Chapter 2

Review of High Gain Bidirectional Converters

2.1 Introduction

The study of bidirectional power converters has become a significant field of research in power electronics. As opposed to conventional unidirectional converters, the power flows in both directions in bidirectional converters. As such, these converters are flexible and are widely used in electric vehicles (EVs) or hybrid electric vehicles (HEVs), renewable energy systems. By interfacing between power sources and energy storage elements, the bidirectional configurations reduce the size and improve the efficiency and performance of the system as there is no need to use two individual converters for the forward and reverse power flow. Depending upon the location of the energy storage system, the converter acts as a buck or boost type and the respective control system is used to regulate the voltage or current of the system.

The general structure of the bidirectional DC-DC converter is depicted in Figure 2.1. A bidirectional DC-DC operates controllable wide-range voltage operation under continuous conduction mode or discontinuous conduction mode by controlling the duty of active switching devices. The application of a bidirectional power converter is not limited to electric vehicles. Another application of this converter is in the broad area of renewable energy systems such as Fuel-cell or Photovoltaic based systems when supplying either DC load or AC load via an inverter.

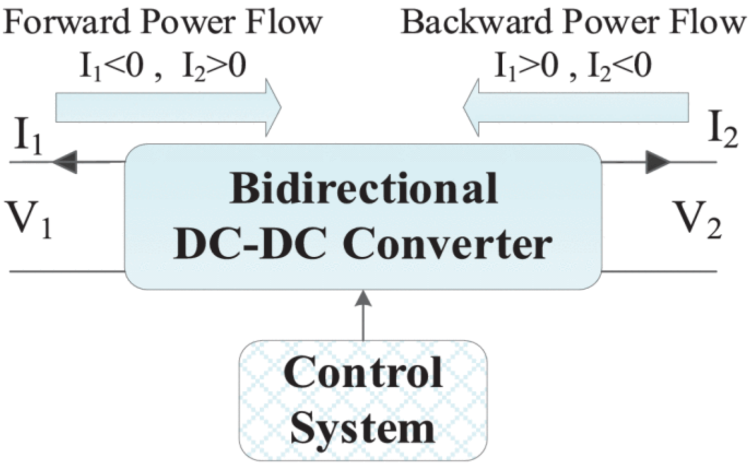

Figure 2.1: The structure of bidirectional DC-DC converter.

2.2 Classification of bidirectional DC-DC converter

The bidirectional DC-DC converters can be categorized into two main groups of configurations, namely isolated and non-isolated topologies. The classification of the bidirectional DC-DC converter is shown in Figure 2.2.

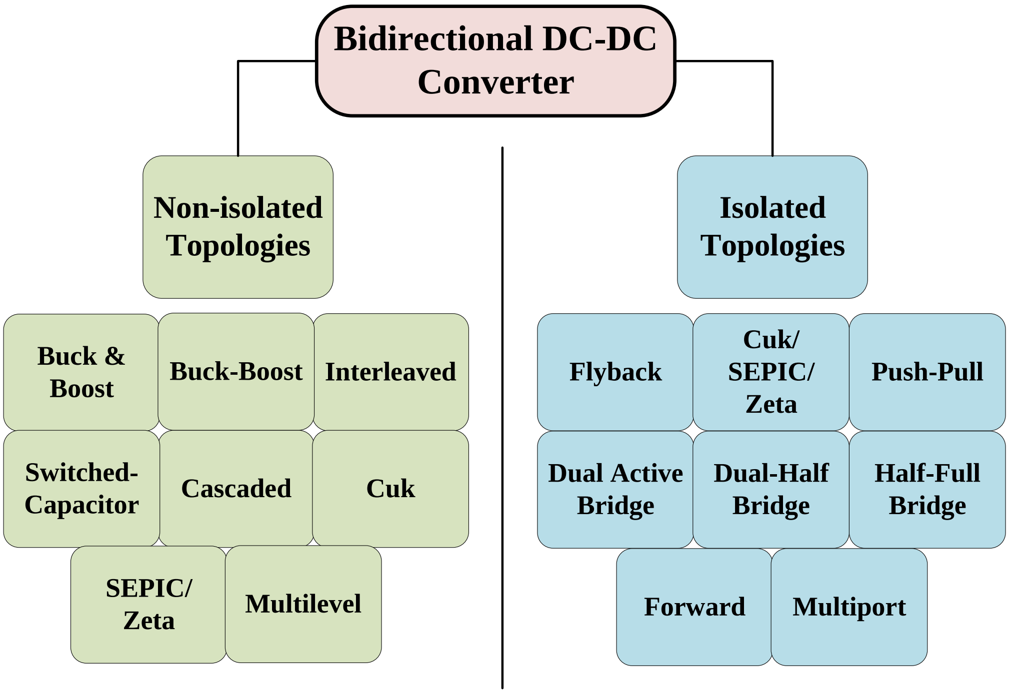

Figure 2.2: The classification of bidirectional DC-DC converters.

2.2.1 Isolated bidirectional DC-DC converter

In some applications, isolated bidirectional DC-DC converters are needed where galvanic isolation is available. These characteristics make them suitable when size and weight are important concerns in electric vehicle application. In contrast, the isolated topologies basically convert the DC voltage to AC voltage waveform which passes through a high-frequency transformer and then is rectified to DC waveform. Depending on the input circuit, the converters are classified as voltage-fed and current-fed converters. The voltage-fed converter is fed ideally by a zero Thevenin impedance voltage source means that there is no input impedance. Voltage boosting is achieved by the winding ratio of the transformer, which requires a high winding ratio. Due to the high transformer ratio, the leakage inductance of the transformer becomes large. The main problem with the full-bridge voltage-fed converter is the pulsating current at the input which increases the filter size; a snubber is also needed on the secondary side.

In [43], presented an isolated bidirectional converter on the primary side of half-bridge and a current-fed push-pull converter on the secondary side of a high-frequency transformer. This type of converter has low power application and its efficiency is low due to transformer. Hui Li et al. presented a dual half-bridge bidirectional converter for hybrid electric vehicle [1]; unified Zero voltage switching (ZVS) was achieved in either directional of power flow with neither a voltage-clamped circuit nor extra switching devices with resonant components which is shown in Figure 2.3. To turn off the main conducting device diverts the current to the corresponding snubber capacitors to charge one and discharge another, resulting in a zero-voltage turn-off.

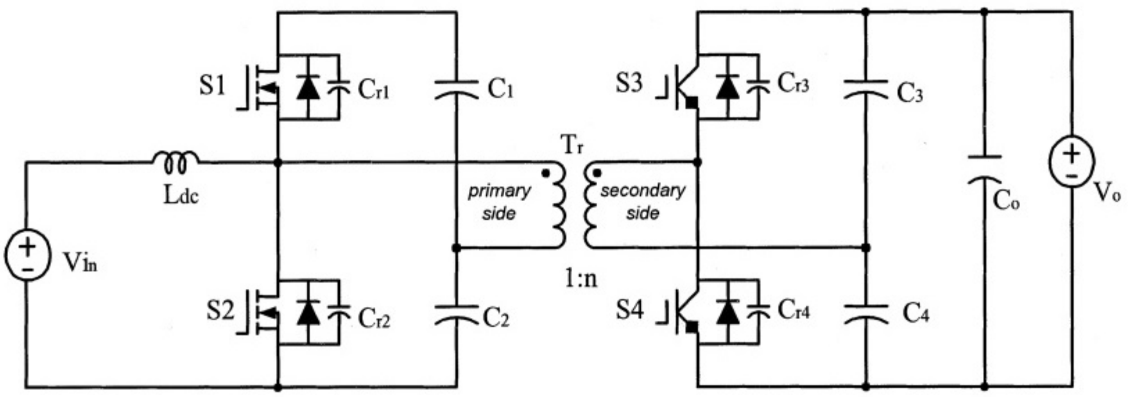

Figure 2.3: Soft-switched bidirectional dual half-bridge dc-dc converter [1].

The zero-voltage turn-on is achieved by gating on the incoming device while the antiparallel diode is conducting. Chui et al. discussed a new bidirectional, isolated topology for fuel cell electric vehicle application [2] which is shown in Figure 2.4.

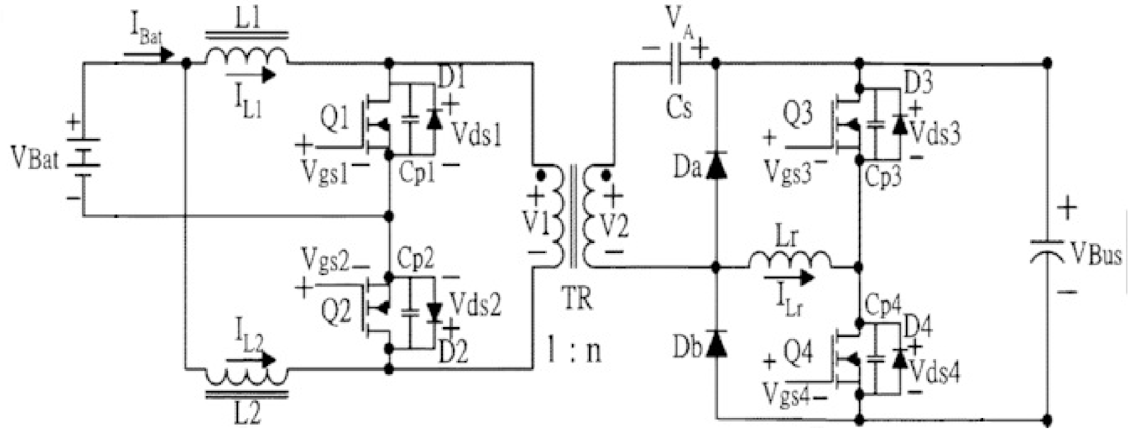

Figure 2.4: Isolated bidirectional converter [2].

Wu et al. presented an isolated bidirectional full-bridge converter with flyback snubber circuit [3] which is shown in Figure 2.5. The use of a capacitor, a diode, and a flyback converter can clamp the voltage spike caused by the current difference between the current-fed inductor and leakage inductance of the isolation transformer and can reduce the current flowing through the active switches at the current-fed side. The extra snubber circuit is employed to reduce voltage stress on switches and it recovers leakage inductance energy of transformer which increase component count. The efficiency of this converter is low due to the transformer.

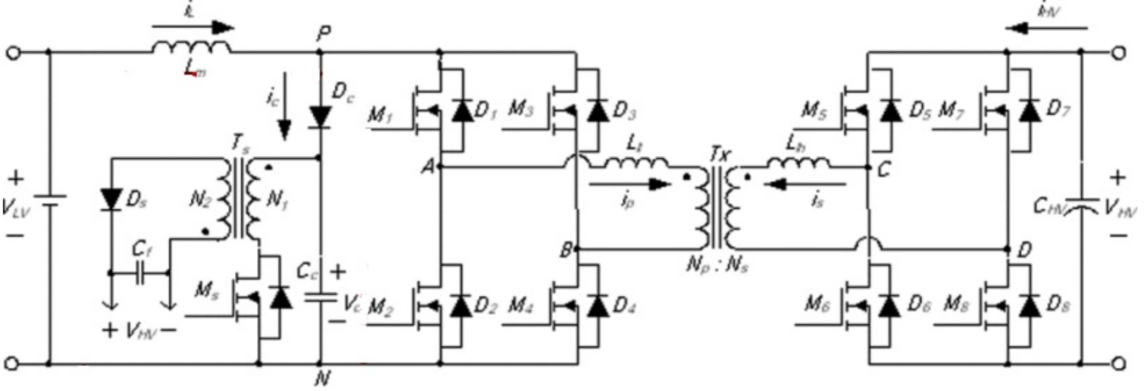

Figure 2.5: Isolated bidirectional full-bridge converter with a flyback snubber [3].

Prasanna et al. discussed the active clamped current-fed full-bridge isolated converter [44]. This converter provides ZVS for all switches and the additional clamping branch eliminates the turn-off voltage spike which helps to reduce the voltage ratings of the power devices. In [4], discussed the Z-source isolated bidirectional converter with H-bridge located o primary and secondary sides of the transformer shown in Figure 2.6. This converter has a large number of components and low efficiency due to the transformer. This type of converter is valid for low-power applications.

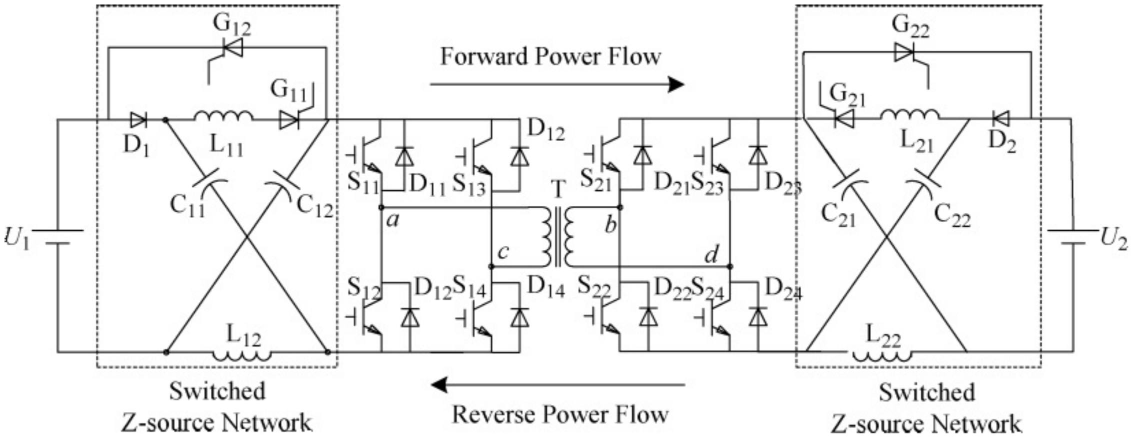

Figure 2.6: Z-source isolated bidirectional full-bridge converter [4].

Liang et al. presented a novel isolated bidirectional converter [5] with dc-blocking capacitor in the high-voltage side to reduce voltage on transformer and current doubler circuit are used in low-voltage side to reduce the output ripple current as shown in Figure 2.7.

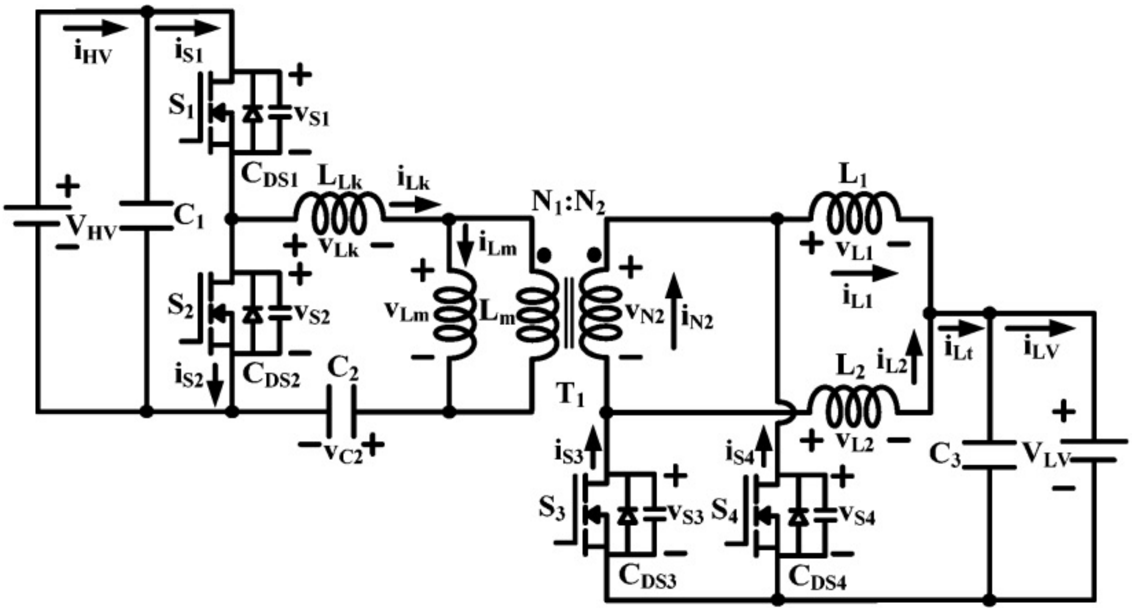

Figure 2.7: High-conversion-ratio isolated bidirectional dc–dc converter [5].

The converter has high voltage gain and high efficiency but it can be used for low power applications. For high power application, the leakage inductance of the transformer will be high and which cause high power losses. Tseng et al. discussed a novel high voltage gain isolated interleaved bidirectional converter [6]; voltage doubler circuit on the high-voltage side and active clamp circuit to recover the energy of leakage inductance. Moreover, some switches are operated with soft-switching and slightly reduced switching losses. The isolated bidirectional interleaved converter is shown in Figure 2.8. Another multiport isolated bidirectional converter is proposed by Savrun et al. [45]. The system integrates quasi-Z-source and H-bridge converters with an existing switch. Thus, a four-port converter is achieved without any need for individual converters or additional switches. Besides, the high-gain quasi-Z-source converter [46, 47] allows the reduction of the rated voltages of the battery and supercapacitor packs, as well as allows using a high-frequency transformer (HFT) with a low turn ratio. The isolation between ports is provided by a secondary centre-tapped HFT. The secondary side of the HFT is equipped with a full-wave controlled rectifier to provide bidirectional power flow.

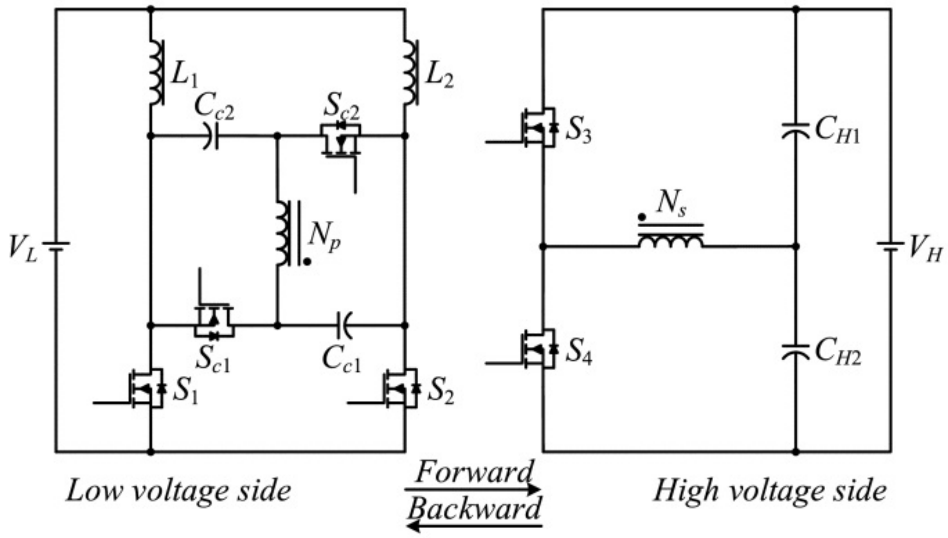

Figure 2.8: Isolated bidirectional interleaved converter [6].

This converter has a large number of components and transformer leakage inductance limits the voltage gain. Wu et al. presented a high gain isolated bidirectional topology with the combination of buck-boost and forward-flyback converter [7] is illustrated in Figure 2.9. There are several flyback bidirectional converters presented in [48–51]. This proposed topology also has the function of leakage inductance energy recovery, reducing the voltage surges on switches, and having the characteristics of zero voltage switching on certain switches. The components count is high which leads to an increase in the losses for high power applications and low efficiency. A snubber circuit is used for energy recovery in the leakage inductance of the transformer as well to reduce the voltage stress on switches. Several researches have been developed isolated flyback, half-bridge, full-bridge, interleaved type topologies in the past decades [52–70].

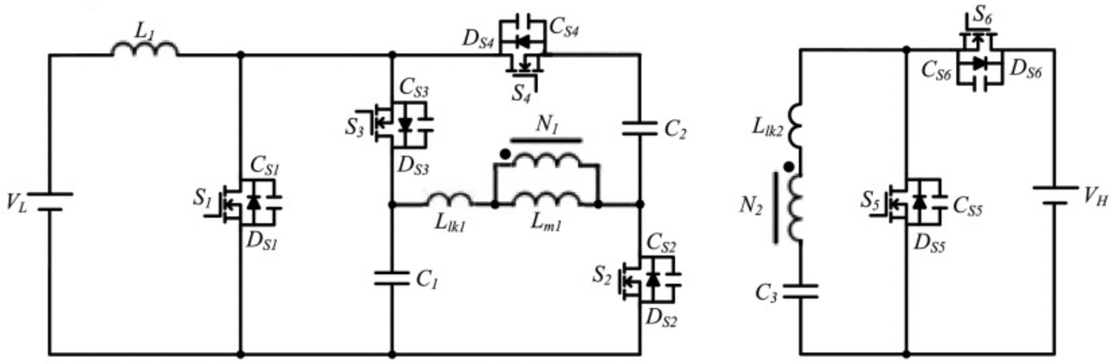

Figure 2.9: High voltage gain isolated bidirectional converter [7].

2.2.2 Non-isolated bidirectional DC-DC converter

Non-isolated bidirectional converters have a simple structure, high efficiency, high reliability, and low cost. The basic non-isolated converter consists of a single switch and a single diode and may have one inductor and one capacitor as storage elements. Other non-isolated converters are having two switches, two diodes, and additional energy storage elements. Non-isolated converters are commonly used in EVs applications. The conventional buck/boost converter is designed and developed by G.W. Wester [8]. Three types of topology (a) buck (b) boost (c) buck-boost convert as shown Figure 2.10. There are the different topologies of buck/boost converter is designed and proposed [71, 72]. A typical non-isolated bidirectional dc-dc converter with soft-switching for high power application is constructed and tested [73].

The Discontinuous conduction mode (DCM) operation associated current ripple can be alleviated by interleaving multiphase currents. However, DCM operation tends to increase turnoff loss because of a high peak current and its associated parasitic ringing due to the oscillation between the inductor and the device output capacitance. Thus, the efficiency is suffered from the conventional DCM operation. Although to reduce the turnoff loss a lossless capacitor snubber can be added across the switch. Pritam et al. presented a non-isolated bidirectional converter [74]; soft-switching with an active clamped circuit. The efficiency of the converter is improved compared to hard-switching but an extra clamped circuit is used and it can be used for low power applications. Pritam et al. also discussed ZVS non-isolated bidirectional converter with a coupled inductor for high voltage gain [75]. An auxiliary circuit is used to reduce the voltage stress and recovery of energy in leakage inductance. Homg et al. discussed a novel non-isolated bidirectional converter with a coupled inductor for high voltage gain [76]. The leakage inductance causes high voltage stress on switches and energy loss. Therefore this converter is suitable for low power applications. The voltage gain of the converter is the same as conventional buck/boost and an extra auxiliary circuit is used to reduce the voltage stress and recovery of leakage energy.

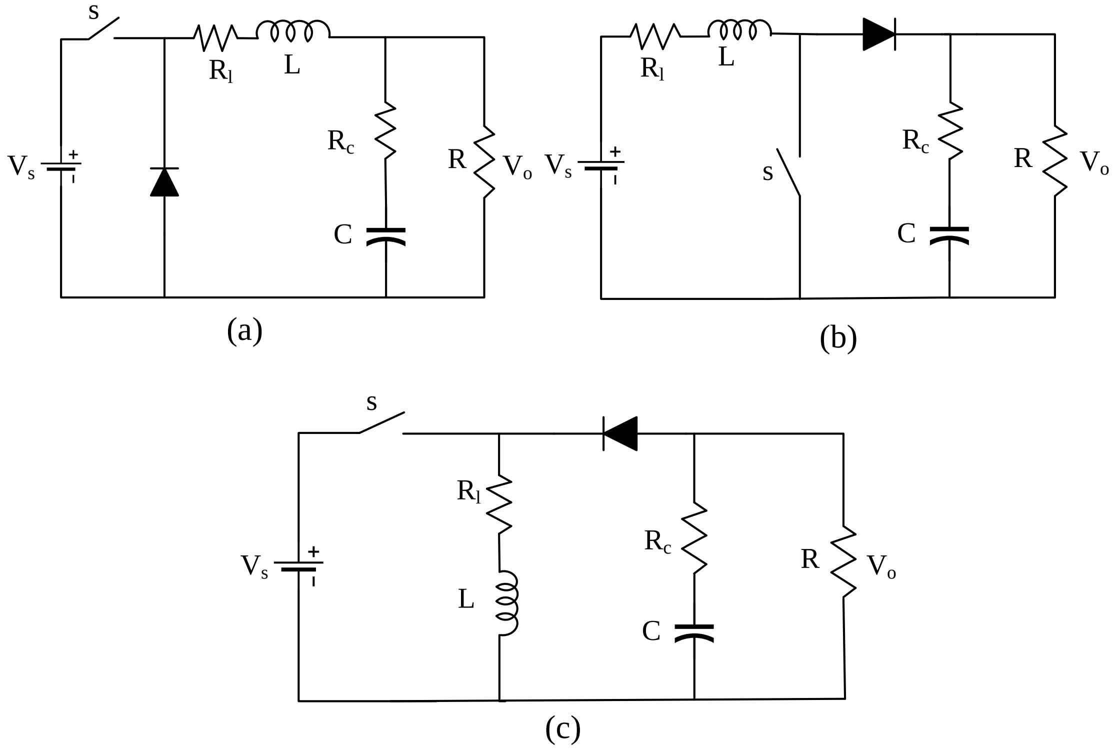

Figure 2.10: The circuit configurations of conventional converter (a) Buck (b) Boost (c) Buck-Boost presented in 1972 [8].

The non-isolated converters, Half-bridge, Cuk, SEPIC, and Luo converters, can be used in EVs application. Fernando et al. presented a novel non-isolated bidirectional converter based on a three-state switching cell and voltage multiplier cell for high voltage gain [77]. A small snubber is necessary for each switch and one additional winding per cell is required for the autotransformer. However, the converter cannot operate adequately when a duty cycle is lower than 0.5 due to magnetic induction issues. The hard commutation of switches and the high component count are also possible drawbacks. The direction of power flow control is complex and a large number of components are required. Sheng et al. proposed a novel bidirectional converter with a coupled inductor for high voltage gain [78]. The converter has higher step-up and step-down voltage gains and a lower average value of the switch current than the conventional bidirectional boost/buck converter. But leakage inductance of coupled inductor voltage stress on switches as well as energy losses. Therefore overall efficiency of the converter is low and it is not suitable for high power application. Lin et al. presented a non-isolated bidirectional converter for wide voltage-conversion range [9] which is shown in Figure 2.11. The voltage gain of the converter is half and double of the conventional bidirectional DC-DC buck/boost converter in the step-down and step-up modes, respectively. The control strategy is easy to implement. The voltage gain of the converter is limited by the duty cycle and it is suitable for low power application.

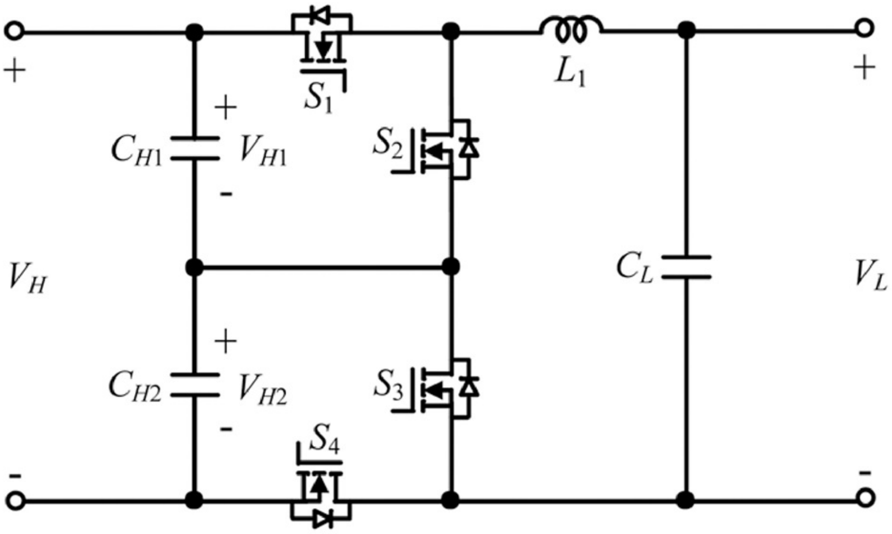

Figure 2.11: Non-isolated bidirectional converter proposed in [9].

Another high-conversion ratio bidirectional converter with a coupled inductor is proposed in [79]. The coupled inductor causes high voltage stress on switches and energy losses. The voltage stress on the main switch is reduced by a passive clamp circuit. Due to two active clamp circuits, the energy of the leakage inductor of the coupled inductor is recycled. In these coupled inductor converters, in general, the effort to overcome the problem associated with a leakage inductor of the coupling inductor is nontrivial, and the capacity of the magnetic core should substantially be increased as the required output power is increased. Therefore, these topologies incorporating the coupling inductor are not suitable for high-power applications. Also, the input current ripple is considerable due to the operation of the coupling inductor. A soft-switching bidirectional converter using active snubber described in [80,81]. ZVS of main switches is achieved by utilizing an active snubber which consists of auxiliary switches, diodes, an inductor, and a capacitor. The disadvantage of this converter is that high circulating current always flows through an auxiliary inductor and a capacitor for satisfying soft-switching of switches, irrespective of load. So, high conduction losses are induced from the resistance of an auxiliary inductor, a capacitor, and switches. The common issue with the soft-switching converters is the limited soft-switching operation range due to the output current dependence of the soft-switching operation. This converter can achieve ZVS turn on of all switches and Zero current switching (ZCS) turn off some switches in both boost and buck operations. However, this converter is not suitable for high voltage gain at a low duty cycle.

The voltage gain of the bidirectional converter can be increased by replacing two inductors with coupled inductor depending on turns ratio [82, 83]. However, these converters suffer from high voltage stresses on the power devices due to the leakage inductor energy of the transformer. To recycle the leakage inductor energy and to minimize the voltage stress on the power devices, an additional voltage clamp circuit is needed. There are different types of non-isolated or transformerless bidirectional dc-dc converter proposed in the past decade [84]. The duty cycle and phase shift angle of the PPS control strategy can not only balance the voltage of the high and low voltage side sources. The high voltage gain of the converter is limited by the duty cycle. Three-level bidirectional converter with the zero-voltage transition for high voltage gain is proposed in [85]. But it has two identical Zero voltage transition (ZVT) cells are deployed for each pair of switches, ensuring that all four switches are turned on under zero voltage in both boost and buck modes. When the ZVT cell designed for a light-load condition operates under heavy load, the effective on-time of the switches becomes less than the reference. To partially compensate for this negative effect on the duty ratio of the main switch, the auxiliary switch is controlled by adjusting the dead time with respect to the peak inductor current. A cascaded switched-capacitor bidirectional converter for high voltage gain is implemented in [10] as shown in Figure. 2.12. The large number of components are required for high voltage gain. The switched-capacitor converter is limited to low power application.

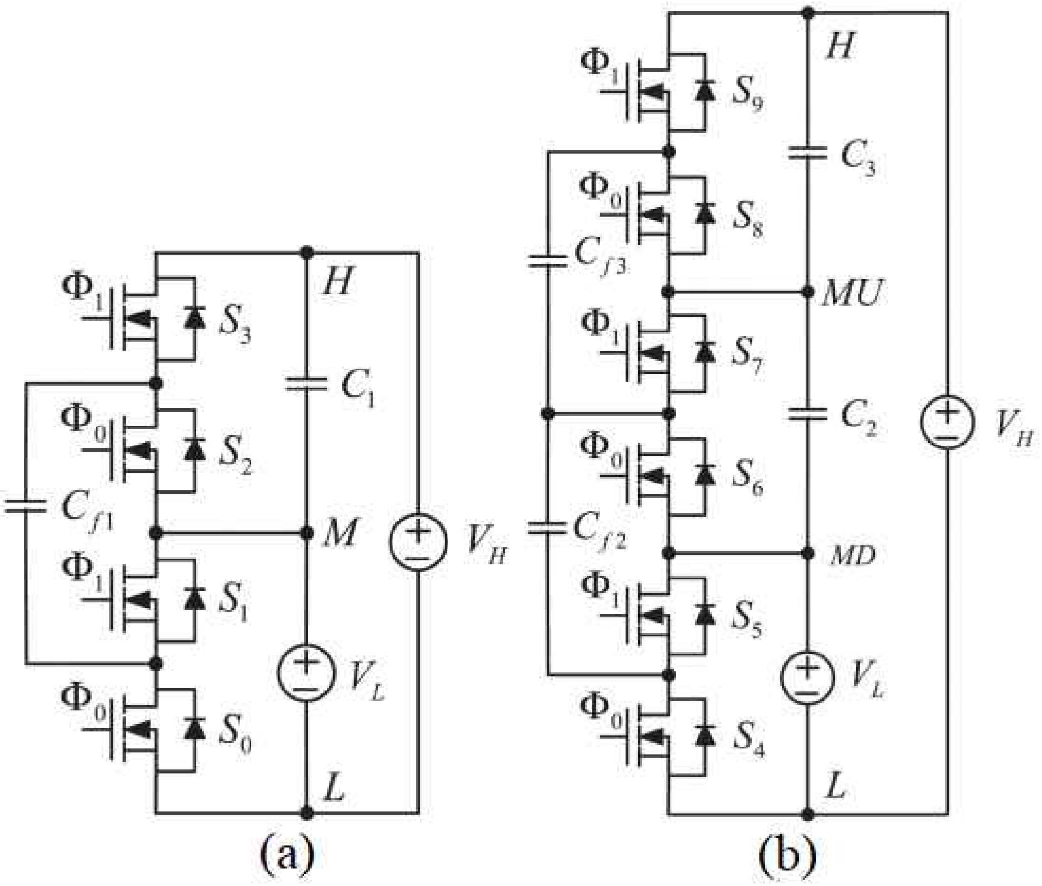

Figure 2.12: Basic bidirectional SC structures of (a) two-time and (b) three-time conversion ratio [10].

Another type of interleaved high gain bidirectional converter based on a switched capacitor and coupled inductor is presented in [86, 87]. This converter required a large number of components for high voltage gain and coupled inductor leads to energy losses. Zhang et al. proposed interleaved switched-capacitor bidirectional converter [11] which is shown in Figure 2.13. The interleaved structure is adopted in the low-voltage side of this converter to reduce the ripple of the current through the low-voltage side, and the series-connected structure is adopted in the high-voltage side to achieve the high step-up/step-down voltage gain. But a large number of components are required to get high voltage gain and large components lead to high losses, therefore its efficiency is low. Another non-isolated interleaved coupled-inductor soft-switching bidirectional converter is discussed by Bahrami et al. [12] as shown in Figure 2.14. The converter combines the interleaved conventional buck-boost converter and the dual-active half-bridge converter.

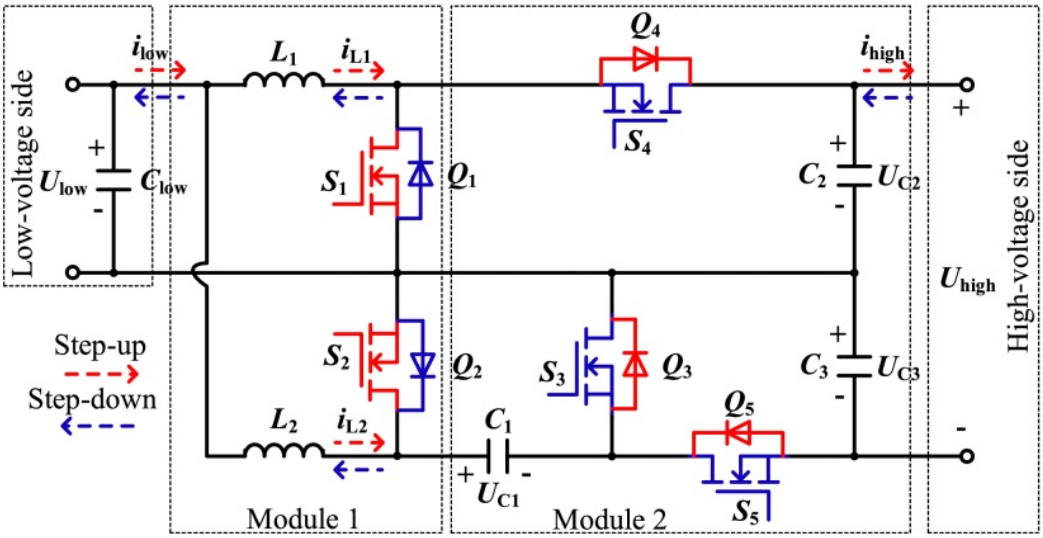

Figure 2.13: Interleaved switched-capacitor bidirectional converter proposed in [11].

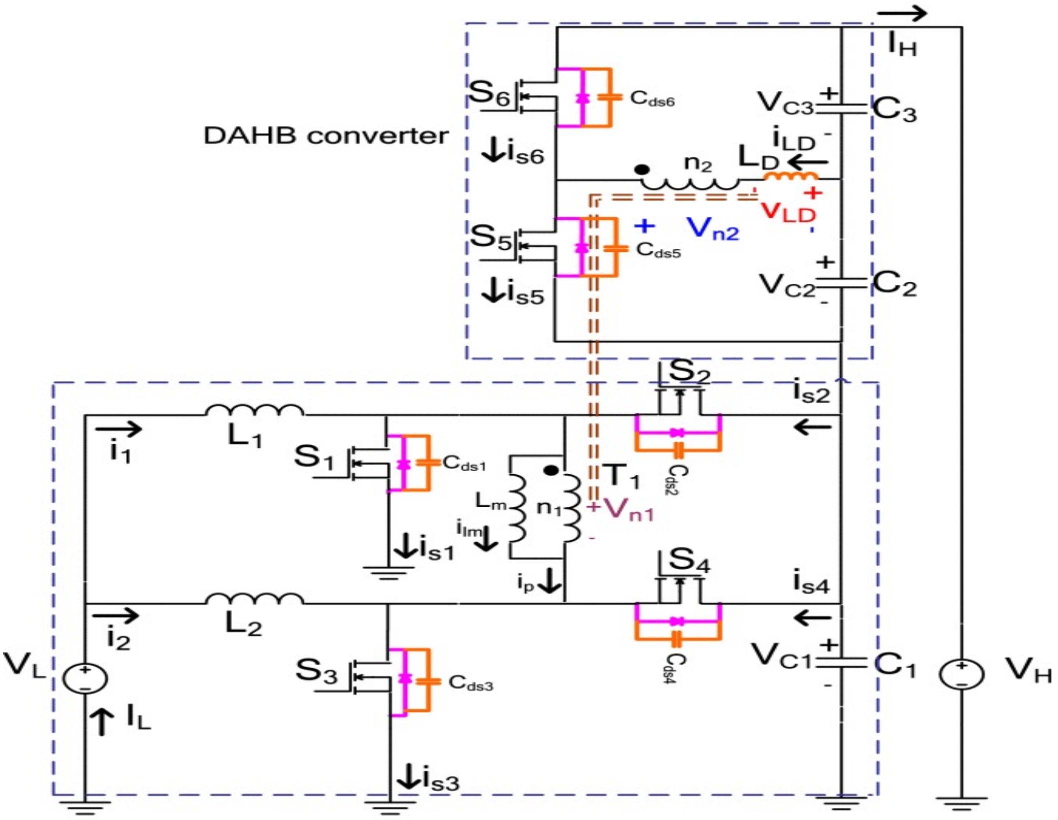

Figure 2.14: Interleaved coupled-inductor bidirectional converter proposed in [12].

By connecting in series the outputs of the converters, the voltage stress across the main switches decreases, and the voltage gain increases. The coupled inductor is placed in such a way, that in addition to increasing the voltage gain, the ZVS turn-on condition for all switches is also realized in both directions of power flow. The disadvantage of this converter is that power rating is limited by the saturation of coupled inductor, control is complex, and dual-active half-bridge increased components counts. Shreelakshmi et al. presented a high voltage gain bidirectional converter with coupled inductor [13] as shown in Figure 2.15. It also has inherent soft-switching capability during turn ON of the switches, enabling high switching frequency operation. This converter uses only one coupled inductor for both boost and buck modes, leading to a compact system. A clamped capacitor network is used to recover the leakage energy. This type of converter has low power application due to coupled inductor.

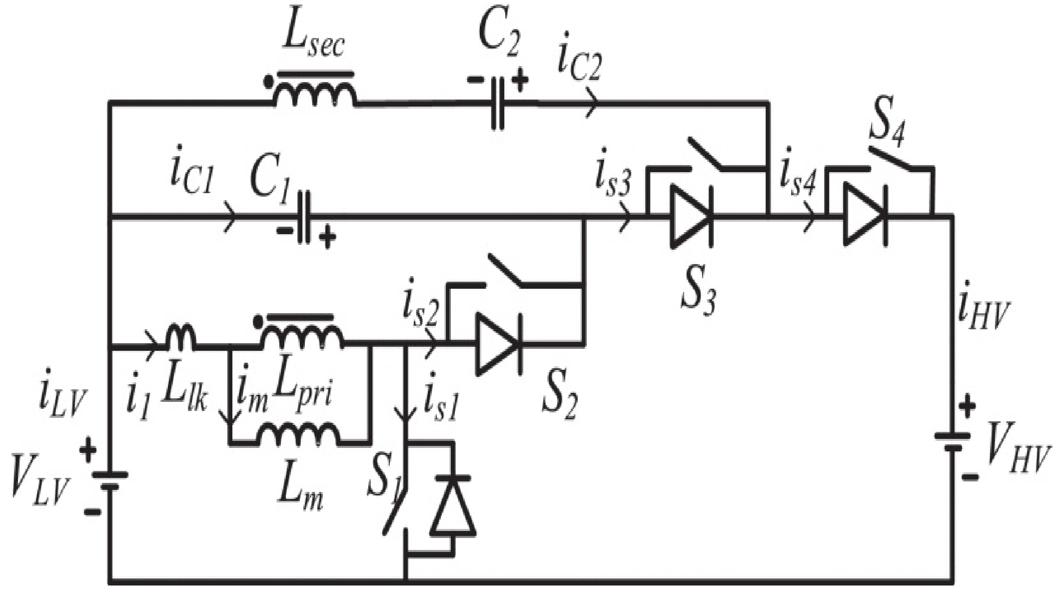

Figure 2.15: Coupled-inductor based high voltage gain bidirectional converter [13].

Lee et al. described a new cascaded buck-boost and auxiliary capacitor bidirectional converter [14] as shown in Figure 2.16. However, operation in DCM causes high ripples in the output voltage and current. The combined structure of the converter reduces the output voltage and increases efficiency by effectively reducing the output current ripple. The converter output current ripple is still high and its power rating low.

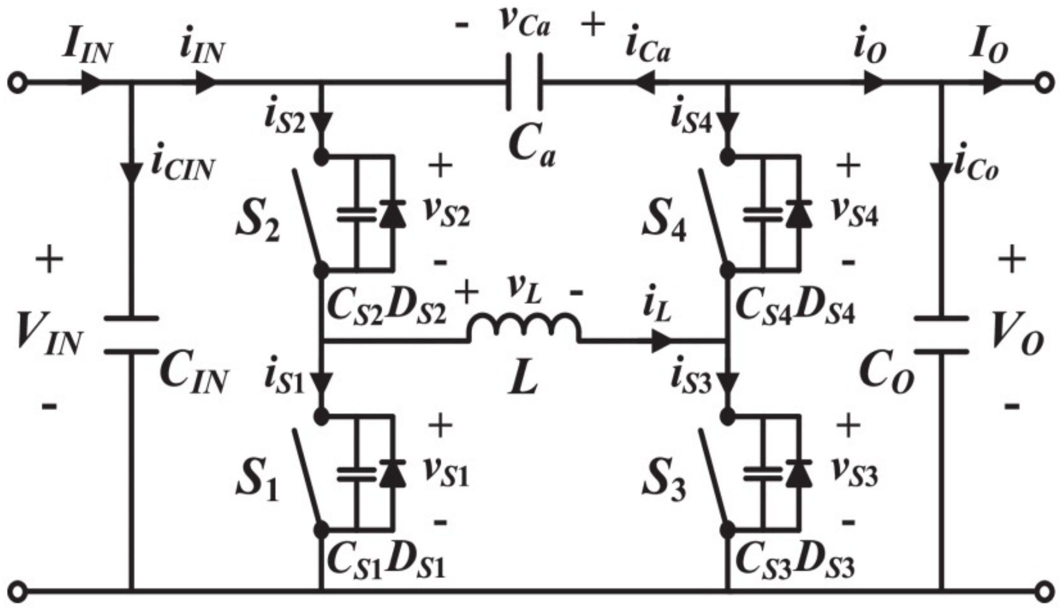

Figure 2.16: A new cascaded buck-boost bidirectional converter [14].

Yan et al. presented a novel interleaved bidirectional converter for high voltage gain [15] as shown in Figure 2.17. A T-type neutral point-clamped circuit is integrated into an interleaved conventional buck-boost BDC to obtain a high voltage-gain ratio and decrease voltage stresses of power switches effectively. The interleaved structure is employed to reduce the current ripple in the low-voltage side and helps to achieve voltage matching on both sides of the built-in transformer under pulse width modulation control. Yan et al. also discussed soft-switching interleaved bidirectional converter [88]. The problem of this converter is complex in control and a large number of components are required for high voltage gain. Another interleaved coupled-inductor bidirectional converter is proposed by Fardahar et al. [89]. The high voltage gain of the proposed converter is achieved through its symmetrical topology with coupled inductors in its structure. Based on the fact that the voltage of the high-voltage side is shared between the two separate modules of the converter, the voltage stress across the switches is decreased. On the primary side, there are two blocking capacitors that assist the converter to maintain its symmetrical topology. The voltage stress across the active switches is reduced and the voltage gain is raised by interleaving and parallel-connecting the converter's modules. Tohid et al. proposed a three-port bidirectional converter in renewable energy application [90]. The demanded power of the load can be provided by each input source individually or simultaneously. The voltage stress on switches is high and the direction of power flow control is complex.

Moreover, this type of converter is suitable for the low-power application.

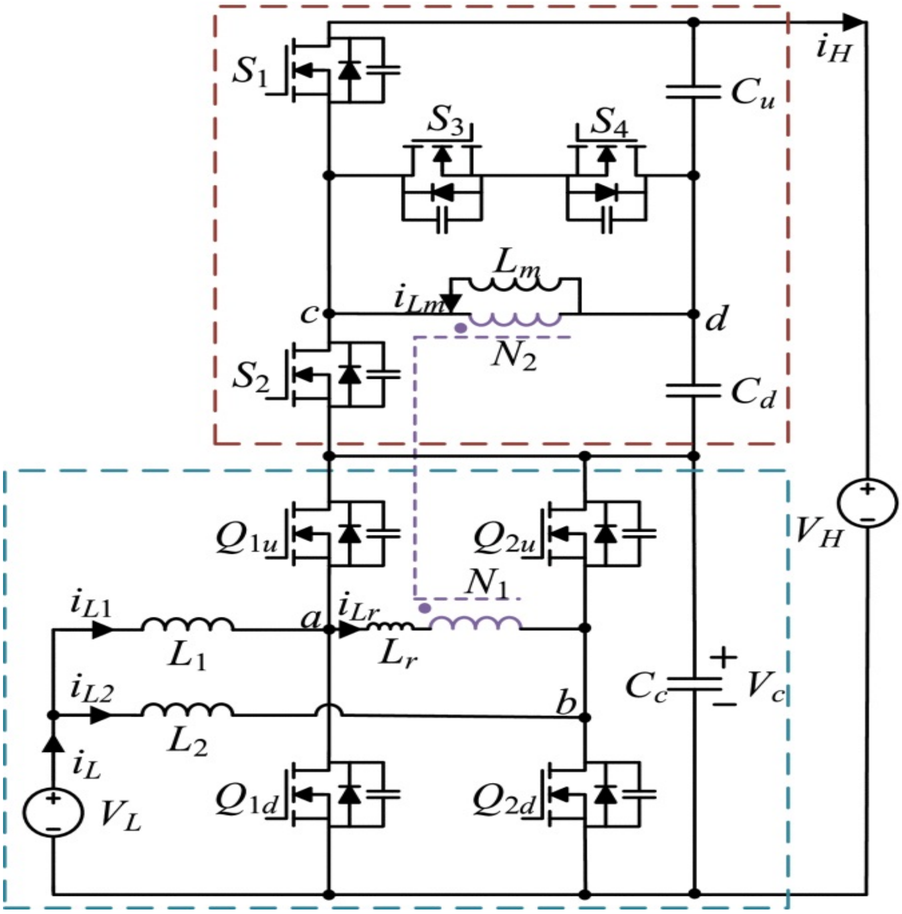

Figure 2.17: A new interleaved bidirectional converter with built-in transformer [15].

A switched-capacitor interleaved bidirectional dc-dc converter that combines a three-phase interleaved structure with switched-capacitor cells is proposed [91]. A three-phase interleaved topology based on switched-capacitor cells also decreases current ripple on the LVS and voltage stresses across the power switches. This converter is simple to modify and has a common ground between the input and output. The switched-capacitor is limited by current because the capacitor can not operates at a high current. Therefore this type of converter is not suitable for high power application. In [92], discussed a non-isolated dc-dc converter with non-inverting output and buck-boost operation, named magnetically coupled buck-boost bidirectional converter. The converter passive components arrangement connects the input and output ports in a non-isolated topology, giving it the same behavior as a dual active bridge converter. This equivalence enables triple phase shift modulation to be applied to the converter. In the DAB converter, triple phase shift modulation is known to reduce conduction losses and achieve soft switching at any load.

A high conversion ratio and high efficiency bidirectional converter topology is optimally designed to integrate both switches capacitor and coupled inductor technique [93]. The coupled inductor's windings are stacked at the low voltage source, transferring any coupled inductor leakage energy straight into the output port and simplifying the clamping circuit. Furthermore, the synchronous rectifiers allow the converter to achieve zero-voltage switching without the need for additional hardware circuitry. This converter's control is complicated, and each switch requires its own gate driver circuit.

Hu et al. proposed a high gain bidirectional converter based on the coupled inductor and switched capacitor [94]. Pulsewidth modulation with phase-shift control is applied, with the duty cycle ensuring that the voltages on both sides are equal and the phase-shift angle control the direction and magnitude of power flow. Faraji et al. presented a multi-port bidirectional converter with soft-switching for EVs application [16] as shown in Figure 2.18. The suggested converter provides bidirectional power exchangeability across ports by altering the topology of a standard three-port converter. Also included is a soft-switching cell that may work independently of the output power levels. One of the key benefits of this multi-port converter is the small number of components and low volume. The size of passive components and heat-sink is minimized due to the suggested converter's soft-switching function. Furthermore, because linked inductors are employed in the soft-switching cell, only one magnetic core is needed, resulting in single-stage power conversion

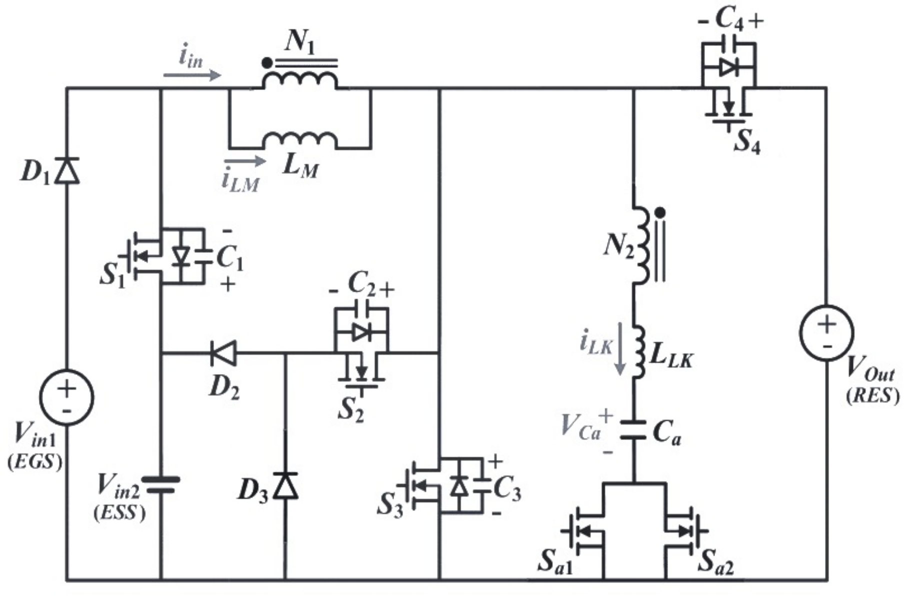

Figure 2.18: A multi-port bidirectional converter proposed in [16].

and lower conduction loss. There are different topologies of multi-port input and output bidirectional converters are presented in [95–99]. Three-ports bidirectional are included in the suggested construction, which may be used in both step-up and step-down modes. In both step-up and step-down operations, this converter can feed the load from two independent voltage sources and achieve a high voltage conversion ratio. The suggested topology has minimal voltage stress across the power switches, good efficiency, and a reduced component count. Another multi-port bidirectional converter for EVs is presented by Savran et al. [45]. The system integrates quasi-Z-source and H-bridge converters with an existing switch. Thus, a four-port converter is achieved without any need for individual converters or additional switches. Besides, the high-gain quasi-Z-source converter allows the reduction of the rated voltages of the battery and supercapacitor packs.

There are different topologies of high voltage gain bidirectional converters proposed recently [100–109]. To enable soft switching in both directions of power flow, the auxiliary circuit uses only a single switch and a pair of linked inductors. In addition, the soft switching state is unaffected by load change or duty cycle. The capacitive voltage-divider stage provides a high voltage gain and low voltage stress across switches, allowing the designer to use a low-voltage switch. There are various topologies of high voltage gain bidirectional converter with coupled inductor to minimize the current ripples [110–119]. The proposed BDC combines the benefits of a high voltage conversion ratio, low power switch voltage stresses, zero ripple current on the low voltage side, and a constant potential difference between the low and high voltage side grounds. At all operational points of continuous and discontinuous conduction modes, the inclusion of a linked inductor in the proposed converter considerably decreases the input and output current ripples in the step-up and step-down modes, respectively . The suggested converter has a voltage gain that is comparable to that of a cascaded boost converter in step-up mode and similar to that of a cascaded buck converter in step-down mode. As a result, both the direction of power flow can achieve for a high-voltage conversion ratio with an appropriate duty cycle. The comparison of different topologies of isolated and non-isolated bidirectional DC-DC converters are done in Table 2.1 and 2.2 respectively.

Table 2.1: Comparison of performance parameters of different isolated bidirectional converter

Converter	No. of devices	Voltage gain	Maximum stress on switch	Current ripples	Maximum efficiency
[2]	1 coupled inductor 1 inductor 2 capacitor 1 transformer 4 power switch 2 power diode	$M_{up}=\frac{n}{D(1-D)}$ $M_{down}=\frac{D(1-D)}{n}$	$V_{sw}=\frac{n}{D(1-D)}$ $I_{sw}=\frac{(1-D)I_s}{n}$	20 %	95 %
[4]	4 inductor 4 capacitor 12 power switch 2 power diode	$M=\frac{n(\pi-\beta)}{\pi-\alpha}$ $0\leq \alpha \leq \pi/2$ $0\leq \beta \leq \pi$	—	—	85 %
[5]	1 coupled inductor 3 capacitor 3 power switch 1 power diode	$M_{up}=\frac{n}{(1-D)}$ $M_{down}=\frac{D}{1+n-nD}$	$V_{sw}=\frac{n}{(1-D)}$	—	94.3 %
[6]	1 coupled inductor 1 inductor 2 capacitor 4 power switch 1 power diode	$M_{up}=\frac{nd_1}{1-d_1}$ $M_{down}=\frac{d_4}{n(1-d_4)}$	$V_{sw}=\frac{V_H}{(1-d_1}$	—	96.4 %
[7]	1 coupled inductor 1 inductor 3 capacitor 6 power switch	$M_{up}=\frac{n}{(1-D_1)^2}$ $M_{down}=\frac{(1-D_6)^2}{n}$	$V_{sw}=\frac{nV_L}{(1-D_1)^2}$	—	95.6 %
Proposed converter in Chapter 3	2 inductor 2 capacitor 4 power switch 2 power diode	$M_{up}=\frac{1}{(1-D)^2}$ $M_{down}=D^2$	$V_{sw}=\frac{V_L}{(1-D)^2}$ $I_{sw}=\frac{I_o}{(1-D)^2}$	10 %	95.4 %
Proposed converter in Chapter 4	2 inductor 2 capacitor 4 power switch	$M_{up}=\frac{1}{(1-D)^2}$ $M_{down}=D^2$	$V_{sw}=\frac{1}{(1-D)^2}$ $I_{sw}=\frac{I_o}{(1-D)^2}$	20 %	96 % (20kHz) 96.5 % (15kHz)
Proposed converter in Chapter 5	1 coupled inductor 3 capacitor 4 power switch	$M_{up}=\frac{1}{(1-D)^2}$ $M_{down}=D^2$	$V_{sw}=\frac{1}{(1-D)^2}$ $I_{sw}=\frac{I_o}{(1-D)^2}$	10 %	95 % (40kHz) 96 % (15kHz)

Table 2.2: Comparison of performance parameters of different non-isolated bidirectional converter

Converter	No. of devices	Voltage gain	Maximum stress on switch	Current ripples	Maximum efficiency
[9]	1 inductor 3 capacitor 4 power switch	$M_{up}=\frac{2}{(1-D)}$ $M_{down}=\frac{D}{2}$	$V_{sw}=\frac{V_L}{1-D}$	—	94 %
[11]	2 inductor 4 capacitor 5 power switch	$M_{up}=\frac{2}{1-D}$ $M_{down}=\frac{D}{2}$	$V_{sw}=\frac{V_L}{1-D}$ $I_{sw}=\frac{I_s}{2(1-D)}$	27.4 %	95.2 %
[12]	1 coupled inductor 2 inductor 3 capacitor 6 power switch	$M_{up}=\frac{R_H n D_{ps}(1-2D_{ps})}{L_D f_s}$ $M_{up}=\frac{R_L n D_{ps}(1-2D_{ps})}{L_D f_s}$ $R_H=\frac{V_H}{I_H},R_H=\frac{V_H}{I_H}$	$V_{sw}=\frac{V_L}{1-D}$ $I_{sw}=\frac{I_s}{2(1-D)}$	20 %	95.4 %
[13]	1 coupled inductor 2 capacitor 4 power switch	$M_{up}=\frac{n+1}{1-D}$ $M_{down}=\frac{D}{n+1}$	$V_{sw}=\frac{n}{1-D}$	—	94.5 %
[15]	1 coupled inductor 2 inductor 3 capacitor 8 power switch	$M=\frac{n+2}{n(1-D)}$	$V_{sw}=\frac{2}{n(1-D)}$	10 %	96.5 %
Proposed converter in Chapter 3	2 inductor 2 capacitor 4 power switch 2 power diode	$M_{up}=\frac{1}{(1-D)^2}$ $M_{down}=D^2$	$V_{sw}=\frac{V_L}{(1-D)^2}$ $I_{sw}=\frac{I_o}{(1-D)^2}$	10 %	95.4 %
Proposed converter in Chapter 4	2 inductor 2 capacitor 4 power switch	$M_{up}=\frac{1}{(1-D)^2}$ $M_{down}=D^2$	$V_{sw}=\frac{1}{(1-D)^2}$ $I_{sw}=\frac{I_o}{(1-D)^2}$	20 %	96 % (20kHz) 96.5 % (15kHz)
Proposed converter in Chapter 5	1 coupled inductor 3 capacitor 4 power switch	$M_{up}=\frac{1}{(1-D)^2}$ $M_{down}=D^2$	$V_{sw}=\frac{1}{(1-D)^2}$ $I_{sw}=\frac{I_o}{(1-D)^2}$	10 %	95 % (40kHz) 96 % (15kHz)

2.3 Conclusion

The performance of an EV battery-pack depends to a great extent on the characteristics of the bidirectional converter. A review of the literature on several types of high voltage gain bidirectional converters assisted in determining the type of converter system that would best satisfy the needs of an EV application. As a result, the Quadratic gain bidirectional converter system created in this research may successfully match the criteria in an EVs application with a design configuration of smaller, lighter, and more efficient than what is presently available.