch than the previous SC cell. The G-SC cell is used in the proposed converter in [6]. In this study, an interleaved converter is combined with an SC cell and a coupled inductor to achieve a high voltage gain; it also provides the zero voltage switching (ZVS) operation for switches through the synchronous rectification method. The voltage stress on the component of the G-SC cell is improved by reconfiguring it into an active-switched capacitor (A-SC) structure, as shown in Fig. 2(c), and this cell is added to a conventional bidirectional SEPIC converter [7]. The lack of a common ground between the input and the output is the main issue of the A-SC structure, resulting in the introduction of a modified A-SC cell, as illustrated in Fig. 2(d), and its simplicity and improved voltage gain make this cell attractive in the literature [8]-[12]. To increase the voltage conversion ratio of the conventional BBBC, this cell is added to the design structure in [9]. A coupled inductor is connected in series with a modified A-SC cell in [8], and the capacitor C_2 also plays the intermediate capacitor role in this structure. In addition to a high voltage gain, this combination provides ZVS for power switches. The expanded version of the modified A-SC is employed in [11]. Alongside SC cells, a switched-inductor (SL) cell is added on the LV side to enhance the voltage gain further. However, the converter's number of elements and volume are relatively high. According to Fig. 2(d), the secondary winding of a coupled inductor (CI) (L_1) can be placed in the modified A-SC cell. This configuration is applied in the conventional BBBC [10]. It can recycle the leakage current of the CI and provide ZVS for switches. Thus, the voltage stress on switches and switching losses can be significantly reduced.

Another bidirectional SC cell is introduced in [12] by inserting L_2 in the modified A-SC cell. This cell is added in series with a voltage doubler to reduce the voltage stress on switches and increase the efficiency by providing ZVS operations for its switches. Furthermore, two LC filters are added on LV and HV sides to reduce current ripples, which are suitable for converters in applications, where current ripples are critical on both sides.

2) Voltage Multiplier Modules

The voltage multiplier modules (VMMs) increase the voltage ratio of the converter by an integer coefficient; they are typically located on the HV side of the converter and in series with previous stages. A voltage doubler cell is shown in Fig. 3(a), where two capacitors are charged by the previous stage through the conduction of power switches; in the next interval, they are discharged in series to the output. This simple technique can multiply the output voltage by two or the half in the forward mode and the backward mode, respectively. This cell is employed in an integrated buck/boost converter with a dual-active half-bridge (DAHB) converter [13]. In this converter, the leakage inductance of the transformer and the synchronous rectification method enable the ZVS operation for all active switches to improve the total efficiency. Although with a simple structure, the basic VMM has voltage ripples on the HV side, and voltage stresses on its elements. Therefore, a

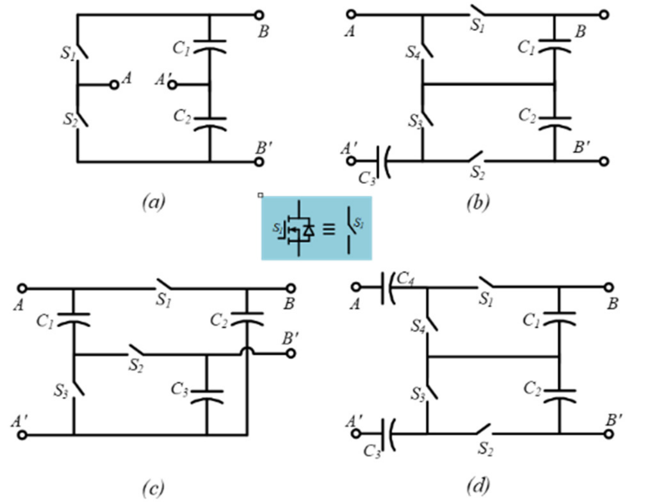

Fig. 3. Different bidirectional VMMs: (a) basic voltage doubler, (b) and (c), modified voltage doublers, (d) voltage quadrupler.

modified voltage doubler is introduced by adding two more switches and one capacitor to the basic module, as shown in Fig. 3(b). This module is inserted in series with an interleaved structure to introduce a high voltage gain BDC with high power handling capability and low current ripples on the LV side [14]. This design not only reduces voltage stresses on switches and capacitors, it also enhances the overall converter efficiency by providing ZVS operations for all switches through the synchronous rectification.

Another modified voltage doubler is introduced in [15] with one less switch than the previous one, as shown in Fig. 3(c). This module is in series with a bidirectional Quasi-Z-source converter to raise its voltage gain. It operates as a voltage doubler in the forward mode, and its combination with a Quasi-Z-source converter acts as a quadratic structure in the backward mode. In Fig. 3(d), a voltage quadrupler module can be achieved by adding an extra capacitor to the VMM in Fig. 3(b), where the voltage can be multiplied by four in the forward mode and ¼ in the backward mode [16]. However, as the output voltage increases, the volume of capacitors on the HV side also increases. Thus, a high volume and high cost of the converter are trade-offs for having such voltage gains. Despite their advantages, capacitor-based voltage boosters suffer from the restricted power handling capacity and voltage ripples on the high HV side, resulting in a larger capacitor size [8]. In addition, a large number of power switches in these structures and their high voltage stresses led to high switching losses and complex control strategies in BDCs.

B. Inductor/Magnetic-based techniques

Another method of increasing the voltage gain is to employ magnetic elements, which can be divided into switched-inductor cells [11], [17]-[19], coupled inductor-based structures [6],[8],[12],[20]-[22], and built-in transformers (BT) [23], [24].

1) Switched-inductor (SL) cells

The concept of SL cells is based on charging inductors in parallel and discharging them in series, and this pumping operation provides a high step-up voltage gain in the converter; or discharging inductors in parallel and charging them in series, providing a high step-down voltage gain in the converter.

The basic form of a bidirectional SL is shown in Fig. 4(a), where odd-numbered switches operate synchronously, and even-numbered switches operate asynchronously. Using a basic SL cell, Ref. [17] introduces a BDC characterized by several key features, including low current ripples on the LV side of the capacitive loop [25], and the soft switching feature using the synchronous rectification technique. Additionally, its auxiliary capacitor cell connecting negative poles of HV and LV sides reduces high-frequency voltage harmonics significantly compared to the basic SL-based converters. Two inductors of the basic SL cell in Fig. 4(a) are coupled in [18] to benefit from advantages of coupled inductors, such as a lower volume and less core losses.

Another SL cell is the active switched-inductor (A-SL), as shown in Fig. 4(b), which has one less switch than the basic SL. Two switches of this cell operate synchronously to magnetize inductors in parallel, and demagnetize inductors in series. This structure is a duality circuit of the A-SC cell, which has also been used in many unidirectional converters; due to its bidirectional power flow capability, it is employed in the proposed BDCs in [11]. The basic SL can form a two-port cell by getting B ports short-circuited, and a hybrid SL structure can be formed by replacing inductors of the basic SL cell by a A-SL cell, as shown in Fig. 4(c) [19].

2) Coupled inductors (CIs)

The coupled inductor-based methods are one of the simplest ways to improve the voltage gain of a DC-DC converter. This magnetic element stores energy at one interval and restores it in another interval. Adding an intermediate capacitor besides the CI can improve the voltage gain further. In the forward mode, this capacitor is charged in parallel with the CI, and is discharged in series with the CI [6], [8], [12], [20]-[22]. The intermediate capacitor is simply added in series with one of the

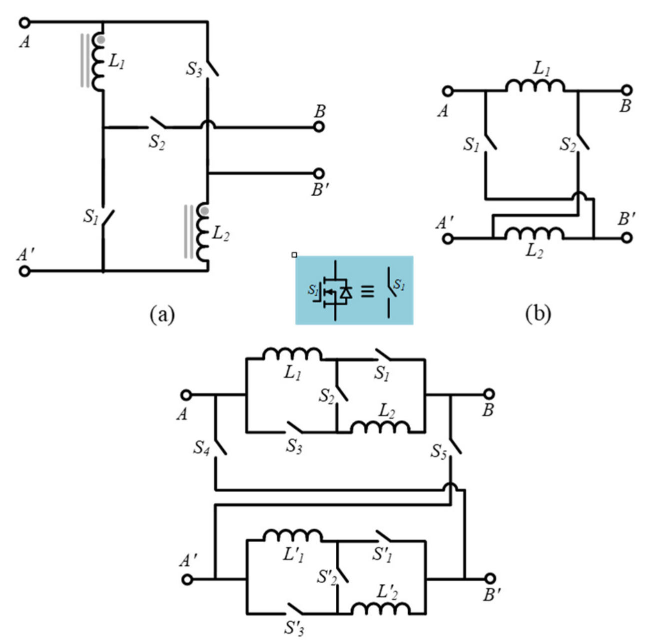

Fig. 4. Bidirectional SL cells: (a) Basic SL, (b) A-SL, (c) Hybrid SL cell.

windings of CI in [6]. The CI is added in series with a modified A-SC in [8], [12] and the intermediate capacitor is common with the SC cell to increase the power density of converters. A CI-based BDC converter equipped with two intermediate capacitors is introduced in [21]. The secondary winding of the coupled inductor is located in an A-SC cell. As a result, capacitors in the A-SC cell also act as intermediate capacitors to increase the power density of the converter and its voltage gain. It also recycles the leakage energy of the CI and avoids undesirable voltages on switches to enhance the converter's efficiency. However, the downside is its complicated structure. To improve it, this converter is modified by [20], in which the number of components is reduced through a trade-off of a lower voltage gain. A three-winding CI-based converter is proposed in [22], where two windings of the CI are in series with intermediate capacitors to improve the voltage gain. Two parallel paths are used to increase the current flow capability and reduce current ripples on the LV side. An active clamp circuit recycles the stored energy in the leakage inductance and transfers it to the output.

3) Built-in transformers

Another magnetic-based method to increase the voltage gain in BDCs is the built-in transformer (BT) approach. Unlike CI-based techniques, this method is based on the idea of direct energy transfer, instead of storing the magnetizing energy. In this approach, the entire topology is at least divided into two parts by BT, and the output energy is processed by each part. This boosts efficiency and increases the voltage gain of the converter, which makes BT a fascinating component in cascaded structures. As BTs have a balanced magnetic flux in the core, and do not store energy in their magnetizing inductance, smaller cores can be used in BTs and the risk of saturation is low [26].

The BT approach is utilized in many studies to introduce a high voltage gain in BDCs. For instance, a BT is integrated between a BBBC and a DAHB to provide a simple high-voltage gain converter [23]. In addition, ZVS is provided for switches by a phase shift control strategy. To increase the power handling capability and the voltage gain of full-bridge (FB)-BDC, Two BTs are integrated into two interleaved FB-BDCs [24]. This structure also benefits from low current ripples on the LV side, the interleaving structure and ZVS conditions for switches can facilitate the resonance operation between leakage inductances of BTs and the converter's capacitors.

C. Combined capacitor and inductor-based circuits

One effective way to take advantage of both capacitor-based and inductor-based techniques is to combine capacitor and inductor in one network. Its operational principle relies on the energy exchange between capacitors and inductors. These networks can be divided into the voltage lift (VL), impedance source (Z-source), and quadratic networks.

1) Voltage lifting networks

The bidirectional elementary VL cell is shown in Fig. 5(a). In the forward mode, the capacitor and inductor are charged in

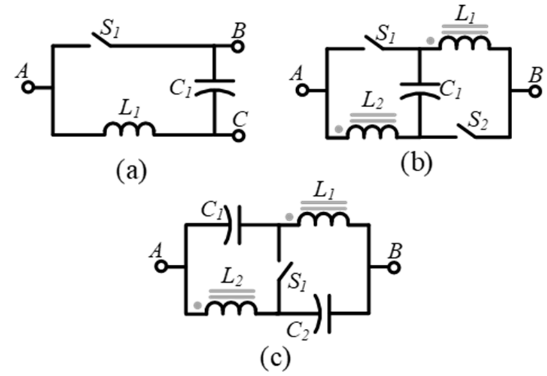

Fig. 5. Different structures of VL cells: (a) elementary VL, (b) SL-based VL, (c) modified SL-based VL.

parallel on the LV side when the switch is on; they will be discharged in series to the load when the switch is off. This VL cell is used alongside an A-SC cell in [27] to benefit from both cells' advantages. The voltage gain of the elementary VL cell can be improved by integrating it into a bidirectional SL cell and producing an SL-based VL cell, as shown in Fig. 5(b). This cell is modified by [28], in which two capacitors are used instead of switches, and its capacitor is replaced by a switch, as shown in Fig. 5(c). Although it has a higher voltage gain, its single switch experiences higher voltage and current stresses, and its total volume is bigger than the SL-based VL due to a higher number of passive components.

2) Impedance source networks

Z-source networks are one of the most popular techniques to increase the voltage gain. The first impedance network introduced in [29] has a simple structure, which is comprised of two inductors and two capacitors. Despite its simple passive structure, it has several drawbacks, such as high current stresses on the switch, a high volume of its passive components, a high inrush current, and the lack of common ground between the input and the output. The quasi-Z-source network is a famous derivation of the Z-source network, which improves the inrush current and provides a common ground [30].

These two networks are used in several BDC studies [15], [28], [31]. A Z-source-based BDC is introduced in [28], where inductors of the Z-source are replaced by the modified SL-based VL cells to increase the voltage gain of the network. In [15], a bidirectional QZ-source converter is introduced. The diode in the unidirectional QZ-source converter is replaced by a power MOSFET to enable bi-directional power flow in the network. This converter is the inspiration of a study in [31] by adding a VMM on its HV side to increase its voltage gain.

3) Quadratic networks

The quadratic network can bring a wide range of voltage gains using a small duty ratio, as the voltage gain in these converters has a relationship to the square of a duty ratio. A quadratic converter based on the BBBC is proposed in [32] with one elementary VL cell in its configuration to boost up the voltage gain. This converter comprises four switches and two diodes. However, only one switch operates in the forward mode, and other switches are always turned OFF; or only one switch operates in the backward mode, and other switches are always turned ON, which imposes high costs on the circuit. To efficiently use semiconductors, an expandable bidirectional quadratic cell is introduced in [33]. This BDC has a simple structure comprised of two active switches, one inductor and one capacitor; its control method is also simple since just one switch is operated in forward and backward modes.

Another method to design a quadratic structure is a cascaded connection of several converters [26]. This method is used in a transformer-less three-port converter, in which all ports have the bidirectional power flow capability [34]. In this converter, an HB-BDC is cascaded with a high-gain converter to achieve a quadratic voltage gain. Another quadratic structure is introduced in [35], which has a modified A-SC cell in its structure to boost its voltage gain; it has a complex structure consisting of seven switches, but only two switches operate in the forward mode, and other switches are utilized for the backward mode. Although offering a wide voltage gain, quadratic converters have a higher sensitivity to the duty cycle, and thus, an accurate control method is needed for these types of converters, and parasitic parameters must be carefully considered.

D. Mixed structures

Mixing several structures in a DC-DC converter design is another approach to obtain a high voltage gain. In this method, at least two structures with a specific arrangement are connected. These arrangements can be categorized into interleaved and cascaded structures.

1) Interleaved structures

The general structure of an interleaved converter is shown in Fig. 6(a), where at least two BDCs are in parallel using two inductors on the LV side, and the inductors can be integrated into one core to reduce the number of magnetic cores. Asymmetrical operations S_1 and S_2 enable the interleaved structure to have low current ripples on the LV side. Interleaved converters typically do not have a direct impact on the voltage gain, but they provide several power flow paths to increase the power handling capability and reduce current and voltage stresses on components. As a result, the interleaved converter can operate at higher duty cycles, and can indirectly contribute to a higher voltage gain [22].

There are many bidirectional interleaved studies in the literature. For instance, two BBBCs are interleaved in [36]; by proposing an auxiliary circuit, power losses can be minimized. The auxiliary circuit guarantees ZVS operations of the main switches, and zero current switching (ZCS) for the auxiliary switches. Another two-phase interleaved BBBC-based converter is introduced in [37] with a resonant network on the HV side to increase efficiency by providing soft-switching operations. Its resonant network comprises a four-winding coupled inductor and four capacitors, and the leakage energy of the coupled inductor is recycled to prevent voltage spikes on switches. The winding-cross-coupling inductor (WCCI) is a coupled inductor-based method that can improve the voltage gain of interleaved converters [38], where two three-winding coupled inductors are used as input inductors, and their windings are shared between two legs of the interleaved BDCs, as shown in Fig. 6(b). The WCCI approach increases the voltage gain, reduces current ripples on both LV and HV sides, and reduces voltage stresses on semiconductors.

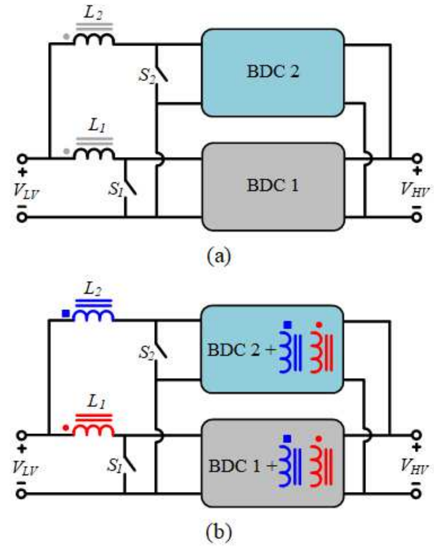

Fig. 6. Configurations of the two-phase interleaved structure: (a) General configuration, (b) with WCCI.

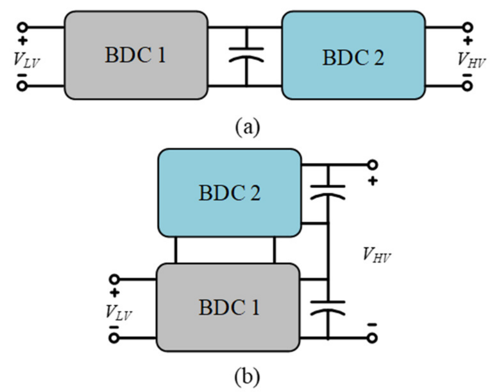

Fig. 7. Schematics of the cascaded structures: (a) horizontal connection, (b) vertical connection.

2) Cascaded structures

The cascaded structures provide a high voltage gain by integrating two or more converters into one structure. As shown in Fig. 7, there are two general cascaded connections of two BDCs, horizontally and vertically. In a horizontal connection, the output of the previous stage is the input of the next stage. Therefore, in the forward mode, the first stage provides a higher input voltage for the second stage, and similarly in the backward mode. Therefore, the resulting structure has a higher voltage gain than those with a single BDC. However, elements of the first stage experience a lower voltage stress than those of the second stage [26]. On the other hand, in vertical cascaded converters, each BDC operates independently, and their HV sides are added up to obtain a higher voltage gain. Thus, voltage stresses are distributed among all components. This method is utilized in [39], where two HB-BDC converters are connected

TABLE I
ADVANTAGES AND DISADVANTAGES OF DIFFERENT METHODS OF INCREASING VOLTAGE GAINS FOR BDCS

Method	Advantages	Disadvantages
Capacitor-based networks	• Simple structure • Expandable capability • Low cost	• High voltage and Current stress on the switches. • Limited power handling • High switching losses • Limited voltage gain
Inductor-based networks	• Low number of components • Adding one more degree of freedom in designing the converter by the contribution of turn ratio in the voltage gain • Expandable capability • Low cost	• An additional circuit is needed to restore energy in leakage inductance and prevent undesirable voltage stress on the power switches. • Increase the complexity of the control circuit. • High current stress on the switches • Limited power handling • Limited voltage gain
Combined capacitor and inductor-based networks	• Lower number of semiconductors • Wider range of voltage gain compared to capacitor and inductor-based techniques.	• High current stress on the switches • High sensitivity to duty cycle variations.
Mixed structures	• High power handling capability • Low current and voltage stress on the components • Low LV side current ripple	• High number of elements • Circulating current and higher conduction losses • High cost

vertically to provide a high voltage gain. In this study, a capacitor is in series with the input inductor of the second HB-BDC to provide a resonant circuit and soft switching operations for all switches. In addition to reducing power losses, the temperature of semiconductors can be reduced, so they only need a smaller heat sink, making the volume of the converter smaller. A combination of interleaved and cascaded structures can take advantage of both structures simultaneously [40], where an interleaved BBBC is cascaded with the secondary side of a DAHB converter. There are two windings in series in the DAHB converter, coupled with each input inductor of the interleaved structure. Besides a high voltage gain, it utilizes a differential voltage method to provide ZVS for all switches.

III. COMPARISON

In this section, a comparison among different high voltage gain techniques is provided for BDCs, as shown in Table I, showing advantages and disadvantages of each method. Capacitor and inductor-based techniques are the simplest solution to increase the voltage gain of a BDC. However, their voltage gain and power handling are limited. These structures can be expanded to increase the voltage gain further, but it increases the number of elements and the total cost of the converter. The combined networks have a higher voltage gain compared to previous methods and utilize a lower number of semiconductors in their structures, but they have a higher sensitivity to variations in the duty cycle, so the parasitic elements and EMI should be carefully considered in the control strategy. The power handling capability and the voltage gain can be increased by integrating several structures. In this method, the converter components experience a lower voltage and current stress than a single structure, but it has a higher number of elements, cost, and conduction losses due to circulating currents between the mixed structures.

IV. CONCLUSION

In this paper, a comprehensive review of recent high voltage gain non-isolated BDCs is conducted. These converters have a compact size, lighter weight, and lower power losses than isolated BDCs. It is identified that there are four primary methods for increasing the voltage gain in the converters: inductor-based, capacitor-based, combination of capacitor and inductor-based, and mixed structures-based methods. Due to increasing renewable energy integration in power grids, energy storage systems and electric vehicle applications require more advanced bidirectional DC-DC converters.

The future research directions of BDCs include:

- Develop compact, high-efficiency bidirectional converters using wide-bandgap (WBG) devices, such as silicon carbide (SiC) and gallium nitride (GaN): this is crucial to improve power density and reduce costs of the converter. WBG devices offer higher efficiency and faster switching speeds, but they also pose challenges, such as lower parasitic capacitance and potential EMI issues.
- Develop high power BDCs using mixed structures: these structures can be utilized instead of multiple lower-power converters, reducing the system size and costs in high power applications. However, their complex structure and control methods present challenges, requiring further optimization in the future research.
- Improve the system reliability by developing fault-tolerant BDCs: faults in converters are inevitable due to the limited component lifespan, and advanced fault-tolerant topologies or control methods are essential to prevent system shutdowns and provide a constant power supply for the load.

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