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Employing various topologies to improve the interleaved boost converters performance

Areej Hamzah Makee, Ali Hussein Al-Omari
Department of Electrical Engineering, Faculty of Engineering, Mustansiriyah University, Baghdad, Iraq

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ABSTRACT

In recent years, there has been a significant amount of literature concerning high step-up DC-DC converters. Whereas the voltage level needs to be raised to a higher value so that the DC conversion can meet the AC mains value. A boost converter is the most popular circuit in the field, but because of its drawbacks, employing it is limited. Interleaved boost converters have attracted considerable attention and are a promising solution for high-power step-up and power factor correction applications. To demonstrate the importance of this topology, a comparison has been made with single-switch converters. For this reason, this paper classifies the topologies into two main categories based on the number of main switching elements: Single-switch and interleaved boost converters. Then, each category was classified, including the conventional and the modified types, to cover the effect of adding voltage multiplier cells, coupled inductors, and a combination of coupled inductors and voltage multiplier cells. Each converter's performance was evaluated by comparing the voltage gain of each unit. Also, this paper highlighted these converters' essential characteristics, topological strategies, benefits, and demerits to clarify the differentiating solutions. Additionally, this work presents the difficulties or directions for developing novel topologies.

Corresponding Author:

Areej Hamzah Makee
Department of Electrical Engineering, Faculty of Engineering, Mustansiriyah University
Baghdad, Iraq
Email: eema2001@uomustansiriyah.edu.iq

1. INTRODUCTION

A non-isolated boost converter is one of the topologies in which increasing the duty cycle is the only way to achieve a high output voltage. However, high-duty-cycle operations result in weak performance due to increased losses, decreased efficiency, employed bulk reactive elements, produced a high input current ripple, and required complex and costly drive circuitry. As a result, the most significant voltage gain that can be achieved is similarly limited [1]. Many circuit changes and strategies were suggested in the literature to raise the voltage gain of conventional step-up converters to overcome the restrictions imposed by excessively high-duty cycles [2]-[4].

The categories of various boost converter topologies, which rely on the number of main converter switches with practical techniques, are analyzed. The first category is the single-switch converters, which utilize various approaches to create significant voltage gain while maintaining a minimum duty cycle. Single-switch topologies have an easy control technique, low cost, and size. One of these types is a quadratic boost converter, a technique that employs two boost converters operated by a single switch [5], [8]. Jana *et al.* [9], the voltage stress across the power MOSFET switch is very low and equals half of the output voltage. A coupled inductor technique achieves a high voltage gain by varying the turns ratio [10], [11]. Coupled-inductor converters integrated with either passive or active clamp circuits were designed to solve the issue of leakage inductance in coupled inductors [12]-[15]. Voltage multiplier cells are joined to obtain a significant voltage gain. The cells consist of diode-capacitor-inductor units [16]. The voltage difference between output and input is significant in such topologies without the need of using magnetic components. However, high-frequency operation minimizes the capacitor’s size, allowing for constructing a single integrated circuit for low-power applications without external components [17]. The number of utilized voltage multipliers (VM) increases to achieve larger voltage conversion ratios. [18]. The most widely investigated is the ultra high-step-up converters based on a coupled inductor and VM. Adding coupled inductor and multiplier cells to traditional converters produces additional attributes while keeping some original properties. Due to these significant features, the converter has become one of the most effective methods to enhance the gain of DC-DC converters [3], [4], [15], [19].

The second category is the multiple switches’ converters, which employ some strategies to generate a significant voltage gain while maintaining a small-duty cycle. A cascaded boost converter has a high voltage gain because they use two or more separated boost converter stages connected in series [20]-[22]. The interleaved boost converter (IBC), which belongs to the second category, effectively reduces the input current ripple. When the power rating rises, the converters frequently prefer to connect in a parallel configuration. Switch current and thermal loads are distributed, as a result, improving the efficiency and reliability [23]-[27]. Because interleaved boost converters have more inductors than ordinary boost converters, it can make circuit build more complex. However, low ripple content at the input and the output sides made the topology desirable [28]. To reduce the complexity, these studies investigated the three types: coupled, uncoupled, and inversely coupled interleaved boost converter inductors [29], [30]. Babaa *et al.* [31], switched capacitor voltage multiplier cells (VMCs) are added to the conventional interleaved boost converter at the output side. The number of switched capacitor cells is the only way to extend this converter’s voltage gain.

To highlight the importance of the interleaved topology, a comparison was made across the single-switch converter topologies. This study focuses on classified converters into two main categories based on the number of main switches that each topology consists of, similarly investigated the performance of various types of single switches and interleaved converters. Furthermore, the overall framework and the converters’ pros and cons are demonstrated and discussed to employ them in appropriate applications, such as renewable energy sources and power factor correction. The two groups are compared, and some difficulties and potential solutions for developing new topologies are described.

2. COMPARISON OF HIGH STEP-UP DC-DC BOOST CONVERTERS

2.1. Basic single switch boost converter

The basic step-up converter is the boost converter Figure 1 which is commonly used for step-up applications because of its simple and efficient construction. The theoretical voltage gain of a boost converter is near to infinite when the duty cycle is close to one. Current ripple and conduction losses rise with longer switch turn-on times. Thus, switching and reverse recovery losses are taken into account. As switching devices’ voltage stress equals the converter’s output voltage, power switches with high voltage ratings and high RDS-ON increase the conduction losses and cost. Consequently, the low system efficiency limits the Boost converter’s voltage gain [32], [33].

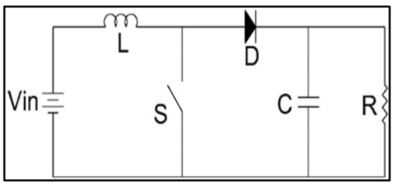


Figure 1. Conventional boost converter

2.2. Single switch quadratic boost converter

A quadratic boost converter is the two stages of a boost converter controlled by single switch, as shown in Figure 2. This technique enables a high conversion ratio with acceptable duty cycle duration. Due to the low-duty cycle used to achieve a high conversion ratio, the quadratic topology components are less stressed than those of conventional converters. However, for high-step-up applications with many microgrids, coupled inductors are used to obtain extra voltage gain. Furthermore, increasing switching frequency reduces the passive parts in these architectures. It is also facilitating to raise the photovoltaic’s voltage level and run it at higher switching frequencies without the need to use a transformer to work in a wide input voltage range [34]. The quadratic operation in a discontinuous mode lowers the output voltage's second-order line frequency ripple, the lower peak input inductor current, and the faster output voltage dynamic response. These features make it suitable for power factor applications [35]. The comparison between quadratic and conventional boost converters for high step-up and PFC applications is demonstrated respectively in [36], [37]. The characteristics of the quadratic converter include high output voltage with low ripple, smoother continuous input current, less total harmonic distortion (THD). Despite its slightly lower efficiency, operating with a single active switch, including a quadratic boost converter, is particularly appealing in the industry applications [5], [38].

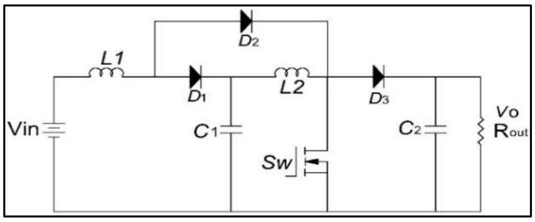
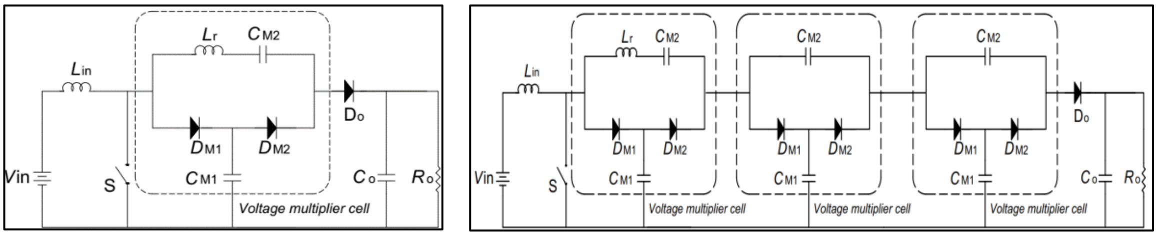


Figure 2. Quadratic boost converter

2.3. Single switch with voltage multipliers

Integrating voltage multiplier cells with classical non-isolated DC-DC boost converters is depicted in Figure 3 [39], whereas Figure 3(a) showing single stage that overcome the conventional converter limitations for high-performance applications that require significant conversion rates. The voltage at the switch is equal to one-half of the output voltage in the simplest case when (m=1), where (m) is the number of multiplier cells. The switch voltage reduction permits low drain-source voltage and low (Rds.-on) for MOSFETs, minimizing the switch conduction losses [16], [40]. Adding more multiplier cells increases the step-up ratios, as displayed in Figure 3(b) [39]. Using a single resonant inductor with a small inductance (usually 1µ H to 4 µH) in the initial voltage multiplier cell enables the power switch to work with zero-current-switching (ZCS) turn-on and reduce the reverse recovery current of every diode. The voltage multiplier cell raises the conventional boost's static gain by (m+1). The number of VM cells allows for the adjustment of voltage conversion ratio and voltage stress of the switch [18], [41].



(a) (b)

Figure 3. BC [39] (a) with single voltage multiplier and (b) with "m" number of voltage multipliers

2.4. Single switch with coupled inductor technique

The tapped-or coupled inductor boost converter, as in Figure 4, is considered one of the most simple and effective methods for achieving a wide range of voltage conversion ratios. The high-boosting solution can be obtained with a few components by adjusting the number of turns ratio N2:N1 of the coupled inductor. The magnetic element is essential for designing the converter; the inductance coupling factor is important. So, a proper building approach must be applied [42]. A detailed discussion of the relevant equations for designing the size of the core, turn ratio, and wire size can be found in [43], even though a high voltage spike produced by the stored energy in the leakage of coupled inductors might cause a problem. A passive voltage clamp circuit can handle this problem, as exhibited in Figure 4(a) [44].

The voltage spike is reduced to twice the input voltage using the buck-boost active-clamp circuit, as evinced in Figure 4(b) [14]. Since the main and auxiliary switches are switched on with ZVS and the boost diode is off with ZCS, the switching loss decreases, and the conversion efficiency is enhanced. As presented in Figure 4(c) [45], the coupled inductor with one input inductor can achieve a significant voltage gain without requiring excessive duty cycles. The low voltage stress on the switch can also be accomplished, allowing the low-voltage-rating MOSFETs to be used and reducing the conduction loss. In addition, the converter's input current is continuous, which is beneficial for battery, fuel cell, and solar applications. The diodes' reverse recovery difficulty can be mitigated, and the resulting leakage energy can be restored [46].

The orientation of the windings has an impact on the performance of single switch coupled inductor converters. Hence, the windings direction must be taken into consideration when designing coupled inductors. The inversely coupled inductors can achieve high gain, while reducing the voltage stress across switching elements, and minimize the input current ripple. Thereby, the size of the main inductor is reduced, which reduces the losses and enhances the converter efficiency. This topology is helpful for photovoltaic applications [47].

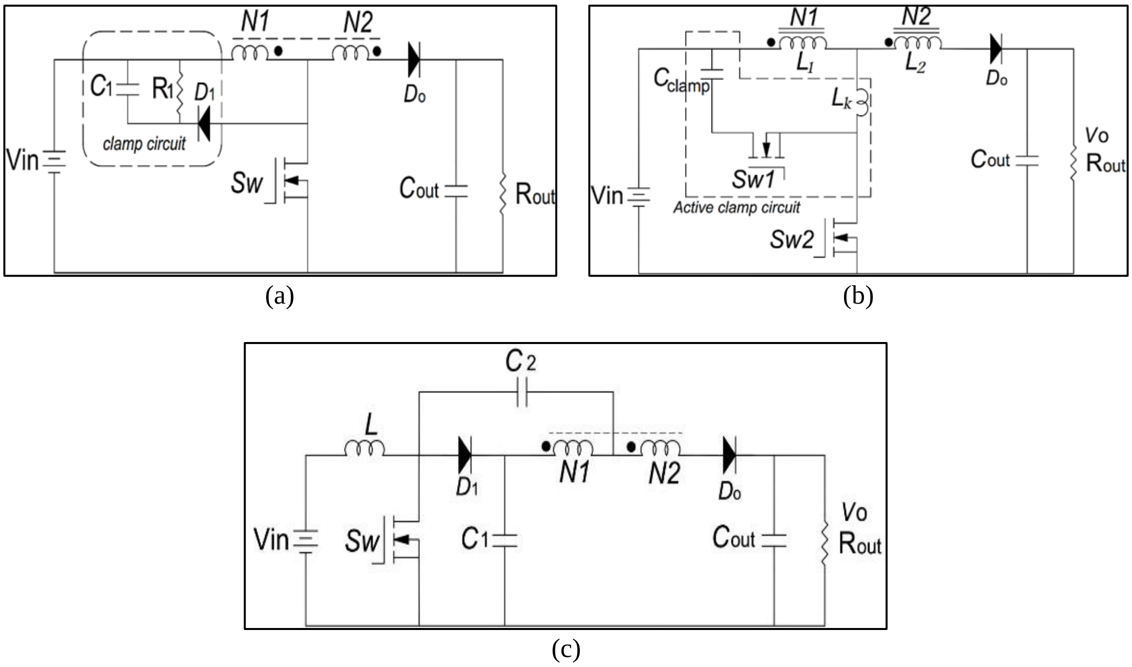


Figure 4. Coupled inductor BC (a) with passive clamp circuit [45], (b) with an active clamp circuit [14], and (c) with one input inductor [45]

2.5. Single-switch with coupled-inductor technique and voltage multiplier cells

General diagram of boost converter with gain cell and an output filter are demonstrated in Figure 5 [10]. A voltage multiplier unit consists of diode-capacitor components, and a coupled inductor is integrated into a standard converter shown in Figure 6. To avoid an exceedingly high duty cycle and lessen the leakage inductance loss imposed by weak high-frequency transformer coupling, a more considerable voltage gain can be achieved by adjusting the duty ratio and the turns ratio of coupled inductors. The switch's voltage stress can be significantly reduced even when the output voltage is significantly high since the voltage multiplier unit isolates the switch and output voltages. The coupled inductor's leakage inductance energy can be stored and fed back to the load, improving the converter's efficiency [48]. There are three degrees of design freedom allowed in this converter by the quantity of voltage multiplier cells and the coupled inductors' turn ratios. These degrees of freedom are utilized to determine the proper voltage stresses of the semiconductors within the desired range and deliver a high voltage gain with optimal duty cycles [49]. The structure explained in Figure 6(a) provides the ZCS in the off-state and the ZVS in the on-state of the diode to facilitate a high efficiency by reducing the diodes' reverse recovery losses. One power MOSFET with a low ON-state resistance simplifies the proposed control circuit. This topology is appropriate for renewable energy sources and LED drivers [50]. A quadratic coupled inductor with a voltage multiplier and absorption circuit is portrayed in Figure 6(b) [51]. This technique effectively extends the adjustable range of the voltage conversion ratio and eliminates the duty ratio constraint. Moreover, the magnetic element's volume can be decreased. An auxiliary inductor and a capacitor make up the ripple absorption circuit, which soothes out the input current to an extremely low level of variation. In a switching period, the diode-capacitor voltage multiplier can absorb the switching-off voltage spikes induced by leakage inductance and restore the leakage inductance loss to the load.

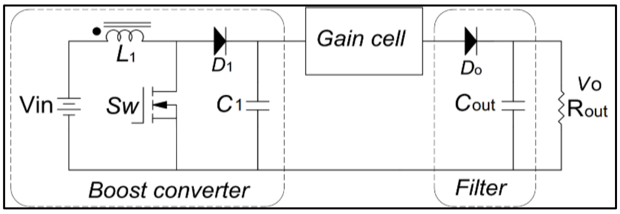
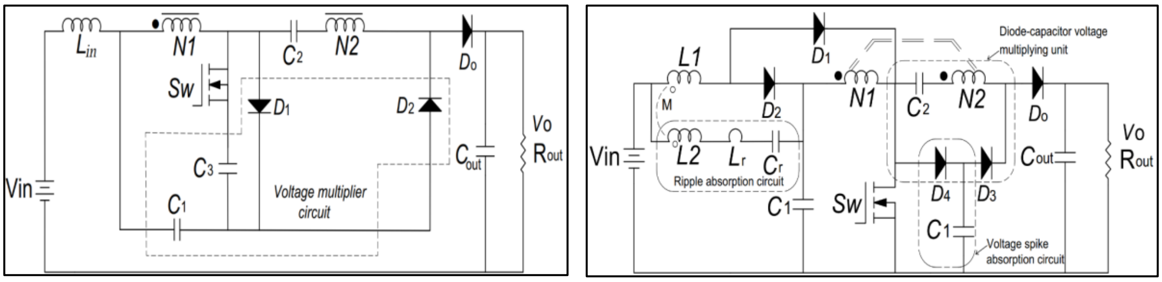


Figure 5. Gain cell included in the generalized boost converter [10]



(a) (b)

Figure 6. Coupled inductor BC and VM (a) with ZCS/ZVS [51] and (b) with ripple absorption circuit [52]

2.6. Basic interleaved boost converter

The interleaving method can be utilized as an alternative approach for reducing the ripple in the input current. In addition, when the rate of the power device grows, it is sometimes desirable to connect many converters in parallel. This process assists in the distribution of the switch current as well as thermal stresses, lower electromagnetic emission, quicker transient response, and accomplishes high efficiency and reliability [25], [52], [53]. The typical interleaved boost converter is revealed in Figure 7. It is considered an effective option for general power factor correction (PFC) applications. However, there are particular limits when used in large step-up systems with approximately or more than ten times the voltage boost [33].

In the high-step-up conversion applications, the switch duty cycle is often high, and the off time is typically quite low. Consequently, the power rating of the devices has substantial peak currents and significant diode reverse recovery issues [54]. An interleaved soft-switching boost converter with a zero-voltage auxiliary inductor can power the active switches and reduce the switching losses, increasing the conversion efficiency. The two boost components that work in parallel are identical. Therefore, the converter module analysis and design are uncomplicated [55].

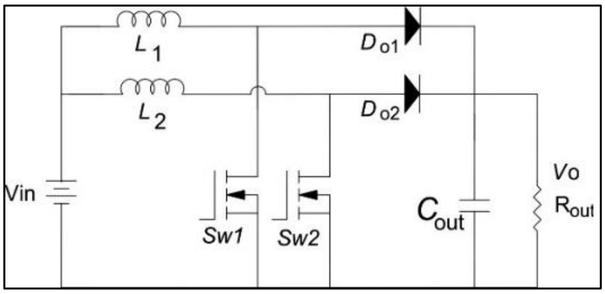


Figure 7. Conventional interleaved BC

2.7. Interleaved quadratic boost converter

The interleaved quadratic boost architecture comprises two stages of quadratic converters connected in parallel, as illustrated in Figure 8. Interleaving converters speed switching times reduce the output voltage ripple, reduce the inductor current ripple, and enable the small-size filters to be used. As a result, the efficiency is improving, so the converter becomes ideal for use in situations requiring high gain when cascaded with a voltage multiplier. These features make converters suitable for high-power applications [56]. Employing the voltage lift and coupling technique with an interleaved quadratic boost converter increases the voltage conversion ratio. This model is appropriate for low-voltage renewable energy sources [57]. Using a voltage lift capacitor with an interleaved quadratic boost converter and cascading with a conventional boost converter gives an ultra-high voltage gain that is proportional to the cube gain of the conventional boost converter [58].

Four inductor designs were studied in [59]. One uncoupled inductors design and three different coupled inductors designs for the interleaved quadratic boost converter. The effects of the four designs on the output voltage, total weight and volume, and the converter's efficiency were investigated. This study showed that the coupled inductor enhances the performance and efficiency of the interleaved quadratic boost converter. An excellent option for photovoltaic high-power, low-input side voltage applications was suggested in [60]. The input photovoltaic panel experiences a lower current ripple than the typical type, and the output load has a lower voltage ripple. Moreover, interleaving has allowed converters to run on high levels of photovoltaic power. When multi-winding coupled inductors are used as the energy storage magnetic element rather than discrete inductors, a multiphase interleaved quadratic boost converter structure is achieved. Therefore, the combination of voltage multiplier cells, the coupled inductors, and a voltage lift capacitor with interleaved quadratic coupled inductor increase the voltage gain even further. This technique can achieve ultra-high voltage gain (21.11) and extremely low input current ripple (4.59% of I_{in}). Further, it provides switches with a low voltage rating (18.9% of V0) and regulates the output voltage to the load. So, this converter is an effective alternative topology for integrating PV sources to a 380 V DC bus used in a DC microgrid [61].

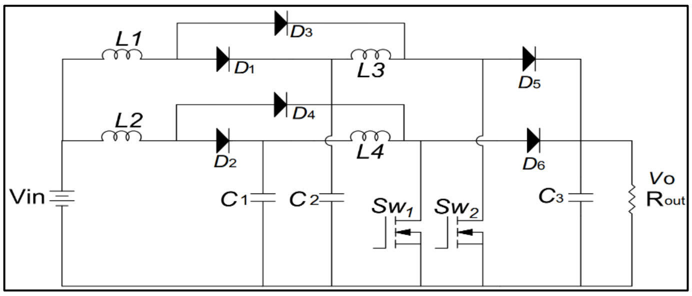


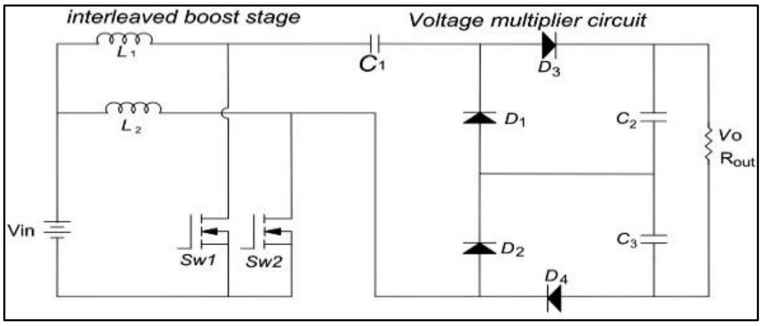
Figure 8. Interleaved quadratic boost converter

2.8. Interleaved with voltage multiplier

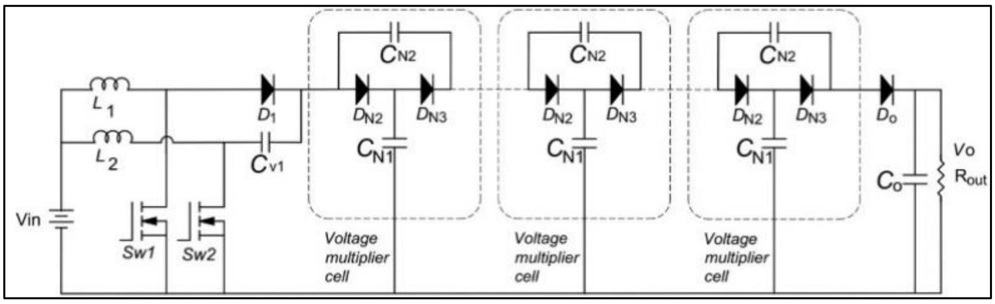
The voltage gain of the interleaved boost converter is equal to that of the conventional boost converter. Therefore, using voltage multiplier cells in cascade with interleaved boost converters, as in Figure 9, enables the DC/DC converter to reach higher voltage gains than obtained with traditional boost converters [62]. This converter can achieve a high voltage gain using a voltage multiplier cell and series capacitor connections on the output side, as revealed in Figure 9(a) [63]. Additionally, the current ripple is significantly decreased by using parallel connections of inductors on the input side. These characteristics enable this converter to be used in renewable energy applications. Furthermore, compared to other architectures, this configuration has reduced the voltage stresses across the power semiconductors [64], [65].

There are two different arrangements for the structure. A capacitor filter and an output diode are used to filter the output of configuration 1, while an LC filter filters the output of configuration 2. The main difference between these types is the internal capacitors' charging and discharging method. Other differences include the type of connection to the load, such as floating, inverted or ground, the stress on the diodes and capacitors, and the number of parts in every VMC (voltage multiplier cell) step. In an interleaved boost converter stage, the VMC structure affects the current from the input source, which is shared across the phases [66].

Typically, the model that offers a gain (m+2) time that of a conventional boost converter uses (m+2) diodes and (m+2) capacitors, including a voltage lift capacitor where the voltage multiplier has a specific number of cells, which is symbolized in (m). The main benefit of this architect is the ability to deliver large conversion ratios without needing a transformer; other benefits include medium-duty cycle operation, continuous input current, and adaptability. Figure 9(b) [67] depicts the general diagram of a power circuit m-level converter. It has advantages over traditional boost converters, including a voltage conversion ratio twice and a lower ripple in the input current due to the interleaved arrangement. In addition, the switches are activated at zero voltage switching, and the diodes are deactivated at zero current switching. The current stresses in the switches and the size of passive components are minimized. Furthermore, changing the quantity of voltage multiplier cells in fundamental arrangement achieves additional freedom in device selection [68].



(a)



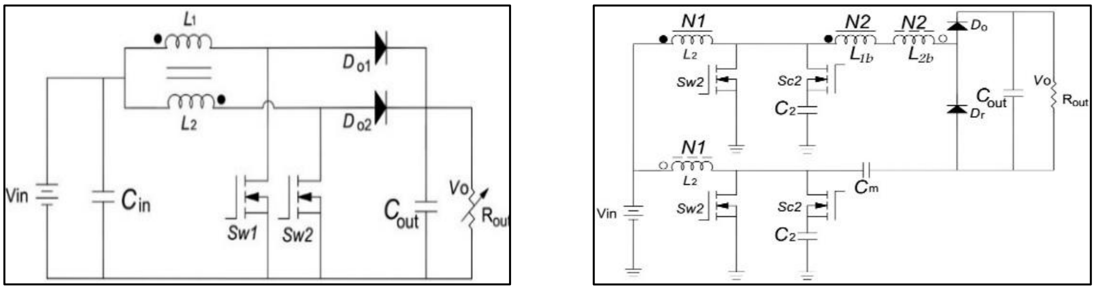
(b)

Figure 9. IBC with (a) VM [64] and (b) with "m" number of voltage multiplier cells [68]

2.9. Interleaved with coupled inductor technique

Using the interleaved technique requires more inductors based on the number of phases. Instead of using many individual inductors, which take up much space and make converters more complicated, the coupled inductor has been presented in [69]. Merging many discrete inductors into one coupled inductor decreases the overall inductor size, cost, and complexity as in Figure 10. The performance of interleaved converters depends on the coupling coefficient (k), which is modified by the direct positioning of windings on the core when designing coupled inductors [59]. Because the flux produced by the two windings has opposite polarities, the inverse-coupled arrangement can cancel out most of the flux in the core when working in a DC environment where the DC current is shared equally between the two windings; therefore, the input current ripple is reduced. Figure 10(a) [29] displays the circuit topology. In the case of the direct-coupled design, the flux produced by the two windings will contribute to one another within the core rather than canceling one another out, thereby increasing the ripple in the inductor current. Consequently, the systems with direct coupling will saturate the core more easily when run at high power levels. In the high-power DC applications, DC flux offers a considerable benefit that can be gained from utilizing an inverse-coupled design. By contrast, the ac flux is reduced when the direct coupling is used [70].

The non-isolated, interleaved boost converter, with an active clamping circuit and zero voltage switching, was suggested in this study [26]. Figure 10(b) exhibits the circuit topology. The circuit is specially made for high-voltage gain applications. By recycling the leakage energy from the coupled inductor and minimizing the conduction and switching losses, the power converter architecture also lowers the voltage stress on semiconductors. The results also showed the circuit's ability to operate efficiently under various load conditions while achieving great output voltage control and fast reaction to load variations.



(a) (b)

Figure 10. Interleaved boost converter with (a) inverse coupled inductors [29] and (b) directly coupled inductor with active clamp circuit [26]

2.10. Interleaved coupled-inductor with voltage multiplier boost converter

A traditional interleaved boost converter, switched capacitor cells, coupled inductors, and voltage multiplier circuits work together to provide the desired output voltage. Figure 11 [71] illustrates the interleaved high step-up converter with a voltage multiplier cell and coupled inductors. It consists of two blocks. The first block is the traditional interleaved high step-up converter with coupled inductors, and the second block is the voltage multiplier cell. Coupled inductors can improve the voltage gain by varying the turn ratio of the primary and secondary windings. Switched capacitor cells and voltage multiplier circuits can achieve further enhanced voltage gain and low voltage stress on diodes and switches. The interleaved construction on the primary side significantly decreased the ripple in the input current. Hence, this converter is suitable for high-power applications due to its low input current ripple and low conduction losses. Furthermore, the leakage energy is recycled and sent to the output terminal, reducing the large voltage spikes on the main switch, and the issue of diodes' reverse recovery has been fixed. [72]. The VMC's lossless clamp performance solves the reverse recovery current of the output diodes and enables the switch to function as ZCS soft switching through the coupled inductor's leakage inductance [23], [73]. The rated voltage of MOSFETs is lower than the typical type, and the ON resistance is lower to reduce the losses of switch conduction and the stress of switching voltage. As a result, efficiency is greatly increased, while the costs are kept low [24], [74], [75].

Soft-switching and hard-switching high step-up interleaved DC-DC converter systems were suggested in [76]. Although the hard-switched approach has a simple construction, the switching losses of switches and diodes could be problematic. The active clamping circuit helps not only clamp the voltage spikes generated by parasitic inductance but also achieves the ZVS turn-on of switches and ZCS turn-off of diodes. In contrast, the soft-switching technique requires two additional switches for clamping. To provide more flexibility in device selection, the components' voltage ratings reduced the voltage stresses and increased the output voltage.

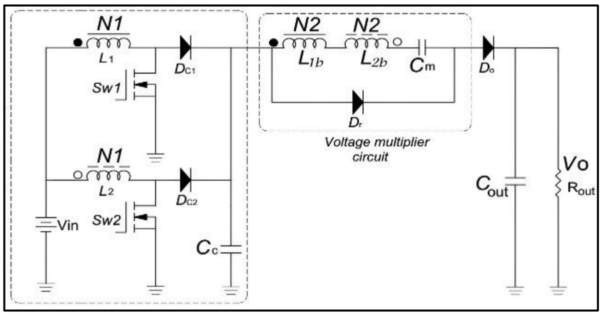


Figure 11. Coupled inductor of IBC with voltage multiplier [72]

3. QUANTITATIVE CHARACTERISTICS AND GENERAL COMPARISONS OF VARIOUS REVIEWED TOPOLOGIES

This section discusses a comparative analysis of the various topologies used in this work to identify their advantages and disadvantages. Table 1 summarizes the comparison findings for the structures presented regarding the estimated peak efficiency, experimental result, component count, voltage stress across diodes and switches, voltage gain, and soft-switching performance. The considered coupling of the coefficient is unity.

Table 1. The comparison among the main categories by using various techniques

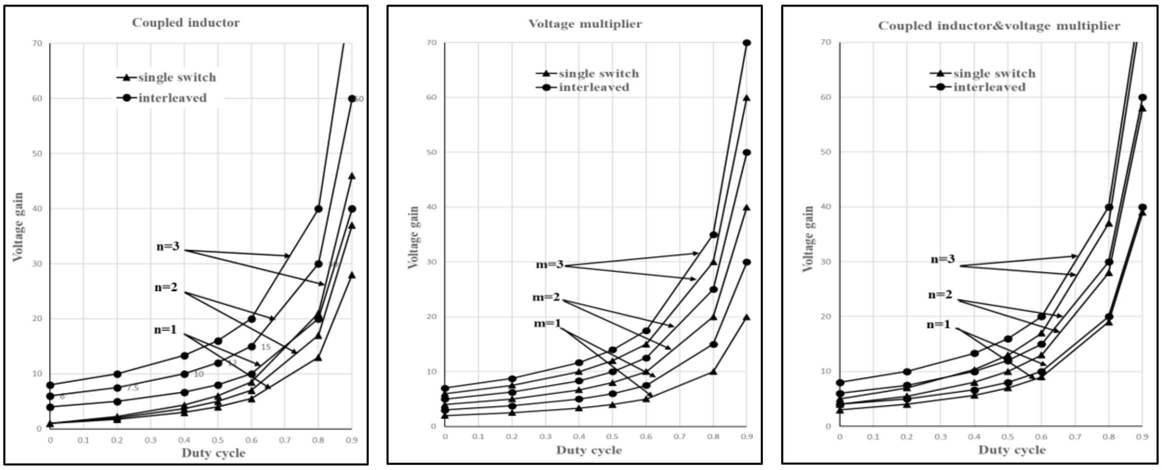
Topology		Component count (Switch/ capacitor/ diode/ magnetic core)	Voltage gain	Switch voltage stress	The maximum diode voltage stress	Experiment: Input/output voltage/switching frequency/Power rating	Experiment: Peak Efficiency
Single switch boost converter With	Quadratic converter [7]	1/2/2/2	$\frac{1}{(1-D)^2}$	Vo	Vo	48 V/150 V/20 kHz/ 100 W	94%
	Voltage multiplier [16]	1/3/3/2	$\frac{1}{(1-D)^2}$	$\frac{Vo}{2}$	$\frac{Vo}{2}$	12 V/100 V/50 kHz/ 100 W	93%
	Coupled inductor [45]	1/3/2/1	$\frac{1+D+nD}{(1-D)}$	$\frac{Vo}{1+D+nD}$	$\frac{Vo+nVo}{2+n}$	20 V/200 V/100 kHz/ 200 W	93.8%
	Voltage multiplier& Coupled inductor [48]	1/4/4/1	$\frac{2+n+nD}{(1-D)}$	$\frac{\mathrm{Vo}+\mathrm{nVin}}{2\mathrm{n}+2}$	$\frac{\mathrm{Vo}+\mathrm{nVin}}{2}$	40 V/400 V/60 kHz/ 300 W	96%
Interleaved boost converter With	Quadratic converter [57]	2/4/6/2	$\frac{2}{(1-D)^2}$	$\frac{\mathrm{Vo}}{2}$	$\frac{Vo}{2}$	24 V/380 V/40 kHz/ 100 W	92.5%
	Voltage multiplier [66]	5/7/4/2	$\frac{2m+1}{1-D}$	$\frac{Vo}{2\mathrm{m}+1}$	$\frac{2\mathrm{Vo}}{2\mathrm{m}+1}$	20 V/400 V/100 kHz/ 200 W	96.3%
	Coupled inductor [26]	4/4/2/1	$\frac{2\mathrm{n}+2}{1-D}$	$\frac{Vo}{2\mathrm{n}+2}$	Vo	12 V/120 V/50 kHz/ 500 W	91.2%
	Voltage multiplier &Coupled inductor [23]	2/7/7/2	$\frac{2n+2}{1-D}$	$\frac{Vo}{2\mathrm{n}+2}$	$\frac{2\,Vo}{2\mathrm{n}+2}$	32 V/800 V/118 kHz/ 400 W	96.7%

4. DISCUSSION

Most of these topologies can achieve greater levels of voltage gain by raising the coupled inductors' turns ratio or by using extra parts (such as multipliers). However, there will be an increment in the cost, complexity, and size of the converter, which are considered drawbacks. The interleaved with coupled inductor topologies in Table 1 can achieve a significant gain through high turns ratio.

After obtaining a more significant voltage gain, the output diode and switch voltage stress are critical since the total system expense may increase using high-rated elements. In addition, the impact of high voltage on semiconductor parts is assessed. Figure 12 represents the relationship between the voltage gain set against the various duty cycles for the topologies in Table 1, which consists of the following three cases: Figure 12(a) when employing a coupled inductor technique for the single switch and the interleaved topologies [45], [26], respectively. For (n) numbers of turns ratio considered (n=NP/NS), the voltage stresses on the switches of the interleaved cases decreased effectively more than the output voltage of the single switch's cases. Therefore, it can offer lower voltage rating devices. Figure 12(b) when employing voltage multipliers cells for the single switch and the interleaved topologies [16], [66], respectively. There is no effect of the number of multiplier cells on the voltage stresses of the power switches for single switch cases. However, in the interleaved cases, the voltage stresses decrease according to the number of multipliers. Figure 12(c) when employing a coupled inductor and one voltage multiplier cell for the single switch and the interleaved topology [48], [23], respectively. The results manifested a sizeable step-up voltage gain for one multiplier cell without requiring a high-duty cycle or significant turns ratio. Furthermore, the voltage stress on the semiconductor devices increases with increasing turns ratio in single switch cases and reduces with increasing turns ratio in the interleaved cases. Consequently, reducing the voltage rating can reduce the losses. Obviously, the interleaved technique can obtain the highest voltage gain in the three cases, as evinced in Figure 13.

Several types of the enhanced boost converters have been used throughout the past two decades, as elucidated in Figure 11. To demonstrate the importance of the reviewed topologies, a statistical figure was created based on the references that were used in this paper. Most of the current research focused on employing and improving the performance of the interleaved converter with a multiplier due to its properties of high gain and high efficiency through its circuit, which is considered more complicated to build than the other types.



(a) (b) (c)

Figure 12. Voltage gains vs. duty cycle for the single switch and interleaved converters: (a) Using different turns ratios of the coupled inductor, (b) Using the different numbers of voltage multiplier cells, and (c) Using different turn ratios of the coupled inductor with one voltage multiplier cell

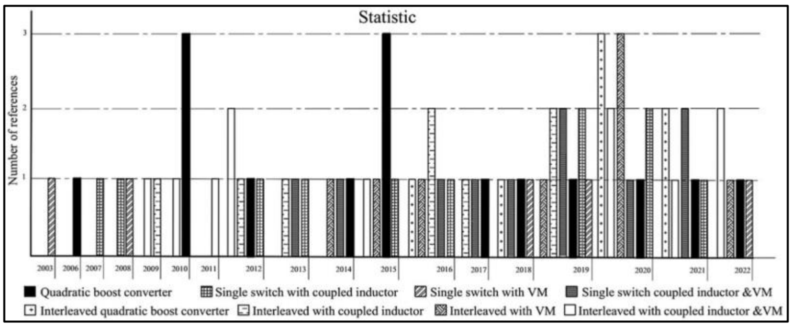


Figure 13. The research distribution during the past two decades

5. OBSTACLES AND STRATEGIES FOR FUTURE TOPOLOGY

The general topological structures shown in this paper can construct a methodical structure for high-step-up voltage multipliers and coupled-inductor boost converters. The difficulties or directions listed below must be considered in the future while introducing new topologies:

Recover the leakage energy. To reuse the leakage energy of the coupled inductor and prevent the switch voltage spike, suitable clamp circuits are required to reach a high-efficiency level. Furthermore, it is preferable to use the clamp circuit to improve the step-up gain of the converter [2], [3], [71], [72], [77].

Lower the ripples in the input current. Using a coupled inductor to obtain a high step-up gain has a few drawbacks, one of which is that it causes large ripples in the input current. As described above, the advanced topologies in this domain rely on integrating and interleaving methods, as well as inverse coupling [63], [78], [79]. Enhance the step-up voltage gain. To regulate a voltage gain, avoid a high-duty cycle, and reduce the dimensions of the magnetic core, the coupled inductor’s turn ratio may be adjusted for optimal performance. A large turn ratio is not desirable in the actual applications. Though, the voltage multipliers are employed in the aforementioned reviewed topologies to enhance the percentage of voltage conversion [80]. m-stage voltage-multiplier cells can be used to produce highly high step-up gains. Nevertheless, it has a great price, an increased number of parts, and excessive conduction loss [43], [81], [82].

Reduce the size of reactive elements. The huge capacitor draws a current in short pulses, decreasing the power, increasing the losses, and reducing the efficiency. As well as a large-size inductor can cause the same results. One suggestion was provided in [83] to deal with this problem. The size of reactive elements is reduced significantly by using a single switch with a parallel LC resonant branch. Al-Omari *et al.* [84] used the same method but with two switches. These techniques are applied in power factor applications. Thus, the small inductor and capacitor will effectively decrease the dimensions, weight, and price. Improve the DC converter efficiency. To achieve high gains, some approaches employ multi-stage converters. Each stage has a magnetic core [85], reducing the converter's efficiency. Magnetic cores have various associated losses, including residual flux, eddy current, and hysteresis. Ahmed *et al.* [86], two interleaved boost converters, each with a low voltage winding and a multiplier, are combined into the magnetic structure. Due to the reduced number of magnetic components, this design can achieve maximum efficiency in a topology where the losses are minimized.

6. CONCLUSION

The DC conversion must meet the AC mains voltage standards by raising the voltage level. Recently, high-step-up DC-DC converters have received much attention. boost converters are the most prevalent in this industry but have downsides. Interleaved boost converters have gained interest as a possible solution for high-power step-up and power factor correction applications. The comparison between them with single-switch converters is to show the value of this architecture. This study divides the topologies into two primary groups based on the number of main switching elements: Single-switch and interleaved boost converters. The performance, framework, and converters' merits and cons are illustrated and explained to be used in the relevant applications. This paper highlighted the specific techniques employed with the topologies derived from the boost converter. The interleaving approach has various benefits, including higher voltage gain, lower input current ripple, higher power output, lower switch voltage ratings, smaller reactive elements, and a lower switching frequency. Thus, higher efficiency can be achieved because of the lower losses. Despite being considered more costly and complicated than single-switch converters, its features make it an excellent solution for essential applications. Both qualitative and quantitative comparison evaluation and the overall design of various models are offered to enable an appropriately informed standard guideline of a single switch and interleaved boost converters. The highlighted difficulties and future directions will also allow for the development of novel topologies.

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BIOGRAPHIES OF AUTHORS

Areej Hamzah Makee awarded B.Sc. in electrical engineering from the University of Technology, Iraq, in 1997. She has since earned several certifications in construction management. Her expertise includes electrical design, cost estimating, project scheduling, and contract administration. She has worked on a variety of high-profile projects, including. commercial and residential buildings. She is currently pursuing a master's study at Al-Mustansiriayah University, college of electrical engineering, Baghdad, Iraq. Her research interests include power electronics and electrical machines. She can be contacted at email: eema2001@uomustansiriyah.edu.iq.

Dr. Ali Hussein Al-Omari awarded Ph.D. in Electrical Engineering from the University of Plymouth, UK, in 2018. He received M.Sc. degree from the University of Technology (Iraq) in 2002 on power converter. Dr. Ali published many patent on related DC converters. Currently, he is lecturing at Mustansiriyah University in Iraq. His research interests on: grid tie converters, SMPS, motor drives, and electric vehicles. He can be contacted at email: ali.jabbar@uomustansiriyah.edu.iq.