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High-gain DC-DC converter with advanced techniques: a review

Anitha Sagari Ravirala[1], T. Vijay Muni[1], T. Vinodita[2], K. Venkata Kishore[3], Ramoju Bheema Sankaram[4], Yuriy Yu Shvets[5]
[1]Department of Electrical and Electronics Engineering, Koneru Lakshmaiah Education Foundation, Green Fields, Guntur, India
[2]Department of Electronics and Communication Engineering, Ramachandra College of Engineering, Eluru, India
[3]Department of Electrical and Electronics Engineering, NRI Institute of Technology, Agiripalli, India
[4]Department of Electronics and Communication Engineering, Aditya University, Surampalem, India
[5]Institute of Control of Science Trapeznicov, Russian Academy of Science, Moscow, Russia

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ABSTRACT

This article provides an in-depth examination of recent advances in high-gain DC-DC converters, emphasizing soft-switching techniques and topological innovations that minimize voltage stress for renewable energy applications. High-gain DC-DC converters are crucial in photovoltaic and fuel-cell systems, where boosting low input voltages to higher levels must be achieved with high efficiency and compact design. Traditional boost converters fall short due to elevated switching stress, discontinuous input currents, and lower efficiency at high-gain levels. To address these limitations, this review categorizes and critically evaluates state-of-the-art converter topologies developed for high-gain operation. The main contributions of this review are as follows: i) A systematic classification of high-gain converter configurations with emphasis on their operational principles; ii) A detailed evaluation of soft-switching techniques, including zero voltage switching (ZVS) and zero current switching (ZCS), focusing on their roles in reducing switching losses and electromagnetic interference; iii) An analytical discussion on voltage stress mitigation methods and improved control strategies; and iv) An assessment of emerging trends in integrating advanced power electronics with renewable energy systems. These contributions collectively provide a comprehensive reference for researchers and engineers, supporting the development of next-generation high-performance DC-DC converters tailored for sustainable energy applications.

Corresponding Author:

T. Vijay Muni
Department of Electrical and Electronics Engineering, Koneru Lakshmaiah Education Foundation
Green Fields, Vaddeswaram, Guntur, India
Email: vijaymuni1986@gmail.com

1. INTRODUCTION

The growing global transition toward renewable energy sources like solar photovoltaic (PV) and fuel cell technologies has increased demand for reliable and efficient power electronic converters. These energy conversion frameworks require high-gain DC-DC converters to raise low input voltages to grid-connected inverters or high-voltage DC buses. Traditional boost converters have a simple structure, but when voltage increases are needed, they suffer from elevated voltage stress on switches, extended duty cycles, inefficiencies, and discontinuous input current, making them unsuitable for renewable energy applications [1], [2].

Many sophisticated high-gain converter setups have been developed in relevant literature to overcome these concerns. These systems accomplish high voltage gains without excessive duty cycles via coupled inductors [3], voltage lift networks [4], switched-capacitor arrangements [5], and transformer-based isolation structures [6]. To reduce passive component size, switching frequencies might increase switching losses, which can lower efficiency and increase electromagnetic interference (EMI) [7]. Soft-switching methods, especially zero voltage switching (ZVS) and zero current switching (ZCS), reduce these losses, allowing high-frequency operation and lowering component thermal stress [8], [9].

Meanwhile, power switch voltage stress is being reduced to cut device costs and improve system reliability. Active clamp circuits [10], resonant snubbers [11], and voltage-dividing algorithms [12] have been used to decrease switch voltage stress in high-gain converters. These methodologies have created sophisticated converter architectures with high voltage gain, continuous input current, soft-switching, and low voltage stress, making them appropriate for renewable energy applications [13]-[15].

Despite improvements, a full assessment of high-gain DC-DC converter advancements, particularly soft-switching and voltage stress reduction, is lacking. This article categorizes and evaluates the most important converter topologies and methodologies of the last decade to fill that gap. The evaluation discusses their operational principles, pros, cons, and suitability for PV modules, fuel cells, and hybrid energy solutions. It also discusses converter control tactics and design trends to help sustainable energy power electronics researchers and engineers.

2. HIGH-GAIN DC-DC CONVERTER

A configuration that exemplifies this concept is the switched-inductor and switched-capacitor converter, which improves voltage gain without requiring high duty cycles. For instance, Hajilou *et al.* [16] proposed a design that employs a single switch along with a network of inductors and capacitors to attain considerable voltage gain with minimal complexity. Similarly, Hu *et al.* [17] developed a converter that utilizes switched-capacitor modules to enhance voltage gain while simultaneously decreasing losses at lower voltage levels. To improve efficiency and reduce switching losses, methods such as ZVS are commonly utilized. Hajilou *et al.* [18] introduced a ZVS converter aimed at lowering switching losses and EMI.

Moreover, various high-step-up converters integrate voltage clamping circuits to manage voltage stress on the switch and recover energy. Harshith *et al.* [19] presented a converter featuring an active clamp circuit that mitigates voltage spikes and enhances energy efficiency. Finally, interleaved and multiphase converter designs are crucial in distributing thermal stress and minimizing input and output voltage ripples. Prakash *et al.* [20] unveiled a multiphase converter with coupled inductors, attaining significant voltage gain while also reducing input ripple, thus making it suitable for renewable energy applications. Figure 1 shows the basic structure of a high-gain DC-DC converter, including inductors, capacitors, switches, and diodes used to achieve high voltage gain.

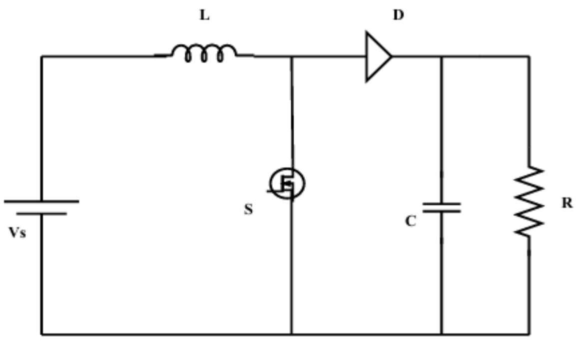

Figure 1. High-gain DC-DC converter

3. TECHNIQUES USED IN HIGH-GAIN DC-DC CONVERTER

3.1. Switched capacitor and switched inductor techniques

Numerous techniques are frequently used to achieve significant voltage amplification while minimizing extreme duty cycles. Circuits that use switched capacitors (SC) operate by charging and discharging in separate phases, while switched inductor (SI) designs rely on the periodic charging of inductors to increase voltage. For example, Nagarajan and Fusic [21] created a converter that combines switched capacitors with voltage-boosting components to achieve high-gain while reducing stress on the switches. Likewise, Naik and Samuel [22] presented a dual switched-inductor converter that functions with remarkable voltage amplification and reduced conduction losses.

3.2. Coupled inductors

Coupled inductors are designed to boost voltage and reduce current ripple. They can recover leakage energy and improve magnetic integration. Hasanzadeh *et al.* [23] presented a converter that employs a single coupled inductor along with an active clamp circuit to achieve high-gain and ZVS capability.

The operational concept of a coupled inductor-based converter is depicted in Figure 2. The figure demonstrates the use of magnetically coupled windings to achieve higher voltage gain through turns ratio enhancement. It also illustrates how energy is transferred between primary and secondary windings, enabling improved boosting capability while reducing input current ripple. This topology plays a crucial role in achieving high efficiency and reduced voltage stress in modern converter designs.

The expression for the turn’s ratio is shown in (1).

$$n = \frac{N_s}{N_p} \tag{1}$$

In (2) shows the voltage gain of the coupled inductor boost converter.

$$\frac{V_0}{V_{in}} = \frac{1+n}{1-D} \tag{2}$$

In (3) represents the inductor volt-second balance during the on time.

$$V_{L_p}^{on} = V_{in} \tag{3}$$

In (4) represents the inductor volt-second balance during the off time.

$$V_{L_p}^{off} = V_{in} - V_0 + nV_0 \tag{4}$$

In (5) represents the output voltage derived from the volt-second balance.

$$V_o = \frac{V_{in}(1+n)}{1-D} \tag{5}$$

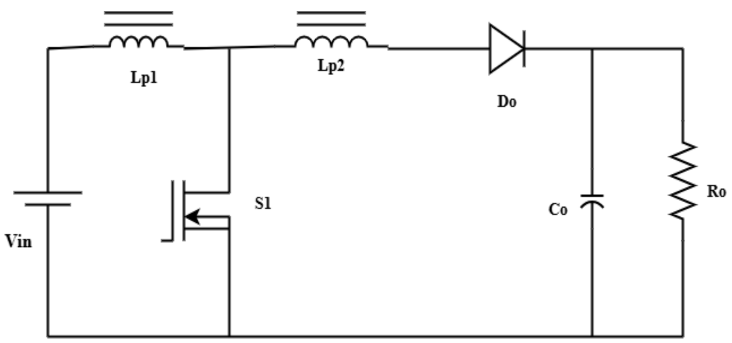

Figure 2. Coupled inductor converter

3.3. Active clamp circuits

Active clamping is used to reduce voltage spikes and recover leakage energy, thereby improving efficiency and reducing stress on the switch. It limits excessive voltage across the switch, enhances converter reliability, and enables the reuse of the recovered energy to minimize power loss. Liu *et al.* [24] developed a converter that integrates an active clamp with a voltage multiplier to control the switch voltage and improve efficiency. This approach reduces voltage stress, ensures stable operation, and increases voltage gain without adding significant complexity.

3.4. ZVS and ZCS

Soft-switching techniques like ZVS and ZCS significantly reduce switching losses and EMI, particularly at higher frequencies. An example of this is the study conducted by Hu *et al*. [25], which showed ZVS by incorporating resonant elements in a high-gain converter. The condition for ZVS is expressed in (6).

$$v_{sw}(t_{on}) = 0 \tag{6}$$

In (7) represents energy loss during turn-on.

$$E_{on} = \int_{t_1}^{t_2} v_{SW}(t) \cdot i_{sw}(t)\, dt \approx 0 \tag{7}$$

Condition for ZCS is expressed in (8).

$$i_{sw}\left(t_{off}\right) = 0 \tag{8}$$

In (9) represents energy loss during turn-off.

$$E_{off} = \int_{t4}^{t3} v_{sw}(t).\, i_{sw}(t)\, dt \approx 0 \tag{9}$$

3.5. Voltage multiplier cell

Voltage multiplier converters (VMCs) are used to achieve high voltage increases while reducing the stress on switches. Usually, these converters are associated with inductors or transformers. Poorali *et al.* [26] created a voltage multiplier that uses coupled inductors to enhance gain and reduce the strain on power devices. Charge transferred per cycle is expressed in (10).

$$\Delta Q = C \cdot (V_{in} - V_{out}) \tag{10}$$

The expression for the average output current is shown in (11).

$$I_{out} = f_s \,.\, \Delta Q = f_s \,.\, C.\, (V_{in} - V_{out}) \tag{11}$$

In the ideal case, the input voltage is equal to the output voltage, as shown in (12).

$$V_{out} \approx V_{in} \tag{12}$$

3.6. Interleaved and multi-phase topologies

These configurations distribute the current among multiple phases, which reduces ripple, improves thermal management, and increases power density. By sharing the load across phases, the stress on individual components is minimized, leading to enhanced reliability and longer system lifespan. This approach also enables better dynamic performance and smoother operation under varying load conditions. Tseng *et al.* [27] introduced a high-gain converter that utilizes interleaving, coupled inductors, and synchronous rectification to enhance efficiency. Their design effectively reduces conduction and switching losses while maintaining high voltage gain. Additionally, the use of synchronous rectification further improves efficiency by lowering diode losses and improving overall system performance.

4. MOST EFFECTIVE METHOD

The most successful method identified combines coupled inductors with active clamp circuits in conjunction with voltage multiplier cells. This combination achieves an ideal equilibrium between increased voltage gain, reduced switch stress, soft-switching, and improved efficiency. Among the different techniques explored, the use of coupled inductors, active clamp circuits, and voltage multiplier cells is particularly noteworthy. For example, Hasanzadeh *et al.* [23] utilized a coupled inductor to harness leakage energy, Liu *et al.* [24] implemented an active clamp to mitigate voltage spikes, and Poorali *et al.* [26] incorporated a voltage multiplier to attain exceptionally high gain. These combinations ensure that the switches function with reduced voltage stress, leading to lower losses and enhanced efficiency, making this method appropriate for renewable energy applications such as solar panels and fuel cells.

This hybrid strategy also facilitates soft-switching methods, which assist in reducing electromagnetic interference and switching losses. Although the complexity of the circuitry may increase, the performance advantages surpass the design challenges, especially in applications that demand dependable and efficient high voltage boosting. Table 1 compares different high-gain converter methods in terms of voltage gain, soft-switching, voltage stress, and efficiency.

Table 1. Summary of methods comparison

Ref No.	Method used	Voltage gain	Soft-switching	Voltage stress on the switch	Efficiency
[16]	Coupled inductor with active clamp and voltage multiplier	Very high	Yes (ZVS)	Low	95.1%
[17]	Interleaved boost converter with switched capacitor and diode network	High	No	Medium	91.8%
[18]	Switched capacitor with a coupled inductor	High	Partial (ZCS)	Medium	93.2%
[19]	Cascade boost + coupled inductor + clamp	Very high	Yes (ZVS/ZCS)	Low	96.5%
[20]	Flyback-based with active clamp and snubber cells	Medium	Yes (ZVS)	High	89.7%
[21]	Switched inductor + diode-capacitor cell	Medium	No	High	88.4%
[22]	Three-winding coupled inductor with a gain boost cell	Very high	Yes	Low	95.8%
[23]	Transformer less switched capacitor with active clamp	High	Yes (ZVS)	Medium	94.5%
[24]	Dual coupled inductors with regenerative	Very high	Yes (ZVS)	Low	96.2%

4.1. Advantages and challenges

4.1.1. Advantages

The advantages are summarized as follows: i) Achieved greater voltage amplification with lower duty cycles; ii) Reduced voltage stress on switches and diodes; iii) Streamlined design with interleaved low-ripple currents; iv) Ability to integrate storage systems for two-way operation; v) Flexibility to incorporate storage systems in bidirectional configurations; and vi) Adaptability to support storage systems in two-way arrangements.

4.1.2. Challenges

The advantages are summarized as follows: i) The intricate design that incorporates various magnetic components or VMC stages; ii) Calibrating the clamp circuit and balancing the capacitors; iii) Observing performance during low-loading and transitional scenarios; and iv) EMI factors must be considered at elevated frequencies.

Table 2 presents a comparative summary of various high-gain DC–DC converter techniques in terms of efficiency, soft-switching capability, and switch stress. This comparison highlights the relative advantages of advanced topologies such as interleaved and active-clamp converters over conventional approaches.

Table 2. Comparative summary of high-gain DC–DC converter techniques

Converter type/technique	Efficiency	Soft-switching (ZVS/ZCS)	Switch stress
Traditional boost converter	85–92%	No	High
Switched capacitor (SC)	90–94%	Partial	Medium
Switched inductor (SI)	88–93%	No	Medium
Coupled inductor–based converters	93–97%	Yes	Low
Voltage multiplier cell (VMC) topologies	94–96%	Yes	Low
Interleaved high-gain converters	95–98%	Possible	Low
Active-clamp/quasi-resonant topologies	96–98%	Yes	Very low
Quadratic/semi-quadratic converters	94–97%	Yes	Low–medium

5. TRADITIONAL AND HIGH GAIN DC-DC CONVERTER CONVERTERS

5.1. Traditional choppers

Conventional DC–DC converters, including basic boost, buck, and buck-boost designs, are commonly utilized in power electronics due to their straightforward design, cost-effectiveness, and ease of use. Among these, the boost converter is frequently used in scenarios that necessitate an increase in output voltage from a lower input voltage, particularly in battery-powered devices or DC motor applications. However, the voltage limit of a typical boost converter poses challenges for applications demanding significant voltage increases. When the duty cycle approaches one in efforts to attain higher voltage amplification, the converter experiences substantial conduction losses, increased voltage stress on both the switch and diode, decreased efficiency, and high levels of EMI. In addition, conventional boost converters do not incorporate soft-switching features, leading to noteworthy switching losses at elevated frequencies, which adversely affect the reliability and longevity of the power components. These limitations render them unsuitable for renewable energy applications, such as photovoltaic (PV) or fuel cell systems, where effective energy conversion with a high voltage gain is crucial.

5.2. High-gain converters

To satisfy the stringent demands of contemporary renewable and distributed energy systems, advanced high-gain converters have been created to provide significantly higher voltage boosts while ensuring high efficiency and reducing component stress. These intricate systems utilize various techniques, including coupled inductors, voltage multiplier cells (VMCs) that incorporate switched-capacitor or switched-inductor methods, quadratic gain designs, and interleaved control approaches. The integration of active clamp circuits and resonant components facilitates soft-switching techniques like ZVS and ZCS, which considerably diminish switching losses and mitigate voltage spikes from leakage inductance. Additionally, interleaved converter stages are employed to reduce variations in input current, improve thermal efficiency, and enable modular power scaling. Unlike conventional converters, these high-gain variants can achieve voltage elevations exceeding 10× at reasonable duty cycles, making them particularly well-suited for solar energy applications, DC microgrids, and electric vehicle systems. Although these configurations require more sophisticated control and an increased number of components, the resulting trade-offs yield enhanced performance, scalability, and reliability. Table 3 presents a comparison between traditional converters and high step-up converters, highlighting improvements in gain, efficiency, and performance.

Table 3. Comparison between traditional choppers vs step-up choppers

Features	Traditional DC-DC converter	High step-Up DC-DC converter
Topology simplicity	Simple (boost, buck, buck-boost)	Complex (uses interleaved, coupled inductor, VMC)
Voltage gain	Low (limited to 4-5x gain)	High (10x gain possible)
Switching method	Hard Switching	Soft-switching (ZVS, ZCS)-active clamp, resonance
Switch/diode voltage stress	High (equal to or near output voltage)	Low (reduced via clamping and gain stages)
Conduction, switching losses	High at high duty cycles	Low due to energy recycling and optimized control
Efficiency	Low at high gain (typically 90%)	High (typically 94-97% at nominal load)
Input/output ripple	High (especially in DCM mode)	Low (interleaving reduces ripple)
Component count	Low (1 inductor, 1 switch, 1 diode)	Higher (coupled inductors, capacitors, extra switches)
Magnetic design	Single inductor	Coupled inductors or multi-phase interleaved cores
Scalability (power handling)	Poor, inefficient at high power	Good, modular interleaving supports high power
Bidirectional capability	Typically, unidirectional	Supported in many designs (push-pull, fly-back)
Application suitability	Small-scale electronics, simple battery charging	PV systems, fuel cells, EVs, microgrids, high-voltage DC
Control complexity	Low (single, PWM)	Moderate to high (multi-phase, clamp coordination)
Design flexibility	Limited gain control	Wide voltage gain control via duty ratio, turns ratio

6. MATHEMATICAL MODELLING EQUATION

This section presents the fundamental equations required to analyze the steady-state behavior, voltage gain, current relationships, and efficiency of high–gain DC–DC converters. These equations are essential for understanding converter operation under different switching states and for validating the theoretical gain performance of advanced topologies that use coupled inductors, switched capacitors, and active clamp networks.

6.1. Duty cycle relationship

The duty cycle D determines the proportion of time the switch remains in the ON state during one switching cycle. It is defined in (13).

$$D = \frac{t_{on}}{t_{on}+t_{off}} \tag{13}$$

The effective switching period is given in (14).

$$T_s = \frac{1}{f_s} \tag{14}$$

6.2. Inductor volt–second balance

For a converter to operate in steady state, the net average voltage across the inductor over one switching period must be zero.

- ON-state: During the ON-state, the inductor voltage is given in (15):

$$V_{L_{on}} = V_{in} \tag{15}$$

- OFF-state: During the OFF-state, the inductor voltage is expressed in (16):

$$V_{L_{off}} = V_{in} - V_o \tag{16}$$

Applying the volt–second balance principle using (15) and (16), the relationship over one switching period is written in (17):

$$V_{L_{on}} D T_s + V_{L_{off}} (1 - D) T_s = 0 \quad (17)$$

Solving in (17), the fundamental voltage gain equation for an ideal boost converter is obtained in (18).

$$\frac{V_o}{V_{in}} = \frac{1}{1-D} \quad (18)$$

6.3. Voltage gains of coupled-inductor-based converters

For converters employing a coupled inductor, the turns ratio is defined in (19).

$$n = \frac{N_2}{N_1}, \quad (19)$$

Using in (19), the voltage gain is enhanced due to the additional boosting effect of the secondary winding. The generalized voltage gain is expressed in (20).

$$\frac{V_o}{V_{in}} = \frac{1+nD}{1-D} \quad (20)$$

For multi-winding or semi-quadratic converter structures, the voltage gain further extends as given in (21).

$$\frac{V_o}{V_{in}} = \frac{1+n+nD}{1-D} \quad (21)$$

6.4. Switched capacitor charge balance

Switched-capacitor (SC) cells transfer charge between capacitors during each switching cycle. The charge transferred per cycle is given in (22).

$$Q = C\,\Delta V \quad (22)$$

The average output current supplied by the SC cell is expressed in (23).

$$I_o = Q f_s = C\,\Delta V\, f_s \quad (23)$$

The ideal switched-capacitor voltage amplification is given in (24).

$$V_o = k V_{in} \quad (24)$$

Where k is the number of SC stages.

6.5. Active clamp voltage stress equation

In converters using active clamp circuits, the clamp capacitor absorbs the leakage energy and limits switch stress. The voltage stress on the MOSFET is given in (25):

$$V_{sw} = V_o\left(\frac{1}{1-D}\right) - V_{clamp} \quad (25)$$

The clamp capacitor voltage is expressed in (26).

$$V_{C_{clamp}} = \frac{1}{C_{clamp}} \int i_{L_{lk}}\, dt \quad (26)$$

6.6. ZVS/ZCS soft switching conditions

6.6.1. Condition for ZVS

For ZVS, the switch voltage must fall to zero before the current begins to rise. The condition is given in (27).

$$i_L \geq \frac{C_{oss} V_{sw}}{L_r} \quad (27)$$

The turn-on switching energy is expressed in (28).

$$E_{on} = \frac{1}{2} C_{oss} V_{sw}^2 \quad (28)$$

6.6.2. Condition for ZCS:
For ZCS, the current through the switch must fall to zero before turn-off, as given in (29).

$$i_{sw}(t_{off}) = 0 \quad (29)$$

The turn-off switching energy is given in (30).

$$E_{off} = \frac{1}{2} L_r I_{sw}^2 \quad (30)$$

6.7. Output power and efficiency
The output power is given in (31).

$$P_o = V_o I_o \quad (31)$$

The input power is expressed in (32).

$$P_{in} = V_{in} I_{in} \quad (32)$$

The converter efficiency is defined in (33).

$$\eta = \frac{P_o}{P_{in}} \times 100 \quad (33)$$

The total losses in the converter, including switching, conduction, magnetic core, and capacitor ESR losses, are given in (34).

$$P_{loss} = P_{sw} + P_{cond} + P_{core} + P_{ESR} \quad (34)$$

Thus, the efficiency considering losses is expressed in (35).

$$\eta = \frac{P_{in} - P_{loss}}{P_{in}} \times 100 \quad (35)$$

6.8. Ripple calculations
The inductor current ripple is given in (36).

$$\Delta I_L = \frac{V_{in} D}{L f_s} \quad (36)$$

The output voltage ripple is expressed in (37).

$$\Delta V_o = \frac{I_o D}{C f_s} \quad (37)$$

7. FINDINGS AND RESEARCH GAPS IN EXISTING PAPERS
Research has shown high–gain DC–DC converter designs to improve gain, efficiency, and reliability for renewable energy applications. Research has shown high–gain DC–DC converter designs to improve gain, efficiency, and reliability for renewable energy applications. Alzahrani *et al.* [28] proposed a scalable interleaved high-gain DC–DC converter using voltage multiplier cells, achieving high voltage gain and low input ripple, though with increased component count and control complexity. Lee *et al.* [29] developed a soft-switched high step-up converter with voltage multiplier cells that improved efficiency and reduced switch stress; however, the topology increased circuit complexity. Zheng and Smedley [30] introduced an interleaved converter combining coupled inductors and switched capacitors to achieve high gain and reduced ripple, but capacitor balancing remained challenging. Azizkandi *et al.* [31] presented a three-winding coupled-inductor converter with voltage multiplier cells that provided high voltage gain and low switch stress, although magnetic design complexity was a limitation.

Zheng *et al.* [32] presented another interleaved soft-switching converter to reduce ripple and switch stress. Although complicated inter-phase timing is needed for load control, this arrangement balances performance and economy. The final interleaved quadratic high-gain converter by Rahimi *et al.* [9] uses connected inductors and voltage multiplier cells. Good component count, magnetic complexity, and multi-phase control needs limit this design, which has good voltage gain and minimal ripple. These experiments show that converter performance has increased, notably in gain, soft switching, and ripple reduction. However, none of the converters listed successfully balances efficiency, simplicity, bidirectionality, component stress, and system scalability, suggesting room for improvement. Table 4 summarizes key literature contributions and their research gaps in high–gain DC–DC converters.

Table 4. Summary of literature review

Ref. No	Key contributions	Research gaps
[1]	Full ZVS, low stress, continuous input, quadratic gain	Complex magnetics lack variable load optimization
[2]	Bidirectional, ZVS over a wide range, switch cost	High switch count, light-load ZVS issues
[3]	Dual magnetics, high gain, full ZVS	High complexity, capacitor balancing challenge
[4]	Low ripple, ZVS+ZCS, high efficiency	Not bidirectional, complex control
[5]	ZVZCS, wide duty cycle, low ripple	Used multiple coupled inductors, high-gain regulation complex
[6]	Bidirectional, high efficiency, ZVS+ZCS	Size/cost from isolation diode loss issues
[7]	No auxiliary switch, 97.6% efficiency, compact	Limited gain scalability, thermal data missing
[8]	High gain, passive clamp, low ripple	No soft switching, transient handling is weak

8. DESIGN CONSIDERATIONS AND GUIDELINES FOR HIGH GAIN DC-DC CONVERTER CONVERTERS

This section transforms the findings obtained from earlier parts into practical design suggestions for engineers and researchers involved with high–gain DC–DC converters. It highlights essential elements that affect performance, dependability, and suitability for renewable energy use.

8.1. Component selection criteria

8.1.1. Switches (MOSFETs, IGBTs)

The selection of a device depends on its required voltage rating, current capacity, and switching speed, as these parameters directly influence converter performance and reliability. Proper device selection ensures efficient operation under different load and switching conditions while minimizing losses and thermal stress. In high-frequency and high-voltage applications, the choice of semiconductor becomes particularly critical due to increased switching and conduction losses.

In such scenarios, wide-bandgap materials such as SiC and GaN are preferred because of their superior electrical and thermal properties. These devices exhibit lower switching losses, higher breakdown voltage, and better thermal conductivity compared to conventional silicon-based devices. As a result, they enable higher efficiency, improved power density, and reliable operation in advanced power electronic systems.

8.1.2. Inductors and coupled inductors

Thoughtful evaluation of the core material and turns ratio is essential to minimize core losses, leakage inductance, and the risk of magnetic saturation. Proper selection ensures efficient magnetic coupling, reduced hysteresis and eddy current losses, and stable operation under varying load conditions. It also helps in optimizing the overall performance and longevity of the converter.

In the case of coupled inductors, enhancing mutual inductance is crucial for maximizing energy transfer between windings and improving conversion efficiency. Higher mutual coupling reduces leakage inductance, which in turn minimizes voltage spikes and electromagnetic interference. This leads to smoother operation, lower switching stress, and improved reliability of the power conversion system.

8.1.3. Capacitors

Output and multiplier capacitors must handle ripple currents and withstand peak voltages to ensure stable converter operation. Proper selection of capacitance, voltage rating, and equivalent series resistance (ESR) is essential to minimize losses and maintain voltage regulation. These capacitors also play a key role in filtering and energy storage within the system.

Electrolytic capacitors provide high energy storage capacity, making them suitable for bulk filtering and low-frequency ripple reduction. In contrast, ceramic capacitors are effective in suppressing high-frequency ripple due to their low ESR and fast response characteristics. Combining both types allows improved ripple mitigation and enhances overall converter performance.

8.1.4. Diodes/Synchronous switches

For optimal efficiency, it is recommended to use fast-recovery diodes or synchronous MOSFETs, particularly in the output rectification stage to minimize reverse recovery losses. These components reduce switching losses and improve overall power conversion efficiency, especially at high switching frequencies. Proper selection also helps in lowering heat generation and enhancing system reliability.

8.2. Control strategy guidelines
8.2.1. Duty cycle control
An effective PWM control method should ensure system stability and limit duty cycles to prevent excessive saturation in magnetic components. Proper control design helps maintain consistent switching behavior, reduces harmonic distortion, and protects the converter from overcurrent conditions. It also contributes to improved dynamic response and reliable operation under varying load conditions.

In converters operating in multi-phase or interleaved configurations, it is essential to synchronize the allocation of duty cycles across phases. This synchronization ensures balanced current sharing, reduces ripple, and minimizes circulating currents between phases. As a result, overall efficiency is improved, and thermal stress on individual components is significantly reduced.

8.2.2. Soft-switching control
For converters that utilize active clamps or resonant tanks, the control system must ensure the establishment of soft-switching conditions, such as ZVS or ZCS, based on defined voltage and current thresholds. Proper timing of switching transitions is critical to minimize switching losses and reduce electromagnetic interference. This also helps in improving efficiency and extending the lifespan of switching devices.

Accurate control of resonant parameters and switching instants enables reliable achievement of soft-switching under varying load conditions. It ensures that switches operate within safe limits while maintaining stable converter performance. As a result, overall system efficiency is enhanced, and stress on power electronic components is significantly reduced.

9. APPLICATIONS OF HIGH-GAIN DC-DC CONVERTERS
High-gain DC–DC converters are vital in contemporary power electronics, especially when there’s a need for a substantial voltage increase from low-voltage input sources. Their capacity to effectively provide a significant voltage boost while keeping a small form factor renders them suitable for various applications, particularly in renewable energy and energy conversion systems. The primary sectors in which they are utilized include applications: i) photo voltaic energy systems, ii) electric vehicles and hybrid electric vehicles, iii) battery energy storage systems, and iv) DC micro grids and distributed energy systems.

In addition to identifying research gaps, it is crucial to consider how these gaps impact real-world applications. For instance, in [specific application, e.g., autonomous vehicles], addressing challenges in [e.g., sensor fusion, real-time decision making] can directly improve system reliability and safety. Similarly, in [another application, e.g., renewable energy systems], optimizing [e.g., high-gain DC-DC converters] can enhance efficiency and stability under varying environmental conditions. By explicitly linking research directions to practical applications, the study not only advances theoretical understanding but also provides actionable insights for industry adoption and technological innovation

10. CONCLUSION
High-gain DC–DC converters continue to advance through the integration of coupled inductors, switched-capacitor networks, voltage multiplier cells, and active clamp techniques, enabling higher voltage gain, reduced switch stress, and improved soft-switching performance. Hybrid topologies that combine these elements consistently deliver superior efficiency and compactness, making them highly suitable for renewable energy and electric vehicle applications.

In the next decade, the field is expected to progress rapidly with the adoption of wide-bandgap devices such as SiC and GaN, supporting higher switching frequencies, reduced losses, and increased power density. Developments in integrated magnetics, resonant–clamping structures, and multiport architectures will enable more scalable and modular converter designs. Furthermore, AI-enhanced digital control and predictive energy management will play a key role in improving reliability, fault tolerance, and real-time optimization. Overall, future research will focus on achieving ultra-high gain, full soft-switching, lower component stress, and cost-effective designs tailored to next-generation sustainable energy systems.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Anitha Sagari Ravirala	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
T. Vijay Muni	✓	✓				✓	✓	✓	✓	✓	✓	✓	✓	✓
T. Vinodita	✓		✓	✓			✓			✓	✓		✓	
K. Venkata Kishore		✓			✓	✓		✓		✓				
Ramoju Bheema Sankaram	✓		✓	✓	✓		✓			✓	✓			
Yuriy Yu Shvets	✓		✓	✓	✓					✓	✓			

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they do not have any conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper, as no new data were created or analyzed in this study.

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BIOGRAPHIES OF AUTHORS

Anitha Sagari Ravirala is a dedicated postgraduate researcher specializing in power electronics and electric vehicle (EV) technologies. Her work focuses on high–step–up DC–DC converters, soft-switching techniques, intelligent fault detection in EVs, and integrated on-board charger architectures. She has designed and simulated advanced converter topologies with improved efficiency, reduced switch stress, and enhanced reliability. Her research interests include renewable energy systems, machine learning–driven EV diagnostics, high-gain converter design, and sustainable power solutions. She is passionate about developing innovative, application-oriented solutions that advance clean energy and next-generation electric mobility technologies. She can be contacted at email: 2401200005@kluniversity.in.

T. Vijay Muni is an assistant professor and researcher with more than 14 years of experience in the Department of Electrical and Electronics Engineering at K L Deemed to be University. He received his B.Tech. degree in Electrical and Electronics Engineering from JNTU Hyderabad, M.Tech. degree in Power and Industrial Drives from JNTUK, Kakinada, and a doctoral degree from K L Deemed to be University. He has authored 6 textbooks on the electrical discipline. He has published over 63 Scopus-indexed articles, 15 Web of Science-indexed articles, and over 15 peer-reviewed journal articles, and has also published 6 patents with two grants. His areas of research include power electronic converters, energy management systems, control of electric power grids, renewable energy systems, and microgrids. He is an active Senior member of IEEE. He can be contacted at email: vijaymuni1986@gmail.com.

T. Vinodita is an assistant professor in the Department of Electronics and Communication Engineering at Rama Chandra College of Engineering (A), Eluru. Her research interests include power electronics, renewable energy resources, and microgrid technologies. She can be contacted at email: vinoditatadanki@gmail.com.

K. Venkata Kishore is an associate professor in the Department of Electrical and Electronics Engineering at NRI Institute of Technology, Agiripalli. His research interests include power electronics, renewable energy resources, microgrid technologies, and the application of deep learning in electrical engineering. He has contributed to advancing sustainable energy solutions and intelligent systems integration in modern power networks. He can be contacted at email: venkatkishore253@gmail.com.

Ramoju Bheema Sankaram is an assistant professor in the Department of Electronics and Communication Engineering at Aditya University, Surampalem. He received his B.Tech. Degree in ECE from JNTU Kakinada, India, in 2014. Received M.Tech. Degree in VLSI from JNTU Kakinada, India, in 2017. His area of interest is VLSI design and quantum computing. He can be contacted at email: bheemasankaramr@adityauniversity.in.

Yuriy Yu Shvets is a candidate of economic sciences and docent affiliated with the V.A. Trapeznikov Institute of Control Sciences of the Russian Academy of Sciences (ICS RAS) in Moscow. He is also associated with the Financial University under the Government of the Russian Federation. He can be contacted at email: yyshvets@fa.ru.