A comparative Analysis of Modern High-Gain Boost Converter Topologies for Efficient Voltage Step-Up in Renewable Solar Energy Systems

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Abstract- For voltage step-up applications, boost converters are a common DC–DC power electronic circuit. A review of the literature on boost converter topologies created to date is presented in this paper. The development of sophisticated high-gain topologies from the traditional boost converter is examined. Based on voltage gain, efficiency, component count, and application suitability, several configurations, including quadratic, cascaded, interleaved, coupled-inductor, and switched-capacitor boost converters, are examined and contrasted. A clear understanding of contemporary boost converter topologies is provided by this review.

Keywords– Boost Converter, DC–DC Converter, High Step-Up Converter, Quadratic Boost Converter.

1. INTRODUCTION

The growing use of power electronic systems in fast developing sectors in the integration of renewable energy, electric vehicles, portable electronic products and energy storage systems has further placed pressure on efficient conversion between DC and DC voltages. One of the frequently used DC- DC converters is the boost converter, which is mostly applied in step-up voltage cases because it consists of a simple design, has continuous input current, and is easy to control. Nevertheless, the traditional boost converter has major restrictions at high voltage gain such as working with severe duty cycles, higher voltage and current strain on power semiconductor devices, higher conduction losses, and lower overall efficiency. To manage these obstacles, a number of enhanced boost-derived converter topologies have been described in literature including quadratic, cascaded, interleaved, coupled-inductor, switched-capacitor, and hybrid converters. Such topologies provide better voltage gain, efficiency, lower ripple and better power density, at the expense of component count, complexity of control, and cost. In this paper, a detailed literature review will be provided on developed boost converter topologies, their underlying principles of operation, their voltage gain characteristics and their suitability of application are compared.

This paper is organized as follows: section 2. Presents the literature review for quadratic boost converter topologies in tabular form with their advantages, limitation and applications. Section 3 is about DC-DC converter and its principle with switched capacitor, cascade, interleaved and quadratic boost converter. finally, the conclusion of this study is summarized in section 4.

2. LITERATURE REVIEW

Table 1: Literature review

Ref.	Author	Key contribution/ Topology	Main advantages	Limitation/Applications
[1]	Barreto et al.	Quasi-resonant quadratic boost (QR-QBOOST) with auxiliary resonant elements	Soft switching, higher voltage gain	Sensitive to resonant sizing and load, design trade offs
[2]	Lascu et al.	Single-switch QBC for PFC with squared duty-ratio gain	Simple control, improved DC-bus regulation	Mainly focused on PFC front-end
[3]	Morales-Saldaña et al.	Multiloop control (current + voltage) with small-signal modelling	Improved dynamic response, systematic PI/PID design	Model sensitivity, EMI and DICM transitions not fully addressed
[4]	Ortiz-López et al.	Current-mode control QBC	Better transient response, inherent over-current protection	Sensitivity to noise, parasitics.
[5]	De Novaes et al.	Quadratic three-level DC–DC converter for fuel cells	Reduced voltage stress, high gain	Increased component count, control complexity

[6]	Leyva-Ramos et al.	Switching regulator based on QBC	Wide conversion ratio, simple single-switch control	Limited dynamic analysis
[7]	Gaubert et al.	Comparative study of QBCs for PV	High gain without extreme duty cycle	Tradeoff between efficiency and complexity
[8]	Zhang et al.	Modified voltage-lift QBC	Higher gain, reduced switch stress	Increased circuit elements
[9]	Yang & Xu et al.	Hybrid voltage-lift/quadratic QBC	Very high gain, redistributed voltage stress	More complex structure
[10]	Lee et al.	QBC for grid-tied PV systems	Reduced duty extremes, inverter compatibility	Application-specific
[11]	Ye & Cheng et al.	Reduced-ripple buffer capacitor QBC	Lower capacitor stress, preserved gain	Higher component count
[12]	Patidar et al.	Tapped-inductor QBC (STQBC, FTQBC)	High gain, reduced stress, FTQBC superior	Added magnetic complexity
[13]	Zhang et al.	QBC with voltage multiplier cell	High gain, reduced switching losses	Additional passive components
[14]	Selva Kumar et al.	Performance comparison: boost vs QBC	Higher gain, reduced losses	Comparative study only
[15]	Dhanesan et al.	Sliding-mode-controlled QBC for PV	Robust, fast dynamic response	Control complexity
[16]	Farooq et al.	Reconfigured QBC for higher gain	Reduced stress, moderate duty cycle	Limited experimental scope
[17]	Veerachary et al.	Two-step single-switch QBC	Reduced ripple, improved efficiency	More passive elements
[18]	Valdez-Resendiz	Modular scalable QBC	Stackable stages, low stress	Moderate increase in parts
[19]	Navamani et al.	QBC + voltage multiplier	Very high gain, compact	Additional multiplier stage
[20]	F. Wang	Ripple-reduced improved QBC	Lower EMI, improved stability	Slight increase in complexity
[21]	Ghaderi et al.	Soft-switching QBC with passive snubber	ZVS/ZCS, reduced EMI	Added resonant elements
[22]	Li et al.	Optimized switching-path QBC	Reduced stress, high efficiency	Design complexity
[23]	Prabhakaran et al.	Interleaved Boost-SEPIC QBC	Balanced DC microgrid voltages	Control and topology complexity
[24]	Hasanpour et al	Soft-switching trans-inverse QBC	Ultra-high gain, ZVS/ZCS	Higher component count
[25]	Wang et al.	Compact single-switch high-gain QBC	Low stress, high efficiency	Application-focused
[26]	Hasanpour et al.	Simplified QBC vs classical QBC	Lower cost, reduced losses	Slightly lower gain
[27]	Ahmad et al.	QBC with voltage multiplier for PV	High gain, constant input current	Medium-power focus
[28]	Acharya et al.	Generalized Quadratic Boosting Cell	Scalable gain, reduced capacitor stress	Modular complexity
[29]	Rezaie et al.	Hybrid QBC with switched capacitor	Extremely high gain, high density	Increased circuit size
[30]	Amudhavalli et al	Interleaved QBC with Dickson VM	High power handling, low ripple	More control effort
[31]	Naresh et al.	Asymmetric inductor QBC	High gain without extreme duty	Uneven inductor stress
[32]	Okati et al.	Bidirectional buck-boost QBC	Compact, stable currents	Design optimization required
[33]	J. Ahmad et al	Constant off-time controlled QBC	Improved gain and dynamics	Control tuning critical
[34]	Tekin et al.	SC-QBC with fuzzy logic control	High gain, better transient response	Computational complexity
[35]	Jana et al.	Optimized passive-network QBC	Low stress, continuous input current	Moderate gain improvement
[36]	Gholizadeh et al.	Voltage-multiplier + coupled-inductor QBC	High gain, low ripple	Coupled inductor design
[37]	Karoda et al.	Adaptive soft-switching QBC	ZVS/ZCS for all devices	Additional auxiliary switch
[38]	Reddy et al.	Single-stage simplified QBC	High gain, reduced losses	Limited scalability
[39]	Izadi et al.	Coupled-inductor non-isolated QBC	Improved gain, low ripple	Magnetic design challenges
[40]	Subhani et al.	Passive-restructured QBC	High gain without coupling	Limited experimental depth
[41]	Karimi Hajiabadi et al.	Ultra-high-gain QBC with VM & coupling	Very large step-up ratios	High complexity

3. DC-DC CONVERTERS

DC-DC converters are invaluable elements of the contemporary power electronics. They allow the conversion of an uncontrollable or fixed DC voltage to a regulated DC voltage which satisfies the needs of a particular load, subsystem, or application. [42] As electrical systems grow swiftly, both scale-sensitive low-power portable products and large-scale sources of renewable power and electric vehicles, the importance of effective DC to DC power conversion has grown exponentially. DC-DC converters operate on power semiconductor devices (MOSFET, IGBT, and diodes) along with passive components (inductance and capacitance), to alter the energy flow between the source and the load. Their construction lies deep in electromagnetic design and the work of switching, which makes them able to control the voltage accurately with complex control measures. The DC voltage produced by the renewable energy source (photovoltaic panels and fuel cells) is dependent on the environment. Therefore, a DC-DC converter is necessary to standardize the voltage and optimize power retrieval by algorithms such as MPPT (Maximum Power Point Tracking). Likewise, in electric vehicles, DC–DC converters control the flow of power between the traction battery (high voltage DC) and auxiliary loads (lights, infotainment, sensors, etc.).

3.1 principle of operation

DC–DC converters operate by controlling the flow of energy between a DC source and a DC load through high-frequency switching of semiconductor devices such as MOSFETs, IGBTs, diodes, and through energy-storage elements like inductors, capacitors, and sometimes transformers.

The main objective is to obtain a regulated DC output voltage that may be either higher, lower or inverted relative to the input voltage.

Most DC–DC converters operate in one of two modes [43]:

1. Continuous Conduction Mode (CCM):

The inductor current never falls to zero during a switching cycle.

2. Discontinuous Conduction Mode (DCM):

In this mode inductor current becomes zero for a portion of the cycle.

CCM is preferred for high-power applications due to lower peak current stress, while DCM is used in light-load conditions.

3.2 Types of DC-DC converters

DC-DC converters are classified in four major categories:

1. Switched-capacitor (charge pump) converters
2. Advanced/Multi-stage DC-DC converters
3. Non isolated DC-DC converters
4. Isolated DC-DC converters

Here, we studied only switched -capacitor converters and advanced / multistage DC-DC converters.

1. Switched-capacitor (charge pump):

SC DC–DC converters use capacitors and switches to convert voltage levels without inductors. They operate as charge pumps, making them suitable for low-power applications such as IoT and mobile devices due to compact size, high integration, and low EMI. However, efficiency depends on switching and charge-sharing losses, limiting high-power applications.

How It Works:

1. Charging Phase: Switches connect flying capacitors to the input voltage source to charge them up.

2. Transfer/Discharge Phase: Switces reconfigure the capacitors, connecting them in series or parallel, to deliver the stored charge to the output, often producing a different voltage (e.g., doubled, halved, or inverted).

3. Repetition: This cycle repeats rapidly, controlled by PWM signals, to provide a steady, regulated output voltage.

The circuit shown in Figure 1(a) represents a basic switched capacitors non-inverting voltage doubler [13,19,27,36]. During operation, two states of equal duration occur. During the first state, the capacitor C_1 is charged with the input voltage V_{in} through the switches $T_1$and T_2($T_3$and $T_4$are open). During the second state, $T_3$and T_4 are closed, while $T_1$and $T_2$are open. The voltage across C_1(i.e., the voltage V_{in} at which C_1has been charged during the first state) is added to the input voltage V_{in}, and provided to the output filter capacitor C_{out}. Therefore, the voltage V_{out} provided to the output is two times the input voltage V_{in}.[30] Thus, the voltage conversion ratio M of this circuit is given by:

$$M = \frac{V_{out}}{V_{in}} = 2$$

In Fig.5(a) & 5(b), structure of the converter is parallel with two voltage-doubler boost converters by interleaving their output voltage.

Fractional converters produce an output voltage which is a fraction (like $\frac{1}{2}, \frac{2}{3}, \frac{3}{4}$,etc.) of the input voltage, instead of only integer multiples like in multipliers. they give more precise voltage control. most literature voltage multiplier cells which behave like fractional converters. [24,26]

Hybrid SC-SL converters are combination of inductor-based voltage transfer (like boost converter) and capacitor-based voltage boosting (like switched charge pump). their goal to achieve very high voltage gain with better efficiency and lower stress. [9,29,34,44].

2. Advanced/multistage DC-DC converters:

2.1 Quadratic converters:

[7,28,32,38] A Quadratic DC-DC Converters (QBC) is a modified form of a conventional boost or buck converter designed to achieve higher voltage step-up or step-down gain without requiring extreme duty cycle. It accomplishes this by cascading or multiplying the voltage conversion stages internally, making the gain proportional to the square of (1/(1-D)) or (D/(1-D)) – hence the name quadratic. Circuit diagram of Conventional quadratic boost converter shown in fig.2(a)

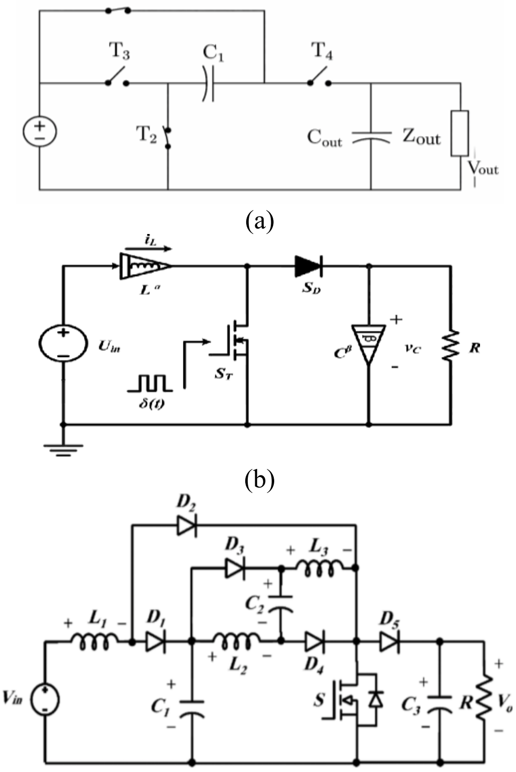
In a CQBC, during the first mode of operation, when the switch is on, the inductor L_1 is charged by the source voltage, whereas the inductor L_2 is charged by the capacitor C_1. At this instance, the diode D_3 will be on reverse bias, and the output capacitor, C_0, will transfer the energy to the load. During the second mode, the diode, D_1, will be on reverse bias, and both inductors transfer the energy to the load through diodes D_2 and D_3 with a boosted voltage. [31,35] Thus,

$$\text{voltage gain} = \frac{1}{(1-d)^2},$$

where the two capacitors store the energy.

Whereas, output voltage of quadratic buck converter is much lower than input:

$$V_{out} = D^2.V_{in}$$



(a)

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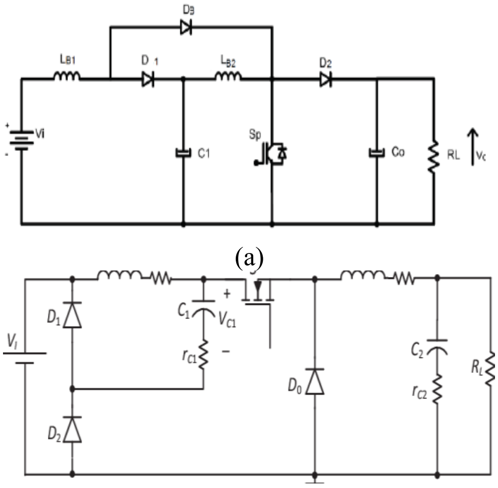
Figure 1 : (a) Voltage doubler converter, (b) Fractional converters, (c) Hybrid inductor-capacitor step up converter



(a)

(b)

Figure 2 : (a) Quadratic boost converter, (b) Quadratic buck converter

Table 2 : Switched-capacitor (charge pump)

Types	Figure	Key feature	Applications
Voltage doubler converter	Figure 1 (a)	Compact size, no magnetic component, efficiency 60- 85%	Low-power circuits
Frictional converter	Figure 1 (b)	Flexible voltage conversion, efficiency 95-99%	Power efficiency IC regulator, mobile processors, low power electronics
Hybrid inductor-capacitor step up converter	Figure 1 (c)	High efficiency+ regulation, output becomes multiple of capacitor gain, efficiency 95-97%	Mobile power stages, solar PV, electrical vehicles, LED devices, fuel cell system etc.

Table 3 : Quadratic converters

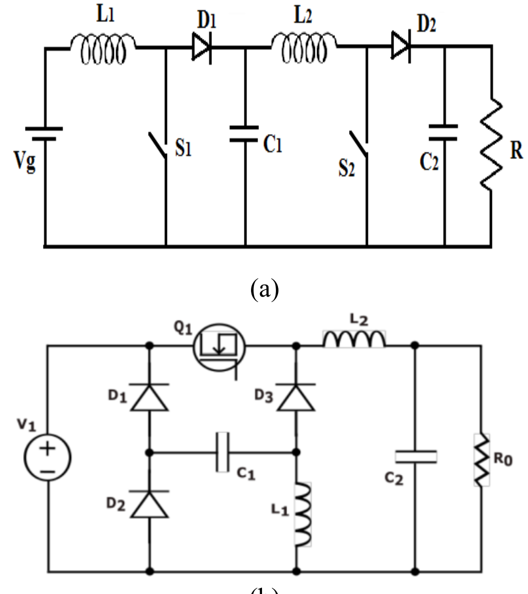
Types	Figure	Key feature	Applications
Quadratic boost converter	Figure 2 (a)	Simple topology, easy control, efficiency 88-94%	PV systems, EV DC link
Quadratic buck converter	Figure 2 (b)	Output < Input² behavior, efficiency 78-90%	Battery powered electronics, microprocessor/IC supply

2.2 Multistage/cascade converter:

In this type, several simpler converter units (stages) in series to achieve high voltage gain, better power quality (fewer harmonics), lower switching stress, or meet specific power/voltage demands, common in high-power applications. [3,4,6,8,25,42]

Voltage gain for n-stage boost $= \frac{1}{(1-D)^n}$

Gain for n-stage buck $= D^n$



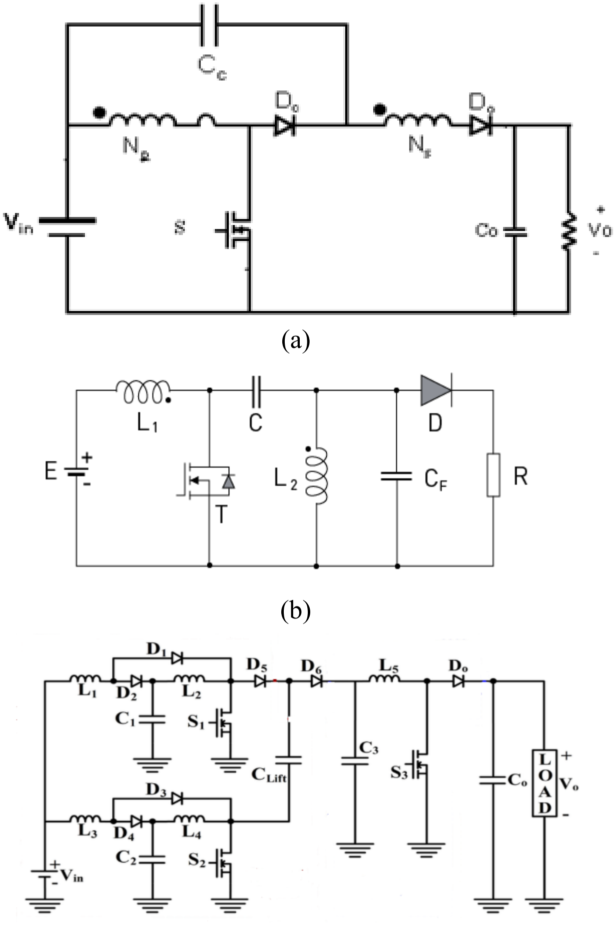
(a)

(b)

Figure 3: (a) Cascade boost converter, (b) cascade buck converter

Table 4: Multistage/cascade converter

Types	Figure	Key feature	Applications
Cascade boost converter	Figure 3 (a)	Very high voltage gain application, efficiency 85-92%	Solar PV boost for grid or battery charging
Cascade buck converter	Figure 3 (b)	Efficient for multistage voltage reduction, efficiency 85-95%	Battery powered devices & embedded systems



(a)

(b)

(c)

Figure 4: (a) Coupled inductor boost, (b) High step-up SEPIC converter, (c) Ultra-high gain topologies

2.3 Coupled inductor converters:

These converters are advanced DC-DC step-up converter that uses coupled inductor (like a transformer with shared core) instead of single inductor to achieve very high voltage gain. It behave like inductor (energy storage) & transformer (voltage boosting).[36,39]

The gain depends on:

- Duty cycle D
- Turn ratio n= $\frac{N_S}{N_P}$

$$V_{out} = \frac{V_{in}}{1-D} * (1+n)$$

So, gain is boost effect*transformer effect (much higher than normal boost)

Single-Ended Primary Inductor Converter (SEPIC) is a DC-DC converter topology that allows the output voltage to be higher, lower, or equal to the input voltage. It maintains a non-inverting output (positive-to-positive) using a single switch, making it ideal for battery-powered systems and LED drivers where input voltage fluctuates around the desired output.[23,45]

$$V_{out} = V_{in}\frac{D}{1-D}$$

Ultra-high gain topologies (typically gain > 10) are specialized DC–DC converter configurations designed to efficiently step up low-voltage inputs such as PV-panels or fuel cells to high voltage. These converters employ advanced design techniques to achieve high voltage conversion ratios while minimizing switch stress and improving efficiency. [40,41]

Table 5: Coupled inductor converters

Types	Figure	Key feature	Applications
Coupled inductor converter	Figure 4 (a)	Uses magnetically coupled winding to multiply boost ratio, efficiency 90-96%	PV system, EV boost stages
High step-up SEPIC converter	Figure 4 (b)	Very high gain without D=1, efficiency 90-over 97%	Renewable energy, elect vehicle, portable,medical,energy storage
Ultra-high gain converter	Figure 4 (c)	Adds multiplier capacitors to secondary, efficiency 90-96%	Solar grid tie, HV capacitor charging

2.4 Interleaved converters:

These are uses multiple identical converter units (phases) operating in parallel, with their switching signals out of phase(for example 180 degree), to achieve better performance than a single converter, mainly by reducing input/output current ripple, lowering component stress, increasing power handling, and improving efficiency, making them great for high-power applications like renewable energy or electric vehicles.

Voltage gain for buck converter:

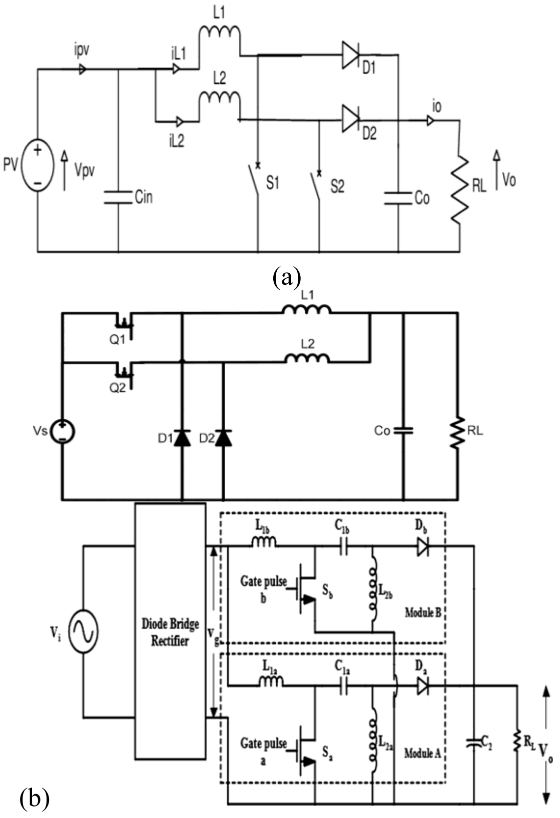
$$V_{out} = D.V_{in}$$

Interleaved improves performance (ripple, thermal, efficiency) but does not increase voltage gain.

The IBC has better characteristics when compared to a boost converter with improved efficiency, reduced size, greater reliability, and lower Total Harmonic Distortions (THD). The gating pulses of the two switches in the converter are shifted by a phase difference of 360/n where n is the number of parallel boost converters.[30]

Interleaved converter with SEPIC has combination of advantages of step- up + step -down capability and interleaved advantage (low ripple, high power). [23] voltage gain is same as SEPIC:

$$V_{out} = \frac{D}{1-D} . V_{in}$$



(a)

(b)

(c)

Figure 5 : (a) Interleaved buck converter, (b) Interleaved boost converter[30], (c) Interleaved SEPIC converter

Standard boost converter gives voltage gain of 2 to 5 and need high duty cycles (more than 0.7). This puts more stress on the voltage and makes them less efficient. Quadratic boost converters can increase gain by up to 10 while running at moderate duty cycles, which is a good balance. Cascaded and coupled-inductor converters increase gain even more (up to 20) and make things more efficient by reducing ripple. Interleaved converters are great for high-power use because they are very efficient and have very little ripple. Hybrid converters, on the other hand, have very high gain (>20–50) but are more complicated. The study shows that advanced boost converter designs perform much better than conventional converters in voltage gain and efficiency. However, higher gain often means more components and added complexity. Interleaved and coupled-inductor converters offer better efficiency and ripple performance, while hybrid designs reach ultra-high gain. Choosing a converter design depends heavily on the specific application requirements, as there is no one-size-fits-all solution.

Table 6 : Interleaved converters

Types	Figure	Key feature	Applications
Interleaved buck converter	Figure 5 (a)	Parallel buck phases with phase-shift, efficiency 85-95%	CPU VRMs, battery charging
Interleaved boost converter	Figure 5 (b)	Parallel boost paths, efficiency 92-97%	PV, DC link boost, EV systems
Interleaved CUK/SEPIC	Figure 5 (c)	Both input & output ripple low Continuous input current, efficiency 90-95%	Audio, telecom circuits Automotive power modules

4. CONCLUSION

This literature review has demonstrated conventional boost converters to be restricted in high voltage gain operation because it requires extreme duty cycles and elevated device stress, but rather quadratic boost converters have offered an increased option at achieving a high voltage gain with moderate duty ratio at higher efficiency and reduced voltage stress. More complex designs that use switched-capacitor, interleaved, and coupled-inductor methods are even better and the quadratic boost converter can be used in electric vehicles and renewable energy systems. Simplification of converter design, minimization of component count, enhanced control and dynamic operation, and utilization of wide bandgap semiconductor devices should be the subject of future research in order to obtain compact, efficient and reliable high step-up DC-DC converters.Future research should concentrate on creating low-complexity, high-gain converters that enhance efficiency and minimize component quantity. Combining wide bandgap devices, advanced control strategies, and hybrid topologies has a lot of potential. It will also be important to focus on thermal management, reliability, and optimization for specific applications in order to make it work in the real world. No single topology is universally optimal; however, hybrid high-gain converters offer the best performance trade-off, while quadratic and coupled-inductor converters provide practical alternatives for moderate complexity applications.

Future research should concentrate on creating low-complexity, high-gain converters that enhance efficiency and minimize component quantity. Combining wide bandgap devices, advanced control strategies, and hybrid topologies has a lot of potential. It will also be important to focus on thermal management, reliability, and optimization for specific applications in order to make it work in the real world.

Table 7 : Duty cycle and VCR for all types

S.no.	DC-DC Converters	Types	Component count	Duty cycle(D)	Voltage conversion ratio(VCR)
1.		Switched-capacitor(charge pump)			
		Voltage doubler/ tripler/Multiplier	4-6	No D- fixed ratio n=stage count	$M = 2$ $M = n.Vin$
		Fractional converters(½,2x,3x gain)	4-5	Duty independent	M=$\frac{1}{2},\frac{2}{3},\frac{3}{4}$
		Hybrid inductor-capacitor step up converter	Upto 20	Combines boost/buck equations	$M = \frac{1}{1-D}$ $or\ \frac{D}{1-D}$
2.		Advanced/multistage DC-DC converters			
A.	Quadratic converter	Quadratic boost converter(QBC)	7to8	$D = 1 - (\frac{V_{in}}{V_{out}})^{1/2}$	$M = \frac{1}{(1-D)^2}$
		Quadratic buck converter	8	$D = (\frac{V_{out}}{V_{in}})^{1/2}$	$M = D^2$
B.	Multi-stage/cascade converter	Cascade boost converters	8-10	Same as QBC	$M = \frac{1}{(1-D)^k}$
		Cascade buck converters	8	Product of individual stages $D = D1 * D2 *\ldots..$	Product of each stages $M = M1 * M2 *\ldots$
C.	Coupled inductor converters	Coupled inductor boost	5to7	$D = \frac{M-1}{k+M}$	$M = \frac{1+kD}{1-D}$
		High step-up SEPIC/Zeta	5to7	$D = \frac{M}{(1+M)}$	$M = \frac{k.D}{(1-D)}$
		Ultra-high gain topologies	12+	$D = \frac{M-1}{M}$	$M = \frac{2+n+nd}{(1-d)^2}$ $M = \frac{1+n+nd^2}{(1-d)^2}$
D.	Interleaved converters	Interleaved buck	9to10(depend on N phase)	$D = \frac{V_{out}}{V_{in}}$	$M = D$
		Interleaved boost	8	$D = 1 - \frac{V_{in}}{V_{out}}$	$M = \frac{1}{1-D}$
		Interleaved Cuk/SEPIC	12	Same as single converter	$M = \frac{D}{1-D}$

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