

Voltage Lifting Techniques for Non-Isolated DC/DC Converters

Subjects: Engineering, Electrical & Electronic

Contributor: Abdulaziz Alkhalidi, Ahmad Elkhateb, David Laverty

The conventional boost DC/DC converter is used to step up the input voltage to a desired higher level within the practical limit required by the load with very few components. Stepping up the voltage is achieved by storing the energy in the inductor and releasing it to the output at a higher voltage. The boost converter is very popular for capacitive load applications such as photo-flashers and battery chargers. It is also used in automotive applications, power amplifiers, adaptive control applications, battery power systems, consumer electronics, DC motor drives and power factor correction circuits.

Keywords: high voltage gain ; DC/DC converter ; step-up techniques

1. High Step-Up Techniques

High step-up DC/DC converters, which are used for voltage boosting, are mainly classified as switched capacitors (SCs) (or charge pumps (CPs)), voltage multipliers (VM), switched inductor (SL), voltage lift (VL) and converters with multistage/multilevel structures. Depending on the application, these have merits and demerits in terms of cost, complexity, power density, reliability and efficiency. Some of the families classified are distinct to one known technique such as switched capacitor, voltage lift and switched inductor. Other families are extended to a few subfamilies such as the multi-stage family where it has been extended to cascaded, interleaved and multilevel.

2. Multistage/Multilevel Structures

One of the simplest methods of stepping up voltage is connecting various stages of a converter. This can be implemented by integrating symmetric or different converter modules (non-symmetric) with various high voltage gain techniques. The voltage gain increases linearly as a function of the topology used. Broadly, such topologies can be further classified as cascaded, interleaved and multilevel.

2.1. Cascaded Topology

2.1.1. Symmetric and Non-Symmetric Converters

In the general setup of cascaded DC/DC converters **Figure 1a,b**, two or more symmetric or non-symmetric converters that use two or more controllable switches [1][2][3] or a single switch [4][5][6] can be connected to increase the voltage gain without high duty cycle operation.

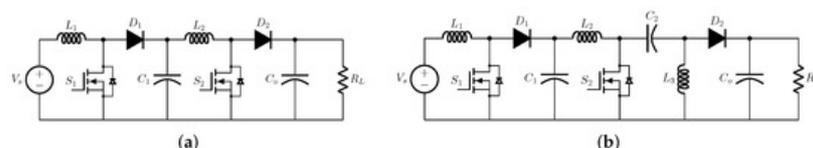


Figure 1. General Configuration of Cascaded DC/DC Converter (a) Symmetric (b) Non-symmetric.

As seen in **Figure 2a**, the low voltage stress on the power switch in the first stage of the cascade enables high frequency operation. A low frequency operates in the second stage [7][8]; hence, the switching losses are reduced [2]. However, a cascaded circuit has two sets of power devices, which makes it not only complex but also expensive [9]. Moreover, both power devices need to be synchronised to prevent the beat frequency from causing circuit stability issues [10]. An n-stage cascade boost converter with a single active switch is presented in [11][12]; such converters are an alternative solution for decreasing the total losses caused by active switches, as shown in **Figure 2b**. Moreover, they have a simple control circuitry. A comparative study on boost and zeta converters is presented in [13]. A single switch step-up DC/DC converter

based on the new SEPIC technology and buck/boost converter [14] is shown in **Figure 2c**. Its voltage gain is higher than those of SEPIC and buck/boost converters. Therefore, the voltage stress on the power switch is low, and the input current is continuous. An integrated double boost and SEPIC converter (IDBS) is presented in [15] as shown in **Figure 2d**; it can attain a high voltage conversion ratio at a low duty cycle. The advantages of this combination converter are its capability to achieve a high step-up voltage gain (boost) and a low input current ripple (SEPIC).

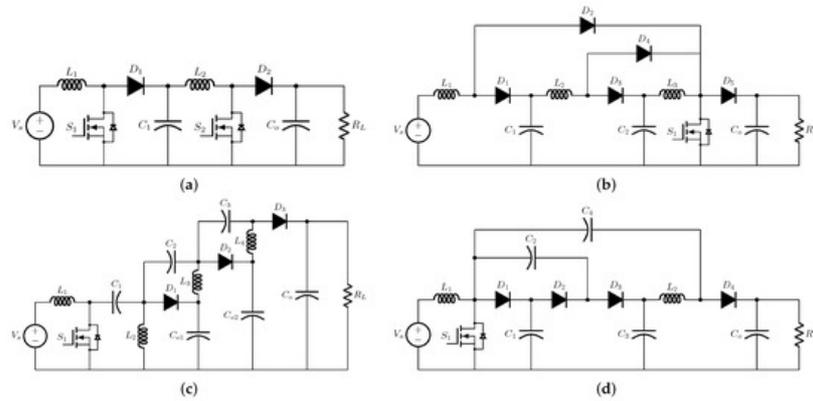


Figure 2. Cascaded Topologies for Symmetric and Non-symmetric Converters. (a) Double Boost Converter (DBC), (b) N-Stage Boost Converter, (c) SEPIC based on Buck-Boost Converter and (d) Double Boost SEPIC Converter.

2.1.2. Quadratic Boost Converters (QBC)

Figure 3 illustrates the general setup of a quadratic boost converter which comprises one switch, three diodes and four passive elements. A high step-up voltage gain can be obtained by using a quadratic converter **Figure 3** at a moderate duty cycle [6][16], but the main drawback of such converters is that the voltage stress on the power switch is equal to the output voltage. Therefore, efficiency is compromised. The conventional quadratic boost converter has a limited voltage gain and is thus unsuitable for high-step-up applications.

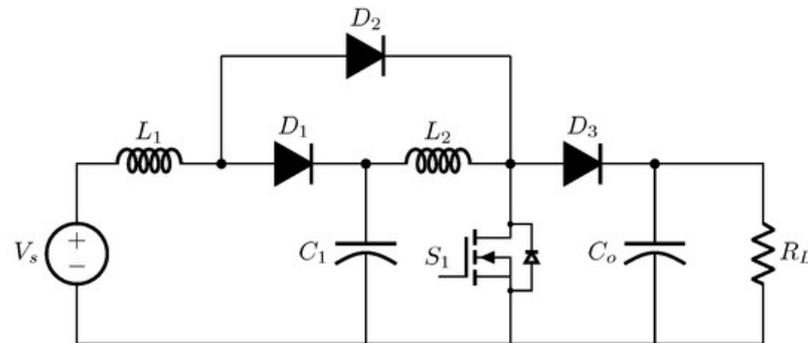


Figure 3. General Setup of Quadratic Boost Converter (QBC).

Figure 4a shows a quadratic boost converter with a modified VL cell [17]; it achieves a high voltage gain at the output side. Furthermore, it reduces the voltage stress on the power switch, which is an issue with traditional quadratic boost converters. In the literature [18][19][20][21][22][23][24][25][26][27][28][29][30][31][32][33][34][35][36], many DC/DC converters based on quadratic boost converters and modified quadratic boost converters have been proposed to inhibit the dominant constraints in conventional boost converters. A quadratic following boost converter (QFBC) is presented in [22]. It consists of two switches, three capacitors, three diodes and two inductors, and it can step up the voltage gain at a moderate duty cycle. In the modified QFBC (MQFBC) proposed in [23], a bootstrap network is integrated to improve the conventional boost converter. In **Figure 4b**, a high voltage gain and reduced voltage stress are achieved by using a quadratic boost converter with a coupled inductor [24][25]. However, the power switch suffers from a high voltage stress caused by the leakage inductance of the coupled inductor. Passive clamping circuits are adopted to reduce this high voltage stress. The quadratic boost converter and SEPIC topologies in **Figure 4c**, which are presented in [26], increase the voltage conversion ratio without an extreme duty ratio. This converter takes advantage of two well-known DC/DC converters, namely, a quadratic boost converter, which has a high step-up capability, and a SEPIC converter which can reduce the input current ripple. A quadratic SEPIC with a switched-coupled inductor, shown in **Figure 4d**, is proposed in [27] to increase the voltage gain. In [28], a quadratic boost converter and a zeta converter are proposed for a high voltage gain and efficiency. Additionally, both the input and output current ripples are low (features of the quadratic boost converter and zeta converter, respectively). A quadratic boost converter and a Ćuk converter are combined in [29] to provide a high step-up voltage. Two configurations of this proposed converter are shown in **Figure 4e,f**. The configuration in **Figure 4e** is called

hybrid QBC type I and its voltage stress is lower than the output voltage of the converter. The configuration in **Figure 4f** is called hybrid QBC type II, and its voltage gain is higher than that of hybrid QBC type I. A novel quadratic boost converter with low inductor currents is proposed in [30]; it can increase the voltage gain as well as the conventional quadratic boost converter can. Furthermore, it has a non-pulsating input current and low voltage stress on the power switch. The main drawback of this converter is its use of two switches. A hybrid cascaded DC/DC converter usually consists of a quadratic boost converter and voltage multiplier circuits. A high voltage gain in [31] is achieved by using a quadratic boost converter and a coupled inductor with an extended voltage doubler cell. Quadratic boost with a voltage multiplier cell was proposed in [32], the output voltage is much higher under the same duty cycle of the traditional quadratic boost converter. Moreover, the input current ripple is low, and the voltage stress is reduced.

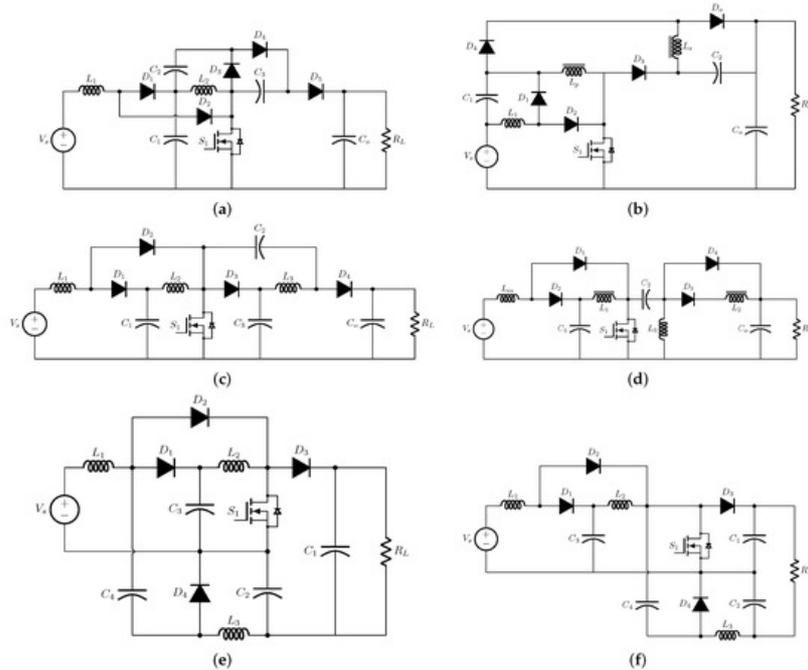


Figure 4. Cascaded Topology of Conventional Quadratic Boost Converter. (a) QBC based on VL, (b) QBC based on Coupled Inductor, (c) QBC and SEPIC Converters, (d) QBC-SEPIC based on SC and coupled Inductor, (e) QBC and Ćuk Converter Type-I and (f) QBC and Ćuk Converter Type-II.

2.2. Interleaved Converters

The interleaved step-up DC/DC converter consists of passive or active clamp circuits and voltage multiplier modules between the input switches and the output diode for providing a high voltage conversion ratio. However, this technique decreases the current ripple and increases the power density because the input current level in the step-up DC/DC converters is higher than the output current level. Various interleaved DC/DC converters with different techniques can be found in the literature [37][38][39][40][41][42][43][44][45][46].

In **Figure 5a**, the interleaved converter with voltage multiplier cell proposed in [37] can reduce the input current ripple and improve the power level because the interleaved structure is employed at the input side. Furthermore, the voltage gain is increased at the output side because of the voltage multiplier cell. In **Figure 5b**, a conventional interleaved boost converter achieves high voltage gain by integrating a voltage multiplier module consisting of switched capacitors and coupled inductors [38][39]. Additionally, it can reduce the input current ripple and doubles the power transfer. In order to increase the voltage gain, the interleaved quadratic boost DC/DC converter has been proposed by using two structures of quadratic boost converter as shown in **Figure 5c**. It can achieve the voltage gain by using a voltage lift capacitor [40]. In [41], an interleaved step-up converter with a single capacitor snubber is presented. A Winding Crossed Coupled Inductor (WCCI) has been presented in [42] consisting of three winding coupled inductors to boost the voltage gain. In addition, the first phase has two windings, while the second phase has the third winding. To recycle the leakage energy and absorb the voltage spike caused by the leakage inductance, either a passive clamp or an active clamp is adopted [43]. In [44], the proposed converter is an interleaved high step-up DC/DC converter combining with three techniques. However, it takes the advantage of the coupled inductor, switched capacitor and the conventional interleaved boost converter. In order to increase the voltage conversion ratio without using a coupled inductor, a non-isolated high gain interleaved DC/DC converter with reduced voltage stress on semiconductor devices has been proposed in [45]. In **Figure 5d**, the proposed converter contains two interleaved modified step-up KY converters. The voltage gain is higher than the conventional interleaved boost, Ćuk, ZETA and SEPIC converters. The voltage stress on the semiconductor devices is low; therefore,

the efficiency of the proposed converter is increased due to low on-state resistance and low conduction loss. A high step-up interleaved DC/DC converter by combining voltage multiplier and coupled inductor has been proposed in [46]. Two coupled inductors and voltage multiplier are utilised to provide a very high step-up voltage gain; hence, the input current ripple is low because the proposed converter uses the interleaved boost converter at the input side. In addition, it can alleviate the reverse recovery current problem of the diode, and it recycles the leakage energy. Eventually, the efficiency of the proposed converter can be improved by implementing low-voltage-rated MOSFETs with a small on-state resistance which can reduce the conduction loss.

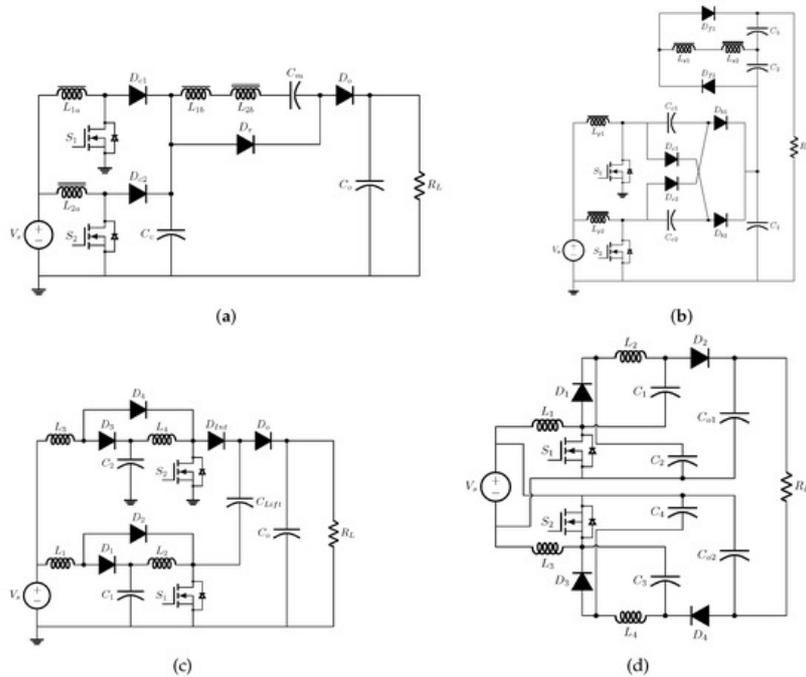


Figure 5. Interleaved Converters. (a) Interleaved with VMC and Coupled Inductor, (b) Interleaved with VMC based on SC and Coupled Inductor, (c) Interleaved QBC and (d) Two Interleaved Modified Step-Up KY Converters.

2.3. Multilevel Converters

A Multilevel DC/DC converter helps to decrease or nearly eliminate the magnetic components leading to desirable cost, size, weight, and managing high-temperature operation [47]. Concerning the input voltage, multiple level converters can be categorised into single DC and multiple DC sources groups. Single source multilevel structures are majorly used in electric or fuel cell-based vehicles and traction motors. In contrast, the multiple DC source multilevel converters with cascaded structures are used in modular renewable energy sources such as PV or fuel cells [48].

The switch capacitor structures are usually used in multilevel converter. The Capacitor-Clamped module for multilevel converters in **Figure 6a** is an essential module for boosting the voltage level, which contains three switches and one capacitor [49][50][51]. In [52], double the DC input voltage can be achieved by utilising two capacitors and four switches, as shown in **Figure 6b**. PV modules can increase the output voltage level by using a series connection; hence, the DC/DC converter should be used with each PV module to maintain the voltage regulated. The advantages of this connection are higher reliability, higher safety/protection, low maintenance and lower cost [53]. This converter is well known as the Modular Multilevel Converter (MMC) [54][55][56].

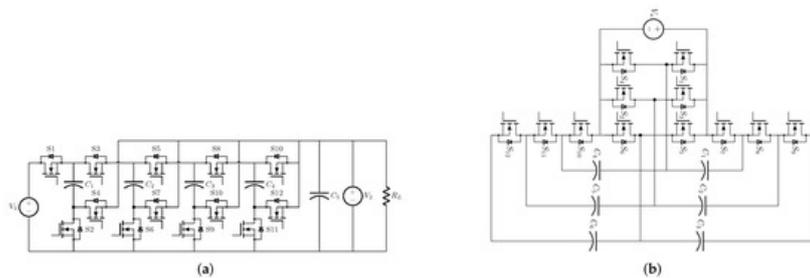


Figure 6. (a) Multilevel Modular Capacitor Clamped Converter (MMCCC) and (b) 6X Switched Capacitor.

Despite its features such as modularity structure, high power density, reliability, the MMC can provide high efficiency and high voltage/current levels. The fundamental multistage/level has shortcomings, such as a complex control scheme and

many components. All of this will be relatively heavy, large and bulky. This technique can be used in HVDC transmission, renewable energy systems, DC microgrids, high power DC supply and space technology.

3. Switched Capacitor (SC)

Topologies using SCs are majorly used in low power electronic applications, especially in systems with limited physical dimensions involving higher power density [57]. The concept of SCs is based on charge pump (CP), which is the number of capacitors used in SC cell where the high step-up ratio is attainable [58][59][60][61]. It comprises only capacitors, MOSFETs and diodes, and does not include any inductive element. Their characteristics allow monolithic integration, minimised levels of EMI, and reduced weight and volume [62]. Depending on the non-inverting and inverting cell terms, the polarity of input and output voltages are the same or opposite [63]. As shown in **Figure 7**, it consists of two capacitors and three diodes, and is placed in conventional DC/DC converters (such as Zeta, SEPIC and Ćuk converters) to build a new converter. The voltage divider circuit describes the functionality of the new converters. During the ON state of the diodes (D1 and D2), the capacitors (C1 and C2) are charged in parallel. During the OFF state of the diodes (D1 and D2), the capacitors (C1 and C2) are charged in series. From **Figure 7a,e**, non-inverting SC or inverting SC are used in many different step-up DC/DC converters. **Figure 7a,b** are non-inverting and inverting SC cell Zeta converters, respectively. It is developed by utilising the cell of non-inverting and inverting SC instead of the capacitor, the output inductor and the output diode of the conventional Zeta converter. As a result of the additional components, the voltage gain is higher than that achieved by a conventional Zeta converter. Moreover, there is a lower voltage stress on the power switch. **Figure 7c** depicts a SEPIC converter based on a non-inverting SC cell. Instead of the conventional SEPIC converter's output diode, the non-inverting SC cell is employed. Compared to a conventional SEPIC converter, it improves the voltage conversion ratio and decreases the voltage stress on the main switch. **Figure 7d** represents an inverting SC cell Ćuk converter. It is established by modifying the conventional Ćuk converter's capacitor, output inductor and output diode with an inverted SC cell. However, it boosts the voltage conversion ratio and decreases the switch's voltage stress. While **Figure 7e** is a similar circuit to **Figure 7d**, the voltage doubler cell has been added to the output side. Thus, the voltage gain is higher than the prior circuit and has lower voltage stress. In addition, the Ćuk converter has inductors on both sides, so current flows continuously in both directions. Combining both coupled inductor and switched capacitor [64], an ultra-high step-up DC/DC converter with low voltage stress and high efficiency has been achieved. It does not need extra windings for an ultra-high step-up conversion ratio. In addition, the passive clamp circuit can recycle the leakage energy, which can avoid the voltage spikes across the switch, and the efficiency is increased. The voltage stress on the main switch is lower than the other converter, and it maintains steady for the entire duty cycle range. Moreover, the reverse recovery current problem of the diode is alleviated through the leakage inductance of the coupled inductor.

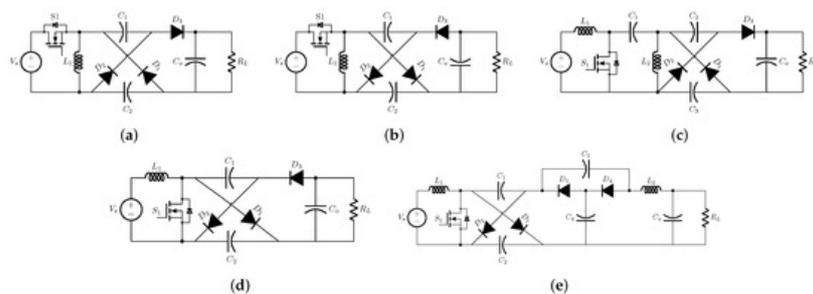


Figure 7. Switched Capacitor (SC) Techniques. (a) Zeta Converter based on Non-inverting SC Cell, (b) Zeta Converter based on Inverting SC Cell, (c) SEPIC Converter based on Non-inverting SC Cell, (d) Ćuk Converter based on Inverting SC Cell and (e) Ćuk Converter with Voltage Doubler based on Inverting SC Cell.

There are five standard techniques based on SC: Voltage Doubler, Ladder, Dickson, Makowski or Fibonacci, and Series-Parallel. The Voltage Doubler SC is based on two phases, where the switching devices are turning ON and OFF in complement, and the output voltage is double the value of the input voltage [65]. The ladder SC consists of two sets of capacitors. Therefore, the capacitor of the lower ladder is changing the input voltage node, which is made different voltage gain [65]. The Dickson SC can be utilised as a voltage multiplier. In the Dickson SC, the diodes are used to charge pumps instead of active switches. Two strings of pulses with proper phase shift are needed to drive the switching devices, typically at tens of kilohertz or up to megahertz. Another technique based on SC is the Makowski SC; it is also known as Fibonacci because its voltage gain can be boosted according to the Fibonacci number. However, the Makowski SC requires fewer devices to obtain high voltage gain [48]. The voltage regulation ranges of techniques have been limited, and the voltage gains of the circuit are predetermined.

An inductor can be utilised in this topology by replacing one active switch in the five standards SC to achieve higher step-up gain and broad voltage regulations [66]. In order to increase the voltage conversion ratio of step-up DC/DC converter, non-isolated high step-up soft-switching DC/DC converter by using interleaving and Dickson SC techniques have been presented [67]. The advantage of this proposed converter is an improved voltage conversion ratio due to the Dickson SC technique. They can alleviate high current spikes by adding a small resonant inductor into the Dickson SC technique [68] [69]. In addition, it can reduce the input current ripple and increase the power density due to interleaving operation.

4. Voltage Multiplier

Voltage Multiplier circuits contain diodes and capacitors to provide high DC voltage at the output side. Hence, it is efficient, low cost and has a simple structure. The Voltage Multipliers are majorly classified into Voltage Multiplier cells (VMC) and Voltage Multiplier Rectifier (VMR). VMC can be placed after the main switch to reduce its voltage stress. Moreover, a high voltage conversion ratio and higher efficiency are the other advantages of the VMC. VMR can be placed at the output stage of the transformer or coupled inductor. However, it helps to rectify the AC or pulsating DC voltage. Meanwhile, it acts as a voltage multiplier [48].

In many applications, the multiplication of the input voltage is applied; hence, various structures have been famous in these cells. In addition, it has low weight, size and cost even if the operation is at high frequency because the bulky capacitors are not used [70]. Some VMCs are also known as switched-diode capacitor voltage multiplier cells, which only contain diodes and capacitors [71]. For a higher voltage conversion ratio, the inductors of some VMC is required [63]; hence, the power switch can operate with zero current switching (ZCS) [70]. The modified conventional boost converter and modified voltage multiplier cell present a high gain non-isolated DC/DC converter [72]. In [73], a high step-up DC/DC converter based on SEPIC converter is introduced by adopting a coupled inductor with voltage multiplier cell. Low input current ripple, high voltage gain and higher efficiency are the advantages of this converter, which combines two voltage boosting techniques with a SEPIC converter. High step-up DC/DC converter based on a new modified single switch SEPIC (-SEPIC) is proposed in [74]. The output voltage gain can be achieved by adding a coupled inductor and voltage multiplier rectifier (VMR). The advantages of the -SEPIC are continuous input current, zero current switching (ZCS) and low reverse recovery loss. Therefore, the voltage spike on the main switch is low.

There are many different configurations of Half-wave [75] or Full-wave voltage multipliers that contain diodes and capacitors [76]. The Greinacher Voltage Doubler Rectifier (G-VD) is illustrated in **Figure 11c**, which is used in many DC/DC converters at the output stage of transformer-based converter or multistage converters with modular series output [77]. The shortage of the VMR is the high voltage stress on diodes, and output capacitor voltage is equal to the output voltage. The Cockcroft–Walton (CW) is another voltage multiplier, same as G-VMR, introduced in different year, but it is famous for its cascading structure [78]. A full-bridge voltage doubler rectifier is commonly used in various DC/DC converters because its voltage stress on the output capacitor is half the output voltage [79][80]. Sometimes the VMR is considered a voltage triple rectifier; therefore, it can be used in many ultra-step-up DC/DC converters. In isolated structures and multilevel output series structures, the VMR can be applied [81]. Despite its features, such as high voltage ability with simple topology and cell-based structure, voltage multiplier can be integrated into various converters. The voltage multiplier also has shortcomings, such as high voltage stress on components. This needs several cells for high voltage application. This technique can be used in medical (X-ray, laser), high power laser and physics (plasma research, particle accelerator) applications.

5. Voltage Lift (VL)

The presence of parasitic elements restricts the output voltage and causes poor transfer efficiency of DC/DC converters. The voltage lift technique provides an excellent opportunity to improve circuit characteristics. The basic structure of the voltage lift is shown in **Figure 8**. A popular converter that uses VL technique is Luo converter which has been introduced in [82][83]. The capacitor is charged to a specific voltage, and the output voltage is lifted with the voltage level of a charged capacitor.

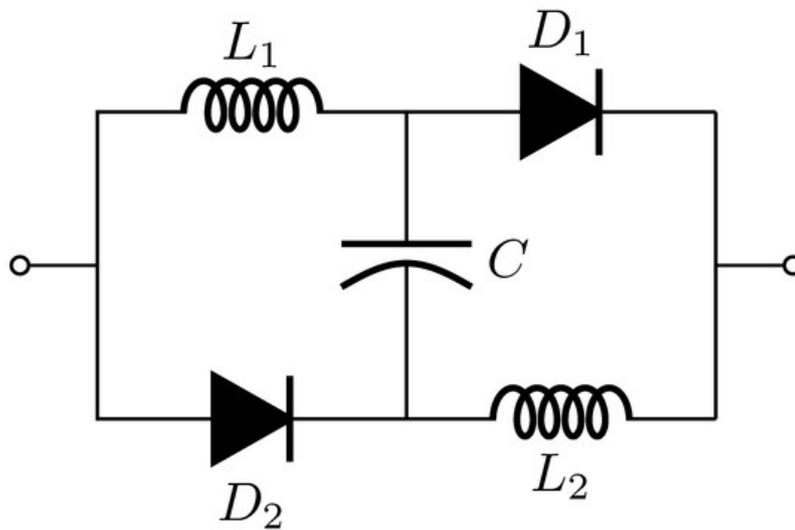


Figure 8. Basic Structure of Voltage Lift (VL) Cell.

Depending on the number of capacitors in the circuit, the output voltage can be further re-lifted, triple-lifted and quadruple lifted by reapplying the method as shown in **Figure 9a** [84][85][86]. The significant advantages of this topology are high power density, high efficiency and cost-effectiveness. In addition, the output voltage ripple is small for high voltage applications. In the literature, various converters, namely, the Ćuk, SEPIC and Zeta converters apply the VL technique [87][88]. The N-Stage quadratic boost converter based on the voltage life technique and voltage multiplier (NQBC-VLVM) described in [24]. By replacing the input inductor of NQBC-VLVM with the VL technique, the voltage conversion ratio with a small duty cycle can be improved. Additionally, the voltage gain can be multiplied by two, which is a benefit of VM, and the voltage stress on the main switch is half the output voltage, leading to higher efficiency. A quadratic boost converter with voltage doubler and voltage life technique is presented in [89][90], which increases the voltage gain four times by utilising the VL technique as shown in **Figure 9b**. In addition, it can double the voltage gain by using a voltage doubler cell and reduce the voltage stress to half of the output voltage on the main switch. The quadratic boost converter based on the elementary VL technique is proposed in [91] to obtain high voltage gain. Depending on the number of inductors, the proposed converter can exponentially step up the voltage gain. Therefore, the voltage gain of the double lift circuit in **Figure 9c** is eight times the input voltage, and the voltage gain of the triple lift in **Figure 9d** is nearly 16 times the input voltage. In contrast, the efficiency decreases with the increase of the number of inductors. In [92], cascaded boost converter based on the double VL technique is proposed. The first stage output of this converter becomes the second stage's input voltage; hence, it can achieve high voltage gain and low voltage stress on the switches at a low duty cycle.

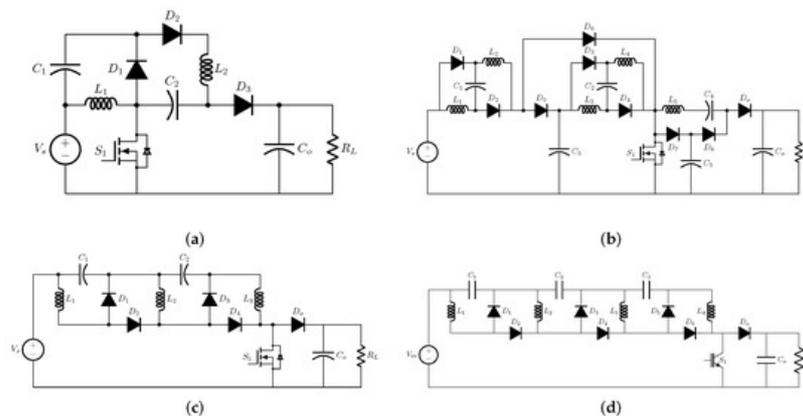


Figure 9. Voltage Lift (VL) Techniques. (a) Boost Converter based on VL, (b) QBC based on Voltage Doubler and VL, (c) QBC based on elementary VL (Double Lift) and (d) QBC based on elementary VL (Triple Lift).

6. Switched Inductor (SL)

The basic Switched Inductor (SL) cell is illustrated in **Figure 10**. The main operation of such cell is that inductors are charged in parallel and discharged in series. This kind of operation was first introduced in [71]. The input inductor replaces a hybrid boost converter in a conventional boost converter to switched inductor circuit. Hence, it provides a higher voltage gain than the conventional boost converter.

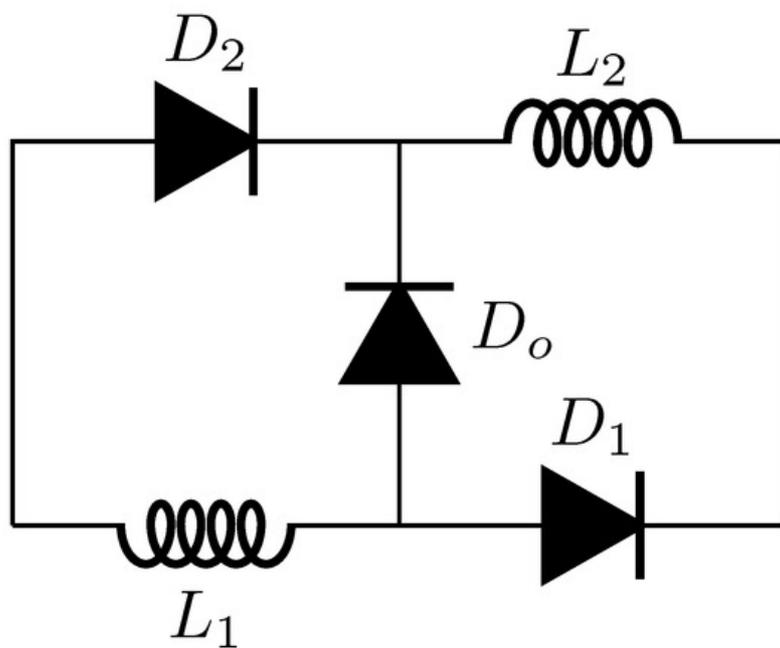


Figure 10. Basic Switched Inductor (SL) Cell.

These two inductors can be integrated into a single inductor because they have the same inductance, which helps reduce the size and weight of the converter. Recently, a high voltage conversion ratio DC/DC converter has been achieved by adding a small resonant inductor to the primary VL cell's circuit and replacing the output diode (D_o) [93]. A simple structure and high efficiency are the main advantages of this converter. The self-lift SL cell is formed by implementing the elementary VL cell in the SL cell, and the double self-lift SL cell is formed by adding another diode and capacitor to the self-lift SL cell [94]. Therefore, the double self-lift SL cell switch is an operation in reverse using (S_o) instead of (D_o) the primary SL cell. For high voltage gain, a transformer-less step-up DC/DC converter based on a switched inductor (SL) and switched capacitor (SC) techniques have been proposed in [95]. Furthermore, it can reduce the voltage stress on the semiconductor switches, but the cost will increase because of the two switches.

7. Magnetic Coupling

One of the most popular voltage boosting techniques is magnetic coupling, which is used in many DC/DC converters as either non-isolated or isolated converters. The outstanding feature of magnetic coupling is its ability to achieve a higher voltage gain in the output by turning the windings beside the switch duty cycle [96]. The magnetic coupling though has some problems such as leakage inductance [97]. Broadly, it can be further classified as transformer, coupled inductor or multi-track topologies.

7.1. Transformer

An electrical isolated DC/DC converter requires a medium/high frequency transformer. There are several isolated DC/DC converters that use such device such as full or half-bridge converter, forward converter, push-pull converter and flyback converter. In the past decade, the performance of the conventional DC/DC converter for many applications has been enhanced by using isolated DC/DC converters [98][99][100][101][102][103][104].

7.2. Coupled Inductor

Since isolation is not required in many applications, coupled inductor circuits can take the advantage of transformer coupling without isolation to increase the voltage in DC/DC converters [105][106][107][108][109][110][111][112][113][114]. **Figure 11** shows a general setup for a step-up converter with coupled inductor. The voltage source is a secondary winding, while the clamp capacitor and diode are used to recover the leakage energy recycled directly or through the secondary winding to the load [105]. In addition, a snubber circuit can be used to absorb the energy of the leakage inductance and to improve efficiency [106] as shown in **Figure 12a**. In [107], a higher voltage gain can be achieved by using a combination of the charge pump and switched capacitor voltage multiplier with a coupled inductor, as shown in **Figure 12b**, which is helpful in distributed generation systems. A non-isolated high step-up DC/DC converter with continuous input current integrating coupled inductor is introduced in [115] and shown in **Figure 12c**. It consists of three diodes, three capacitors and one inductor. Further, the coupled inductor in this converter is employed, which achieves higher voltage gain and low input

current ripple because the inductor is connected in series to the input. The clamp circuit reduces the voltage stress on the main switch. As a result, low on-state resistance $R_{DS(ON)}$

can be achieved, which helps to reduce the conduction losses. Therefore, the switching loss is reduced when the switch is turned on under zero current. A single switch high voltage gain and high-efficiency DC/DC converter are proposed in [116]. The voltage gain is achieved by charging the intermediate capacitors through the coupled inductor in parallel and discharging in series. In [117], a high step-up DC/DC converter based on three winding coupled inductors using two Cockcroft–Walton was proposed, as shown in **Figure 12d**. Impedance (Z -) source is another area of research in high step-up DC/DC converters. It can increase the voltage gain by using a small duty cycle [118][119][120][121][122].

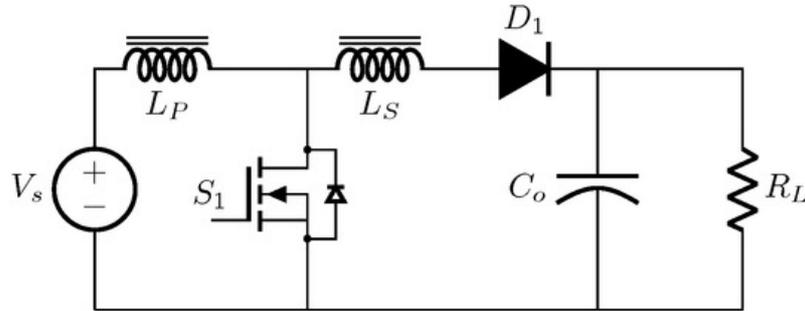


Figure 11. General Setup of the Coupled Inductor Circuit.

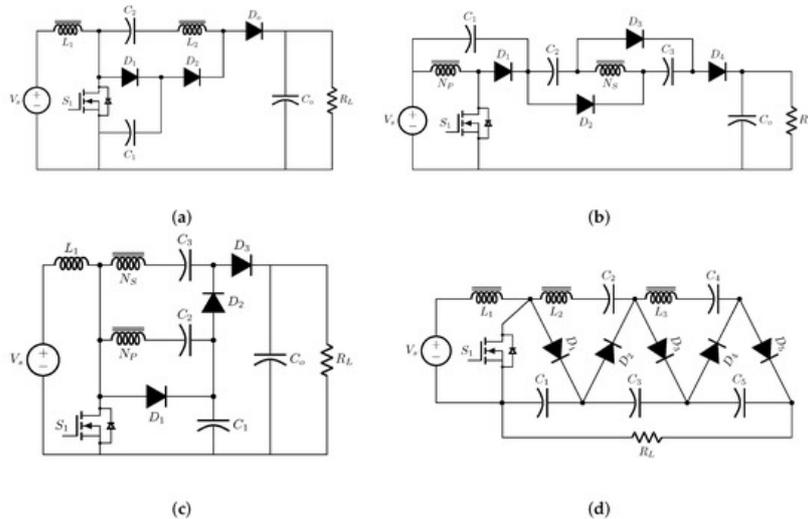


Figure 12. Coupled Inductor Techniques. (a) Boost Converter based on Coupled Inductor, (b) Boost Converter based on Two Capacitors and Coupled Inductor, (c) Boost Converter based on a Coupled Inductor and (d) Boost Converter with 3-winding Coupled Inductor.

7.3. Multi-Track Structure

A DC/DC converter can be classified into single-stage structure and multi-stage structure. A single-stage structure can perform multiple functions in a single stage; hence, it is not a complex circuit and has simple control. However, single-stage structure cannot achieve high performance with a wide range of operations. A multi-stage structure can perform one or more function in each stage, which is better in terms of system performance. In contrast, the number of components in this structure is high and the complexity increases.

In the literature [123][124][125][126], the basic block diagram of the multi-stage structures has a switched capacitor, switched inductor and magnetically coupled circuits, which is considered one of the essential solutions. The switched inductor circuits are used for providing voltage regulation, but their size is large and the performance at high voltage conversion ratios, and their power density is limited. The switched capacitor circuits are used for providing balance efficiency, but they cannot have voltage regulation capability. The magnetic circuits provide a high voltage conversion ratio, galvanic isolation and soft switching, but they cannot keep high performance across a wide range of operations. Cascaded two-stage structures for laptop power supply are presented in [127] to provide a high performance. The first stage has a switched capacitor voltage divider, inductor-less, soft switching and high-power density [128]. The second stage is a buck converter in which the power density is lower than the voltage divider, and it can provide regulated bus voltage.

Multi-Track integrates various high voltage techniques with magnetic circuits. In [129], multi-track power conversion is proposed by integrating switched capacitors and magnetics. It merges a hybrid switched capacitor/magnetics circuit structure that splits the wide voltage conversion range into smaller ranges, delivers power in multiple tracks and functionally merges the regulation and isolation stages.

Magnetic coupling has some attractive features such as high design freedom and versatility in boost ability due to tuneable turns ratios of magnetic coupling. Furthermore, providing the converters with a switch can be implemented at the low voltage side to help reduce conduction loss and high efficiency in soft switched operation. However, converters with magnetic coupling have some shortcomings such as adverse effects of leakage inductance, which provides a high voltage spike. In addition, such converters are considered bulky due to the magnetic elements included in their design. This technique can be used in high power/voltage DC supply, high voltage applications, DC microgrids, telecommunication and data centres, regenerative (elevator, tram/trolleybus) and bidirectional (Fuel Cell (FC), PV, UPS, Plug-in Electric Vehicle (P-EV), Hybrid Electric Vehicle (H-EV), Vehicle to Grid (V2G)) applications.

References

1. Morales-Saldana, J.; Gutierrez, E.; Leyva-Ramos, J. Modeling of switch-mode dc-dc cascade converters. *IEEE Trans. Aerosp. Electron. Syst.* 2002, 38, 295–299.
2. Wu, T.F.; Yu, T.H. Unified approach to developing single-stage power converters. *IEEE Trans. Aerosp. Electron. Syst.* 1998, 34, 211–223.
3. Haroun, R.; Cid-Pastor, A.; Aroudi, A.E.; Martínez-Salamero, L. Synthesis of Canonical Elements for Power Processing in DC Distribution Systems Using Cascaded Converters and Sliding-Mode Control. *IEEE Trans. Power Electron.* 2014, 29, 1366–1381.
4. Leyva-Ramos, J.; Ortiz-Lopez, M.; Diaz-Saldierna, L.; Morales-Saldana, J. Switching regulator using a quadratic boost converter for wide DC conversion ratios. *IET Power Electron.* 2009, 2, 605–613.
5. López-Santos, O.; Martínez-Salamero, L.; García, G.; Valderrama-Blavi, H.; Mercuri, D.O. Efficiency analysis of a sliding-mode controlled quadratic boost converter. *IET Power Electron.* 2013, 6, 364–373.
6. Choudhury, T.R.; Nayak, B. Comparison and analysis of cascaded and Quadratic Boost Converter. In *Proceedings of the 2015 IEEE Power, Communication and Information Technology Conference (PCITC)*, Bhubaneswar, India, 15–17 October 2015; pp. 78–83.
7. Boujelben, N.; Masmoudi, F.; Djemel, M.; Derbel, N. Design and comparison of quadratic boost and double cascade boost converters with boost converter. In *Proceedings of the 2017 14th International Multi-Conference on Systems, Signals and Devices (SSD)*, Marrakech, Morocco, 28–31 March 2017; pp. 245–252.
8. Chen, Z.; Yong, W.; Gao, W. PI and Sliding Mode Control of a Multi-Input-Multi-Output Boost-Boost Converter. *WSEAS Trans. Power Syst.* 2014, 9, 87–102.
9. Amir, A.; Amir, A.; Che, H.S.; Elkhateb, A.; Abd Rahim, N. Comparative analysis of high voltage gain DC-DC converter topologies for photovoltaic systems. *Renew. Energy* 2019, 136, 1147–1163.
10. Feng, X.; Liu, J.; Lee, F. Impedance specifications for stable DC distributed power systems. *IEEE Trans. Power Electron.* 2002, 17, 157–162.
11. Leyva Ramos, J.; Ortiz-Lopez, M.G.; Morales-Saldana, J.A. Control of a cascade boost converter with a single active switch. In *Proceedings of the 2008 IEEE Power Electronics Specialists Conference*, Rhodes, Greece, 15–19 June 2008; pp. 2383–2388.
12. Ortiz-Lopez, M.G.; Leyva-Ramos, J.; Diaz-Saldierna, L.H.; Carbajal-Gutierrez, E.E. Multiloop Controller for N-Stage Cascade Boost Converter. In *Proceedings of the 2007 IEEE International Conference on Control Applications*, Singapore, 1–3 October 2007; pp. 587–592.
13. Andrade, A.M.S.S.; Hey, H.L.; Schuch, L.; da Silva Martins, M.L. Comparative Evaluation of Single Switch High-Voltage Step-Up Topologies Based on Boost and Zeta PWM Cells. *IEEE Trans. Ind. Electron.* 2018, 65, 2322–2334.
14. Banaei, M.R.; Sani, S.G. Analysis and Implementation of a New SEPIC-Based Single-Switch Buck–Boost DC–DC Converter With Continuous Input Current. *IEEE Trans. Power Electron.* 2018, 33, 10317–10325.
15. Sabzali, A.J.; Ismail, E.H.; Behbehani, H.M. High voltage step-up integrated double Boost–Sepic DC–DC converter for fuel-cell and photovoltaic applications. *Renew. Energy* 2015, 82, 44–53.

16. Wijeratne, D.S.; Moschopoulos, G. Quadratic Power Conversion for Power Electronics: Principles and Circuits. *IEEE Trans. Circuits Syst. Regul. Pap.* 2012, 59, 426–438.
17. Zhang, S.; Xu, J.; Yang, P. A single-switch high gain quadratic boost converter based on voltage-lift-technique. In *Proceedings of the 2012 10th International Power and Energy Conference (IPEC), Ho Chi Minh City, Vietnam, 12–14 December 2012*; pp. 71–75.
18. Morales-Saldana, J.A.; Loera-Palomo, R.; Palacios-Hernández, E.; Gonzalez-Martinez, J.L. Modelling and control of a DC-DC quadratic boost converter with R^2P^2 . *IET Power Electron.* 2014, 7, 11–22.
19. Ye, Y.m.; Cheng, K.W.E. Quadratic boost converter with low buffer capacitor stress. *IET Power Electron.* 2014, 7, 1162–1170.
20. Kadri, R.; Gaubert, J.P.; Champenois, G.; Mostefaï, M. Performance analysis of transformless single switch quadratic boost converter for grid connected photovoltaic systems. In *Proceedings of the The XIX International Conference on Electrical Machines - ICEM 2010, Rome, Italy, 6–8 September 2010*; pp. 1–7.
21. Alkhalidi, A.; Akbar, F.; Elkhateb, A.; Laverty, D. N-Stage Quadratic Boost Converter Based on Voltage Lift Technique and Voltage Multiplier. In *Proceedings of the The 11th International Conference on Power Electronics, Machines and Drives (PEMD 2022), Newcastle, UK, 21–23 June 2022*.
22. Veerachary, M.; Kumar, N. Analysis and Design of Quadratic Following Boost Converter. *IEEE Trans. Ind. Appl.* 2020, 56, 6657–6673.
23. Veerachary, M.; Kumar, N. Modified Quadratic Following Boost Converter - Robustness Considerations. In *Proceedings of the 2020 IEEE International Conference on Computing, Power and Communication Technologies (GUCON), Greater Noida, India, 2–4 October 2020*; pp. 745–750.
24. Lee, S.W.; Do, H.L. Quadratic Boost DC-DC Converter With High Voltage Gain and Reduced Voltage Stresses. *IEEE Trans. Power Electron.* 2019, 34, 2397–2404.
25. Jahangiri, H.; Mohammadpour, S.; Ajami, A. A high step-up DC-DC boost converter with coupled inductor based on quadratic converters. In *Proceedings of the 2018 9th Annual Power Electronics, Drives Systems and Technologies Conference (PEDSTC), Tehran, Iran, 13–15 February 2018*; pp. 20–25.
26. Maheshwari, M.; Arounassalame, M. A Novel Integrated High Gain DC-DC Converter. In *Proceedings of the 2019 IEEE International Conference on Electrical, Computer and Communication Technologies (ICECCT), Coimbatore, India, 20–22 February 2019*; pp. 1–6.
27. Axelrod, B.; Berkovich, Y.; Beck, Y. New Quadratic Sepic Converter with a Switched-Coupled Inductor. In *Proceedings of the 2018 20th European Conference on Power Electronics and Applications (EPE'18 ECCE Europe), Riga, Latvia, 17–21 September 2018*; pp. P.1–P.9.
28. Andrade, A.M.S.S.; Martins, M.L.d.S. Quadratic-Boost With Stacked Zeta Converter for High Voltage Gain Applications. *IEEE J. Emerg. Sel. Top. Power Electron.* 2017, 5, 1787–1796.
29. Pires, V.F.; Cordeiro, A.; Foito, D.; Silva, J.F. High Step-Up DC-DC Converter for Fuel Cell Vehicles Based on Merged Quadratic Boost-Ćuk. *IEEE Trans. Veh. Technol.* 2019, 68, 7521–7530.
30. Li, G.; Jin, X.; Chen, X.; Mu, X. A novel quadratic boost converter with low inductor currents. *CPSS Trans. Power Electron. Appl.* 2020, 5, 1–10.
31. Hu, X.; Gong, C. A High Voltage Gain DC-DC Converter Integrating Coupled-Inductor and Diode-Capacitor Techniques. *IEEE Trans. Power Electron.* 2014, 29, 789–800.
32. Zhang, N.; Sutanto, D.; Muttaqi, K.M.; Zhang, B.; Qiu, D. High-voltage-gain quadratic boost converter with voltage multiplier. *IET Power Electron.* 2015, 8, 2511–2519.
33. Ghafour, Z.A.; Ajel, A.R.; Yasin, N.M. A New High Gain Quadratic DC-DC Boost Converter for Photovoltaic Applications. In *Proceedings of the 2022 10th International Conference on Smart Grid (icSmartGrid), Istanbul, Turkey, 27–29 June 2022*; pp. 137–144.
34. Alizadeh, D.; Babaei, E.; Sabahi, M. High Step-Up Quadratic Impedance Source DC-DC Converter Based on Coupled Inductor. *IEEE J. Emerg. Sel. Top. Power Electron.* 2022.
35. Gupta, A.; Korada, N.; Ayyanar, R. Quadratic-Extended-Duty-Ratio Boost Converters for Ultra High Gain Application with Low Input Current Ripple and Low Device Stress. *IEEE Trans. Ind. Appl.* 2022, 1–11.
36. Abbasi, V.; Rostami, S.; Hemmati, S.; Ahmadian, S. Ultrahigh Step-Up Quadratic Boost Converter Using Coupled Inductors With Low Voltage Stress on the Switches. *IEEE J. Emerg. Sel. Top. Power Electron.* 2022, 10, 7733–7743.
37. Li, W.; Zhao, Y.; Deng, Y.; He, X. Interleaved Converter With Voltage Multiplier Cell for High Step-Up and High-Efficiency Conversion. *IEEE Trans. Power Electron.* 2010, 25, 2397–2408.

38. Tseng, K.C.; Huang, C.C. High Step-Up High-Efficiency Interleaved Converter With Voltage Multiplier Module for Renewable Energy System. *IEEE Trans. Ind. Electron.* 2014, 61, 1311–1319.
39. Li, W.; Xiang, X.; Li, C.; Li, W.; He, X. Interleaved High Step-Up ZVT Converter with Built-In Transformer Voltage Doubler Cell for Distributed PV Generation System. *IEEE Trans. Power Electron.* 2013, 28, 300–313.
40. Samuel, V.J.; Keerthi, G.; Prabhakar, M. High Gain Interleaved Quadratic Boost DCDC Converter. In Proceedings of the 2019 2nd International Conference on Power and Embedded Drive Control (ICPEDC), Chennai, India, 21–23 August 2019; pp. 390–395.
41. Tseng, S.Y.; Hsu, C.Y. Interleaved step-up converter with a single-capacitor snubber for PV energy conversion applications. *Int. J. Electr. Power Energy Syst.* 2013, 53, 909–922.
42. Li, W.; Wu, J.; Wang, D.; Deng, Y.; He, X. A Family of Interleaved DC/DC Converters Deduced from a Basic Cell with Winding-Coupled Inductors for High Step-Up/Step-Down Conversions. In Proceedings of the 2007 IEEE Power Electronics Specialists Conference, Orlando, FL, USA, 17–21 June 2007; pp. 2335–2340.
43. Li, W.; He, X. An Interleaved Winding-Coupled Boost Converter With Passive Lossless Clamp Circuits. *IEEE Trans. Power Electron.* 2007, 22, 1499–1507.
44. Mittle, A.; Singh, R.K.; J, S.C. A New Interleaved High Step-up DC-DC Converter. In Proceedings of the 2019 IEEE Students Conference on Engineering and Systems (SCES), Allahabad, India, 29–31 May 2019; pp. 1–5.
45. Sedaghati, F.; Eskandarpour Azizkandi, M.; Majareh, S.H.L.; Shayeghi, H. A High-Efficiency Non-Isolated High-Gain Interleaved DC-DC Converter with Reduced Voltage Stress on Devices. In Proceedings of the 2019 10th International Power Electronics, Drive Systems and Technologies Conference (PEDSTC), Shiraz, Iran, 12–14 February 2019; pp. 729–734.
46. Alghaythi, M.L.; O'Connell, R.M.; Islam, N.E.; Khan, M.M.S.; Guerrero, J.M. A High Step-Up Interleaved DC-DC Converter With Voltage Multiplier and Coupled Inductors for Renewable Energy Systems. *IEEE Access* 2020, 8, 123165–123174.
47. Zhang, F.; Peng, F.; Qian, Z. Study of the multilevel converters in DC-DC applications. In Proceedings of the 2004 IEEE 35th Annual Power Electronics Specialists Conference (IEEE Cat. No.04CH37551), Aachen, Germany, 20–25 June 2004; Volume 2, pp. 1702–1706.
48. Forouzesh, M.; Siwakoti, Y.P.; Gorji, S.A.; Blaabjerg, F.; Lehman, B. A survey on voltage boosting techniques for step-up DC-DC converters. In Proceedings of the 2016 IEEE Energy Conversion Congress and Exposition (ECCE), Milwaukee, WI, USA, 18–22 September 2016; pp. 1–8.
49. Khan, F.H.; Tolbert, L.M. A Multilevel Modular Capacitor-Clamped DC–DC Converter. *IEEE Trans. Ind. Appl.* 2007, 43, 1628–1638.
50. Cao, D.; Peng, F.Z. Zero-Current-Switching Multilevel Modular Switched-Capacitor DC–DC Converter. *IEEE Trans. Ind. Appl.* 2010, 46, 2536–2544.
51. Khan, F.H.; Tolbert, L.M. Multiple-Load–Source Integration in a Multilevel Modular Capacitor-Clamped DC–DC Converter Featuring Fault Tolerant Capability. *IEEE Trans. Power Electron.* 2009, 24, 14–24.
52. Qian, W.; Cao, D.; Cintron-Rivera, J.G.; Gebben, M.; Wey, D.; Peng, F.Z. A Switched-Capacitor DC–DC Converter With High Voltage Gain and Reduced Component Rating and Count. *IEEE Trans. Ind. Appl.* 2012, 48, 1397–1406.
53. Walker, G.; Sernia, P. Cascaded DC-DC converter connection of photovoltaic modules. *IEEE Trans. Power Electron.* 2004, 19, 1130–1139.
54. Echeverría, J.; Kouro, S.; Pérez, M.; Abu-rub, H. Multi-modular cascaded DC-DC converter for HVDC grid connection of large-scale photovoltaic power systems. In Proceedings of the IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society, Vienna, Austria, 10–13 November 2013; pp. 6999–7005.
55. Rivera, S.; Kouro, S.; Wu, B.; Leon, J.I.; Rodríguez, J.; Franquelo, L.G. Cascaded H-bridge multilevel converter multistring topology for large scale photovoltaic systems. In Proceedings of the 2011 IEEE International Symposium on Industrial Electronics, Gdansk, Poland, 27–30 June 2011; pp. 1837–1844.
56. Kutkut, N.; Divan, D. Dynamic equalization techniques for series battery stacks. In Proceedings of the Proceedings of INTELEC'96 - International Telecommunications Energy Conference, Boston, MA, USA, 6–10 October 1996; pp. 514–521.
57. Cheong, S.; Chung, S.; Ioinovici, A. Development of power electronics converters based on switched-capacitor circuits. In Proceedings of the 1992 IEEE International Symposium on Circuits and Systems, San Diego, CA, USA, 10–13 May 1992; Volume 4, pp. 1907–1910.
58. Ueno, F.; Inoue, T.; Umeno, T.; Oota, I. Analysis and application of switched-capacitor transformers by formulation. *Electron. Commun. Jpn. Part II: Electron.* 1990, 73, 91–103.

59. Cheong, S.; Chung, H.; Ioinovici, A. Inductorless DC-to-DC converter with high power density. *IEEE Trans. Ind. Electron.* 1994, 41, 208–215.
60. Mak, O.C.; Wong, Y.C.; Ioinovici, A. Step-up DC power supply based on a switched-capacitor circuit. *IEEE Trans. Ind. Electron.* 1995, 42, 90–97.
61. Seeman, M.D. *A Design Methodology for Switched-Capacitor DC-DC Converters*; University of California: Berkeley, CA, USA, 2009.
62. Ioinovici, A. Switched-capacitor power electronics circuits. *IEEE Circuits Syst. Mag.* 2001, 1, 37–42.
63. Ismail, E.H.; Al-Saffar, M.A.; Sabzali, A.J.; Fardoun, A.A. A Family of Single-Switch PWM Converters With High Step-Up Conversion Ratio. *IEEE Trans. Circuits Syst. Regul. Pap.* 2008, 55, 1159–1171.
64. Hassan, W.; Lu, D.D.C.; Xiao, W. Single-Switch High Step-Up DC–DC Converter with Low and Steady Switch Voltage Stress. *IEEE Trans. Ind. Electron.* 2019, 66, 9326–9338.
65. Umeno, T.; Takahashi, K.; Ueno, F.; Inoue, T.; Oota, I. A new approach to low ripple-noise switching converters on the basis of switched-capacitor converters. In *Proceedings of the 1991., IEEE International Symposium on Circuits and Systems*, Singapore, 11–14 June 1991; pp. 1077–1080.
66. Li, S.; Li, Z.; Shang, W.; Zheng, S.; Jia, P. A Family of Hybrid Step-up DC-DC Converters based on Switched-capacitor Converters. In *Proceedings of the 2020 IEEE 9th International Power Electronics and Motion Control Conference (IPEMC2020-ECCE Asia)*, Nanjing, China, 29 November–2 December 2020; pp. 497–502.
67. Lei, H.; Hao, R.; You, X.; Li, F. Nonisolated High Step-Up Soft-Switching DC–DC Converter With Interleaving and Dicks on Switched-Capacitor Techniques. *IEEE J. Emerg. Sel. Top. Power Electron.* 2020, 8, 2007–2021.
68. Law, K.; Cheng, K.; Yeung, Y. Design and analysis of switched-capacitor-based step-up resonant converters. *IEEE Trans. Circuits Syst. Regul. Pap.* 2005, 52, 943–948.
69. Schaef, C.; Stauth, J.T. A Highly Integrated Series–Parallel Switched-Capacitor Converter with 12 V Input and Quasi-Resonant Voltage-Mode Regulation. *IEEE J. Emerg. Sel. Top. Power Electron.* 2018, 6, 456–464.
70. Prudente, M.; Pfitscher, L.L.; Emmendoerfer, G.; Romanelli, E.F.; Gules, R. Voltage Multiplier Cells Applied to Non-Isolated DC–DC Converters. *IEEE Trans. Power Electron.* 2008, 23, 871–887.
71. Axelrod, B.; Berkovich, Y.; Ioinovici, A. Switched-Capacitor/Switched-Inductor Structures for Getting Transformerless Hybrid DC–DC PWM Converters. *IEEE Trans. Circuits Syst. Regul. Pap.* 2008, 55, 687–696.
72. Elmakawi, A.M.; Bayındır, K.Ç. Novel Single Switch High Gain Non-isolated DC-DC Converter for Building Integrated Photovoltaic Systems. In *Proceedings of the 2019 1st Global Power, Energy and Communication Conference (GPECOM)*, Nevsehir, Turkey, 12–15 June 2019; pp. 265–269.
73. Moradpour, R.; Ardi, H.; Tavakoli, A. Design and Implementation of a New SEPIC-Based High Step-Up DC/DC Converter for Renewable Energy Applications. *IEEE Trans. Ind. Electron.* 2018, 65, 1290–1297.
74. Hasanpour, S.; Baghrmian, A.; Mojallali, H. A Modified SEPIC-Based High Step-Up DC–DC Converter with Quasi-Resonant Operation for Renewable Energy Applications. *IEEE Trans. Ind. Electron.* 2019, 66, 3539–3549.
75. Zhao, Y.; Xiang, X.; Li, C.; Gu, Y.; Li, W.; He, X. Single-Phase High Step-up Converter With Improved Multiplier Cell Suitable for Half-Bridge-Based PV Inverter System. *IEEE Trans. Power Electron.* 2014, 29, 2807–2816.
76. Lee, W.J.; Kim, C.E.; Moon, G.W.; Han, S.K. A New Phase-Shifted Full-Bridge Converter With Voltage-Doubler-Type Rectifier for High-Efficiency PDP Sustaining Power Module. *IEEE Trans. Ind. Electron.* 2008, 55, 2450–2458.
77. Hu, X.; Gong, C. A High Gain Input-Parallel Output-Series DC/DC Converter With Dual Coupled Inductors. *IEEE Trans. Power Electron.* 2015, 30, 1306–1317.
78. Lee, S.; Kim, P.; Choi, S. High Step-Up Soft-Switched Converters Using Voltage Multiplier Cells. *IEEE Trans. Power Electron.* 2013, 28, 3379–3387.
79. Park, K.B.; Moon, G.W.; Youn, M.J. High Step-up Boost Converter Integrated With a Transformer-Assisted Auxiliary Circuit Employing Quasi-Resonant Operation. *IEEE Trans. Power Electron.* 2012, 27, 1974–1984.
80. Nymand, M.; Andersen, M.A.E. High-Efficiency Isolated Boost DC–DC Converter for High-Power Low-Voltage Fuel-Cell Applications. *IEEE Trans. Ind. Electron.* 2010, 57, 505–514.
81. Liang, T.J.; Lee, J.H.; Chen, S.M.; Chen, J.F.; Yang, L.S. Novel Isolated High-Step-Up DC–DC Converter with Voltage Lift. *IEEE Trans. Ind. Electron.* 2013, 60, 1483–1491.
82. Luo, F.L. Luo-converters, voltage lift technique. In *Proceedings of the PESC 98 Record. 29th Annual IEEE Power Electronics Specialists Conference (Cat. No.98CH36196)*, Fukuoka, Japan, 22 May 1998; Volume 2, pp. 1783–1789.

83. Totonchi, N.; Gholizadeh, H.; Mahdizadeh, S.; Afjei, E. A High Step up DC-DC Converter Based on the Cascade Boost, Voltage Multiplier Cell and Self Lift Luo Converter. In Proceedings of the 2020 10th Smart Grid Conference (SGC), Kas han, Iran, 16–17 December 2020; pp. 1–5.
84. Mohammadzadeh Shahir, F.; Babaei, E.; Farsadi, M. Voltage-Lift Technique Based Nonisolated Boost DC–DC Converter: Analysis and Design. *IEEE Trans. Power Electron.* 2018, 33, 5917–5926.
85. Shahir, F.M.; Babaei, E.; Farsadi, M. Extended Topology for a Boost DC–DC Converter. *IEEE Trans. Power Electron.* 2019, 34, 2375–2384.
86. Luo, F.L.; Ye, H. *Advanced dc/dc Converters*; CRC Press: Boca Raton, FL, USA, 2016.
87. Luo, F.L. Six self-lift DC-DC converters, voltage lift technique. *IEEE Trans. Ind. Electron.* 2001, 48, 1268–1272.
88. Zhu, M.; Luo, F. Series SEPIC implementing voltage-lift technique for DC–DC power conversion. *IET Power Electron.* 2008, 1, 109–121.
89. Laha, A. A High Voltage Gain Quadratic Boost Converter using a Voltage Doubler and Voltage-Lift Technique. In Proceedings of the 2020 IEEE International Conference on Power Electronics, Smart Grid and Renewable Energy (PESGRE2020), Cochin, India, 2–4 January 2020; pp. 1–6.
90. Chakraborty, S.; Kumar, A. A High Step-Up Transformerless DC-DC Quadratic Boost Converter using Voltage-Lift Switched Inductor and Voltage Multiplier. In Proceedings of the 2022 IEEE IAS Global Conference on Emerging Technologies (GlobConET), Arad, Romania, 20–22 May 2022; pp. 170–175.
91. Li, Y.; Sathikumar, S. Improved Quadratic Boost Converter Based on the Voltage Lift Technique. In Proceedings of the 2017 Asia Modelling Symposium (AMS), Kota Kinabalu, Malaysia, 4–6 December 2017; pp. 139–144.
92. Radhika, S.; Margaret, V. A Comparative Assessment of Cascaded Double Voltage Lift Boost Converter. In Proceedings of the 2020 Fifth International Conference on Research in Computational Intelligence and Communication Networks (ICRCICN), Bangalore, India, 26–27 November 2020; pp. 177–180.
93. Ye, Y.; Cheng, K.W.E. A Family of Single-Stage Switched-Capacitor–Inductor PWM Converters. *IEEE Trans. Power Electron.* 2013, 28, 5196–5205.
94. Jiao, Y.; Luo, F.; Zhu, M. Voltage-lift-type switched-inductor cells for enhancing DC–DC boost ability: Principles and integrations in Luo converter. *IET Power Electron.* 2011, 4, 131–142.
95. Almalaq, Y.; Alateeq, A.; Matin, M. A Non-Isolated High Gain Switched-Inductor Switched-Capacitor Step-Up Converter for Renewable Energy Applications. In Proceedings of the 2018 IEEE International Conference on Electro/Information Technology (EIT), Rochester, MI, USA, 3–5 May 2018; pp. 0134–0137.
96. Choudhury, T.R.; Nayak, B.; Santra, S.B. A Novel Switch Current Stress Reduction Technique for Single Switch Boost-Flyback Integrated High Step Up DC–DC Converter. *IEEE Trans. Ind. Electron.* 2019, 66, 6876–6886.
97. Eskandari, R.; Babaei, E.; Sabahi, M.; Ojaghkandi, S.R. Interleaved high step-up zero-voltage zero-current switching boost DC–DC converter. *IET Power Electron.* 2020, 13, 96–103.
98. Song, W.; Lehman, B. Dual-bridge DC-DC converter: A new topology characterized with no deadtime operation. *IEEE Trans. Power Electron.* 2004, 19, 94–103.
99. Song, W.; Lehman, B. Current-Fed Dual-Bridge DC–DC Converter. *IEEE Trans. Power Electron.* 2007, 22, 461–469.
100. Du, Y.; Lukic, S.; Jacobson, B.; Huang, A. Review of high power isolated bi-directional DC-DC converters for PHEV/EV DC charging infrastructure. In Proceedings of the 2011 IEEE Energy Conversion Congress and Exposition, Phoenix, AZ, USA, 17–22 September 2011; pp. 553–560.
101. Forouzesh, M.; Baghrmian, A. Galvanically isolated high gain Y-source DC–DC converters for dispersed power generation. *IET Power Electron.* 2016, 9, 1192–1203.
102. Husev, O.; Liivik, L.; Blaabjerg, F.; Chub, A.; Vinnikov, D.; Roasto, I. Galvanically Isolated Quasi-Z-Source DC–DC Converter With a Novel ZVS and ZCS Technique. *IEEE Trans. Ind. Electron.* 2015, 62, 7547–7556.
103. Chub, A.; Vinnikov, D.; Blaabjerg, F.; Peng, F.Z. A Review of Galvanically Isolated Impedance-Source DC–DC Converters. *IEEE Trans. Power Electron.* 2016, 31, 2808–2828.
104. Alhurayyis, I.; Elkhateb, A.; Morrow, J. Isolated and Nonisolated DC-to-DC Converters for Medium-Voltage DC Networks: A Review. *IEEE J. Emerg. Sel. Top. Power Electron.* 2021, 9, 7486–7500.
105. Zhao, Q.; Lee, F. High-efficiency, high step-up DC-DC converters. *IEEE Trans. Power Electron.* 2003, 18, 65–73.
106. Wai, R.J.; Duan, R.Y. High step-up converter with coupled-inductor. *IEEE Trans. Power Electron.* 2005, 20, 1025–1035.
107. Hsieh, Y.P.; Chen, J.F.; Liang, T.J.; Yang, L.S. Novel High Step-Up DC–DC Converter for Distributed Generation System. *IEEE Trans. Ind. Electron.* 2013, 60, 1473–1482.

108. Siwakoti, Y.P.; Blaabjerg, F.; Loh, P.C. Ultra-step-up DC-DC converter with integrated autotransformer and coupled inductor. In Proceedings of the 2016 IEEE Applied Power Electronics Conference and Exposition (APEC), Long Beach, CA, USA, 20–24 March 2016; pp. 1872–1877.
109. Forouzesh, M.; Yari, K.; Baghrmian, A.; Hasanpour, S. Single-switch high step-up converter based on coupled inductor and switched capacitor techniques with quasi-resonant operation. *IET Power Electron.* 2017, 10, 240–250.
110. Hasanpour, S.; Siwakoti, Y.P.; Blaabjerg, F. A New High Efficiency High Step-Up DC/DC Converter for Renewable Energy Applications. *IEEE Trans. Ind. Electron.* 2023, 70, 1489–1500.
111. Talebi, P.; Packnezhad, M.; Farzanehfard, H. Fully Soft Switched Ultra-High Step-Up Converter With Very Low Switch Voltage Stress. *IEEE Trans. Power Electron.* 2022, 38, 3523–3530.
112. Taheri, S.M.; Baghrmian, A.; Pourseyedi, S.A. A Novel High Step-Up SEPIC-Based Non-Isolated Three-Port DC-DC Converter Proper for Renewable Energy Applications. *IEEE Trans. Ind. Electron.* 2022.
113. Habibi, S.; Rahimi, R.; Ferdowsi, M.; Shamsi, P. Coupled Inductor Based Single-Switch Quadratic High Step-Up DC-DC Converters with Reduced Voltage Stress on Switch. *IEEE J. Emerg. Sel. Top. Ind. Electron.* 2022, 1–12.
114. Schmitz, L.; Martins, D.C.; Coelho, R.F. Three-Terminal Gain Cells Based on Coupled Inductor and Voltage Multipliers for High Step-Up Conversion. *IEEE Trans. Circuits Syst. II Express Briefs* 2022.
115. Ardi, H.; Ajami, A.; Sabahi, M. A Novel High Step-Up DC-DC Converter With Continuous Input Current Integrating Coupled Inductor for Renewable Energy Applications. *IEEE Trans. Ind. Electron.* 2018, 65, 1306–1315.
116. Das, M.; Pal, M.; Agarwal, V. Novel High Gain, High Efficiency DC-DC Converter Suitable for Solar PV Module Integration with Three-Phase Grid Tied Inverters. *IEEE J. Photovoltaics* 2019, 9, 528–537.
117. Minami, M.; Tomoeda, K. An Analysis of Operation in Single-Switch High Step-up DC-DC Converter with Three-winding Coupled Inductor. In Proceedings of the 2019 IEEE Applied Power Electronics Conference and Exposition (APEC), Anaheim, CA, USA, 17–21 March 2019; pp. 2135–2137.
118. Siwakoti, Y.P.; Peng, F.Z.; Blaabjerg, F.; Loh, P.C.; Town, G.E. Impedance-Source Networks for Electric Power Conversion Part I: A Topological Review. *IEEE Trans. Power Electron.* 2015, 30, 699–716.
119. Siwakoti, Y.P.; Peng, F.Z.; Blaabjerg, F.; Loh, P.C.; Town, G.E.; Yang, S. Impedance-Source Networks for Electric Power Conversion Part II: Review of Control and Modulation Techniques. *IEEE Trans. Power Electron.* 2015, 30, 1887–1906.
120. Siwakoti, Y.P.; Loh, P.C.; Blaabjerg, F.; Andreasen, S.J.; Town, G.E. Y-Source Boost DC/DC Converter for Distributed Generation. *IEEE Trans. Ind. Electron.* 2015, 62, 1059–1069.
121. Siwakoti, Y.P.; Blaabjerg, F.; Loh, P.C. Quasi-Y-Source Boost DC-DC Converter. *IEEE Trans. Power Electron.* 2015, 30, 6514–6519.
122. Siwakoti, Y.P.; Blaabjerg, F.; Chiang Loh, P. High Step-Up Trans-Inverse (T_x-1) DC-DC Converter for the Distributed Generation System. *IEEE Trans. Ind. Electron.* 2016, 63, 4278–4291.
123. Lai, J.S.; Peng, F.Z. Multilevel converters—a new breed of power converters. *IEEE Trans. Ind. Appl.* 1996, 32, 509–517.
124. Meynard, T.; Foch, H. Multi-level conversion: High voltage choppers and voltage-source inverters. In Proceedings of the PESC '92 Record. 23rd Annual IEEE Power Electronics Specialists Conference, Toledo, Spain, 29 June–3 July 1992; pp. 397–403.
125. Sanders, S.R.; Alon, E.; Le, H.P.; Seeman, M.D.; John, M.; Ng, V.W. The Road to Fully Integrated DC-DC Conversion via the Switched-Capacitor Approach. *IEEE Trans. Power Electron.* 2013, 28, 4146–4155.
126. Hama, F.; Meynard, T.; Tourkhani, F.; Viarouge, P. Characteristics and design of multilevel choppers. Proceedings of PESC '95 - Power Electronics Specialist Conference, Atlanta, GA, USA, 18–22 June 1995; Volume 2, pp. 1208–12142.
127. Sun, J.; Xu, M.; Ying, Y.; Lee, F.C. High power density, high efficiency system two-stage power architecture for laptop computers. In Proceedings of the 2006 37th IEEE Power Electronics Specialists Conference, Jeju, Republic of Korea, 18–22 June 2006; pp. 1–7.
128. Xu, M.; Sun, J.; Lee, F. Voltage divider and its application in the two-stage power architecture. In Proceedings of the Twenty-First Annual IEEE Applied Power Electronics Conference and Exposition, 2006. APEC '06, Dallas, TX, USA, 19–23 March 2006; p. 7.
129. Chen, M.; Afridi, K.K.; Chakraborty, S.; Perreault, D.J. Multitrack Power Conversion Architecture. *IEEE Trans. Power Electron.* 2017, 32, 325–340.

