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Performance evaluation of a high-gain 50 W DC-DC flyback boost converter for variable input voltage low-power photovoltaic applications

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ABSTRACT

DC-DC boost converters are essential for stabilizing the voltage output of photovoltaic (PV) modules. This paper analyzes a unique 50 W high-gain DC-DC flyback boost converter for various input voltage PV applications. Scientific analysis was employed to determine suitable parameters for critical circuit components. Simulations were conducted to evaluate the proposed high-gain DC-DC boost converter's performance. Subsequently, a prototype of the high-gain DC boost converter was fabricated with a printed circuit board (PCB) size of 100×100 mm. The proposed prototype's performance is compared to that of conventional boost converters based on criteria such as input voltage, output voltage, component count, voltage stress, voltage gain, efficiency, and rated power. The results indicate that the proposed converter can achieve a 300 V output voltage with a 50 W power rating from variable input voltages ranging between 12 V and 36 V. The highest gain achieved was 25 with a 12 V input voltage, though at a lower power rating of 15 W. A peak efficiency of 84.30% was measured with a 24 V DC input voltage. The proposed converter's features, particularly its high step-up voltage gain, make it suitable for industrial and renewable energy applications.

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1. INTRODUCTION

Photovoltaic (PV) systems are instrumental in advancing global sustainable and clean energy initiatives. These systems directly convert solar radiation into electricity, thereby mitigating greenhouse gas emissions and decreasing reliance on fossil fuels. The rapid expansion of the PV industry underscores its critical role in transitioning towards a greener energy landscape [1]. However, a core challenge lies in the efficient harvesting and conversion of solar energy [2]. PV panels inherently generate direct current (DC) power. For seamless integration into existing energy infrastructure [3], this DC power necessitates efficient conversion, typically facilitated by a DC-DC boost converter. The efficacy of this converter is fundamental to maximizing solar energy utilization and ensuring the commercial viability of PV systems, as it elevates the voltage to levels suitable for grid interconnection or energy storage. Technically, DC-DC boost converters provide a stable power supply through output voltage regulation and overall system performance optimization. They also integrate maximum power point tracking (MPPT) algorithms, which adjust input voltage to maximize power extraction from PV panels, thereby enhancing energy harvest and system efficiency [4]. While traditional DC-DC boost converters have found extensive application in power electronics, including within PV systems, they face limitations when applied to the unique characteristics of PV-generated electricity. Specifically, PV panels often produce low-voltage DC power with highly variable output, contingent upon factors such as solar irradiance and electrical loads. This inherent voltage fluctuation poses a significant challenge for conventional DC-DC boost converters, as their efficiency can be compromised when handling these low-voltage inputs. Consequently, there is a compelling need for advanced, high-gain DC-DC boost converters explicitly designed for PV applications. The literature proposes various approaches to achieve high-voltage gain in DC-DC converters, including single-ended primary-inductor converters (SEPIC) [5], Cuk converters [6], voltage multiplier cells [7], coupled inductors [8], switched inductors [4], and switched capacitors [9]. These cutting-edge converters are meticulously engineered to achieve substantial voltage amplification while maintaining operational efficiency, even under dynamic environmental conditions. As such, they emerge as a critical component in enhancing the performance and efficiency of PV systems, a paramount concern in a world striving to maximize renewable energy utilization.

This research introduces a unique approach by optimizing the converter's design for enhanced efficiency and scalability under fluctuating input conditions. By thoroughly analyzing the converter's performance across various operational parameters, we provide new insights into its efficiency, stability, and practical application in real-world renewable energy setups. This research fills a gap in the literature where few studies have systematically explored high-gain boost converters for low-power photovoltaic systems, offering valuable data that can guide future design improvements and implementations. Table 1 summarizes relevant research undertaken by previous researchers.

Table 1. A comparative analysis of the proposed research work differs from prior studies

Reference	Published year	Topology	Advantage	Drawbacks
[10]	2024	Two-switch flyback microinverter	Single control signal, galvanic isolation, and simplicity	Not suitable for high power ratings above 400 W
[11]	2024	Multilevel current-driven DC-DC converter	High efficiency with any input voltage input	High complexity, high cost
[12]	2024	Quadratic boost converter	Continuous conduction mode, compact converter design	High complexity, high component count
[13]	2023	High-voltage gain step-up	Low voltage stress on diodes and switches	High component count, high complexity
[14]	2023	Magnetic coupling and voltage multiplier	Low duty cycle, high efficiency, long lifetime components with low ripple	Soft switching operation absent, low output voltage
[15]	2022	Modified Buck-Boost Converter	Low duty cycle, continuous input current	High component count
[16]	2022	Series LC-based single-stage boost converter with switch capacitors	Continuous conduction mode, high efficiency	Larger overall size of the system
[17]	2022	Flyback microinverter	High efficiency, low losses and voltage stress	Complexity, large overall size of the system
[18]	2022	Three-phase single-carrier PWM inverter	Galvanic isolation, small passive elements	Low gain, low efficiency
[19]	2021	Dual-Mode resonant flyback	High efficiency, low cost	Leakage current observed at the primary side switch, fixed voltage input
[20]	2021	Multilevel flyback converter	Simple design, galvanic isolation, multiple DC outputs	High number of components, low power output
[21]	2021	Interleaved flyback converter	Low cost, easy control, galvanic isolation	Low power density
[22]	2020	Flyback micro-Inverter	Scalability, isolated DC-DC converter	Low efficiency, two-stage boost converter

2. PROPOSED METHODOLOGY

Designing a high-gain DC-DC converter system specifically for PV applications involves a systematic approach. Initially, establishing clear system requirements, including input and output specifications, efficiency targets, and any constraints, is vital. Various factors need to be considered, such as efficiency, control complexity, and component stress. The design requirements and component selection for both boost converters are calculated, followed by simulation. The proposed design is simulated using software to ensure correct functionality. During the final stage, the hardware will be fabricated to assess the performance of both converters. Figure 1 shows a block diagram illustrating the proposed stand-alone PV system incorporated with a DC-DC boost converter.

This research focuses on the design of a standard stand-alone DC boost converter, as depicted in Figure 2, along with an innovative high-gain DC-DC boost converter, both rated for a power output of 50 W. As depicted in Figure 3, the flyback boost converter uses a combination of flyback transformer and boost converter principles to elevate the voltage. It operates by storing energy in the transformer's magnetic field during the initial part of each switching cycle, subsequently transferring this stored energy to the load through its secondary winding(s) in the latter half.

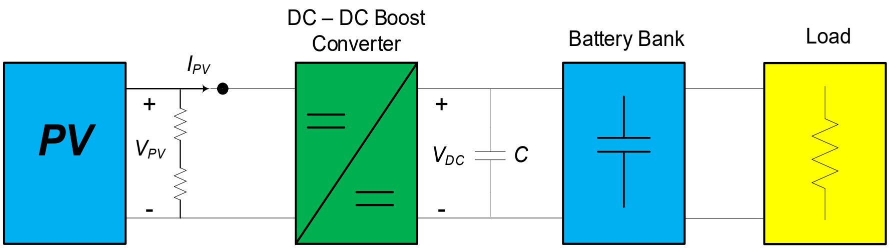


Figure 1. A block diagram illustrating the proposed stand-alone PV system

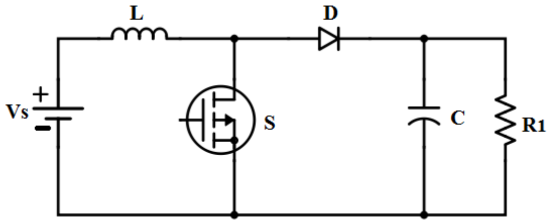


Figure 2. Conventional DC-DC boost converter

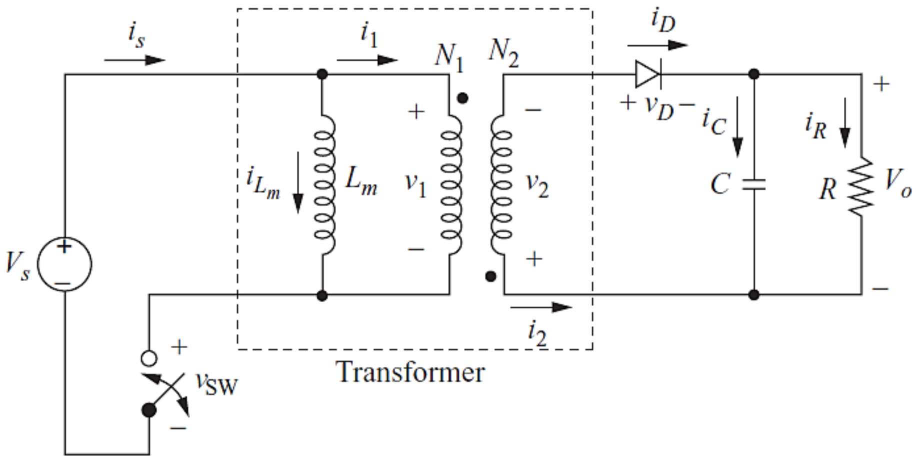


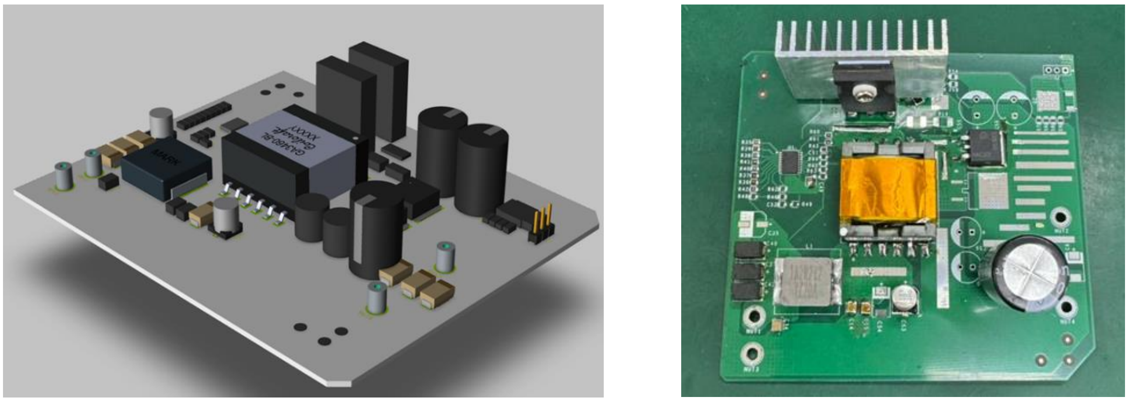
Figure 3. Flyback boost converter [23]

Flyback transformers stand out due to their gapped-core design, which enables them to store significant energy without experiencing core saturation. This capability differentiates them from other converter types, like forward-mode converters, where energy transfers directly from the primary to the secondary winding without substantial energy storage in the core. Often referred to as coupled inductors because of this gapped-core construction, flyback transformers are highly efficient at storing and transferring energy. This makes them ideal for applications that need efficient voltage conversion and a compact design, such as power supplies for consumer electronics and industrial equipment. Table 2 provides the parameters necessary to boost a 24 V DC input to a 60 V DC output, maintaining a power rating of 50 W with an output voltage ripple of 5%.

Table 2. Designated list of parameters for both types of converters

Parameters	Type of DC-DC boost converter	
	Conventional	Proposed flyback
Duty cycle	0.76	0.55
Main controller	TL494	LT3751
MOSFET	IRF540N	IRF4668
Inductor current	4.17A	2.93 A
Inductor	47 µH	-
Capacitor	4.70 µF	4.70 µF
Transformer ratio	-	1:10 turn ratio
Input voltage	24 V	12-36 V
Output voltage	60 V	300 V
Output voltage ripple	5%	5%
Switching frequency	100 kHz	26 kHz
Power rating	50 W	50 W

LTspice, a versatile and free SPICE simulator, features an integrated schematic capture. This allows users to directly embed simulation commands and parameters as text on the schematic using standard SPICE syntax. Users can easily visualize circuit behavior by plotting waveforms of circuit nodes and device currents with a simple click, either during or after a simulation. Initially created by Linear Technology for internal high-performance analog product design, LTspice offers a vast library of components and product models that enable confident simulation of Analog Devices (ADI) products without licensing restrictions. Figure 4 shows the final product of the proposed high-gain DC-DC boost converter. For the design, OrCAD Cadence is employed for 3D printed circuit board (PCB) design and generating the necessary manufacturing files, as depicted in Figure 4(a). Before a PCB goes into production, creating a prototype is crucial for evaluation and assessment. This prototyping process, which includes circuit design, PCB fabrication, electronic component procurement, and functional testing, is time-consuming and resource-intensive, but essential for timely product development. To reduce electromagnetic interference (EMI) on the PCB, several techniques are implemented. These include using surface mount devices (SMDs), optimizing power delivery, strategically placing ferrite beads and bypass capacitors, applying PCB board zoning, and utilizing via shielding and stitching. The completed prototype of the proposed converter is shown in Figure 4(b).

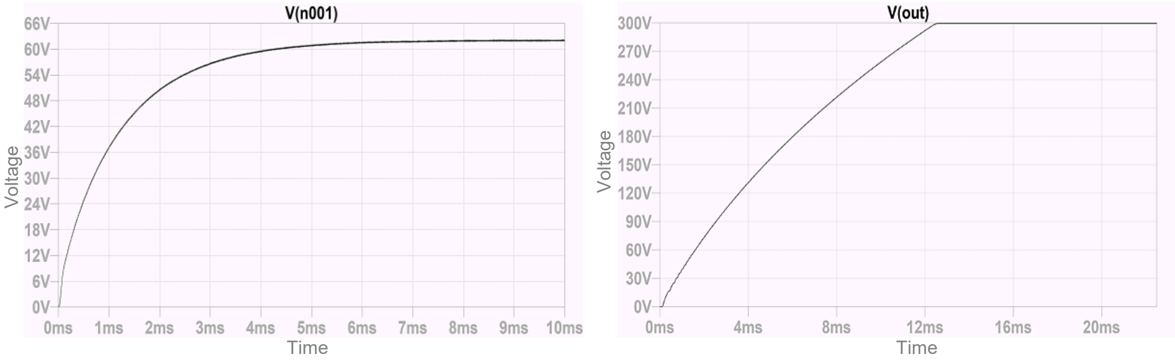


(a) (b)

Figure 4. Final product of the proposed high-gain DC-DC boost converter (a) 3D layout of proposed boost converter and (b) prototype of proposed boost converter

3. RESULTS AND DISCUSSION

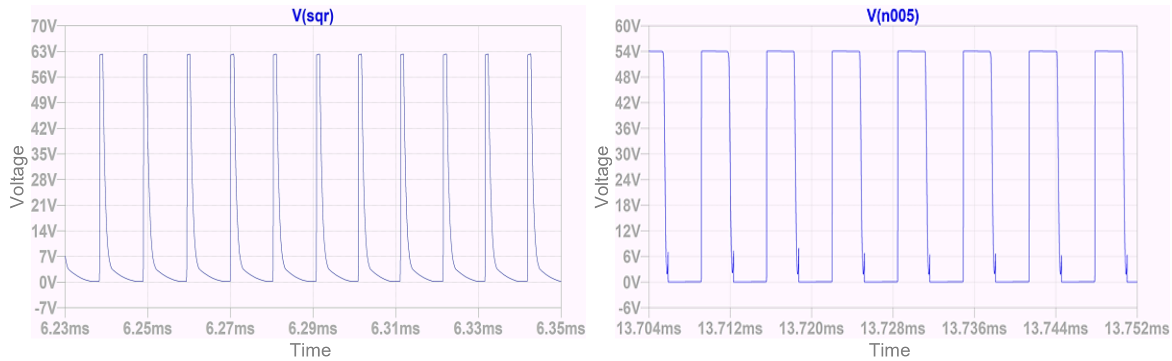
Figure 5 displays the output voltage waveforms for both the conventional and proposed DC-DC boost converters. The horizontal axis represents time in milliseconds (ms), while the vertical axis indicates voltage in volts (V). Figure 5(a) shows the output voltage of the conventional DC-DC boost converter upon startup. The voltage rises from 0 V to about 60 V within 4.5 milliseconds, then stabilizes at 60 V, confirming the circuit successfully achieved its target output. Conversely, Figure 5(b) illustrates the output voltage of the proposed converter. Here, the voltage climbs from 0 V to approximately 300 V within the initial 12 milliseconds, subsequently stabilizing at 300 V, indicating it also successfully reached its desired output voltage.



(a) (b)

Figure 5. Output voltage of converters in LTspice environment (a) conventional DC-DC boost converter and (b) proposed DC-DC boost converter

Next, Figure 6 shows the MOSFET drain-source voltage (Vds) waveform during switching for both the conventional and proposed boost converters. The waveform's periodic nature confirms the MOSFET's regular switching operation. In Figure 6(a), the conventional boost converter's MOSFET exhibits a Vds of nearly 0 V when on, indicated by the flat sections at the bottom of the graph. When the MOSFET is off, Vds rises to approximately 63 V. Similarly, Figure 6(b) displays the Vds waveform for the proposed boost converter. Here, Vds also drops close to 0 V when the MOSFET is on, and increases to around 54 V when it's off. Both MOSFETs operate at a switching frequency of about 26 kHz with a 40% duty cycle under the thermal design current load. Based on these findings, it is recommended to use a MOSFET with a Vds rating exceeding 70 V to ensure safe operation.



(a) (b)

Figure 6. MOSFET Vdrain-source voltage of boost converters in LTspice (a) conventional DC-DC boost converter and (b) proposed DC-DC boost converter

Figure 7 illustrates the relationship between input power, output power, and heat loss in a conventional boost converter across different output current levels. This test maintains a constant output voltage of 60 V while varying the output current from 0.10 A to 0.90 A. As the output current increases, both the input and output power also rise. The difference between the input and output power represents the heat generated due to the converter's inefficiency. This power disparity, and thus the heat generated, becomes more pronounced at higher output currents. This indicates that more power is wasted as heat when the converter operates under heavier current loads.

Figure 8 illustrates the efficiency of the proposed boost converter across varying load currents for three different input voltages, namely 12, 24, and 36 V. For a 12 V input, efficiency starts at approximately 70% at a 0.025-amp load, climbs to about 75% at 0.05 amps, and then either stabilizes or slightly drops as the load reaches 0.075 amps. With a 24 V input, the converter begins with a higher efficiency of around 75% at 0.025 amps and steadily increases to roughly 85% at 0.075 amps, demonstrating superior performance compared to the 12 V input. The 36V input shows a similar starting efficiency of about 75% at 0.025 amps, steadily rising to around 82% at 0.075 amps. Overall, the data clearly indicates that the voltage regulator operates more efficiently with higher input voltages (24 V and 36 V) compared to the 12 V input. Generally, as the load current increases, efficiency improves across all input voltages. Notably, the 24 V input achieves the highest efficiency at maximum load, closely followed by the 36 V input, with the 12 V input trailing behind. This chart underscores that utilizing higher input voltages for the voltage regulator leads to improved efficiency, especially under increased load currents.

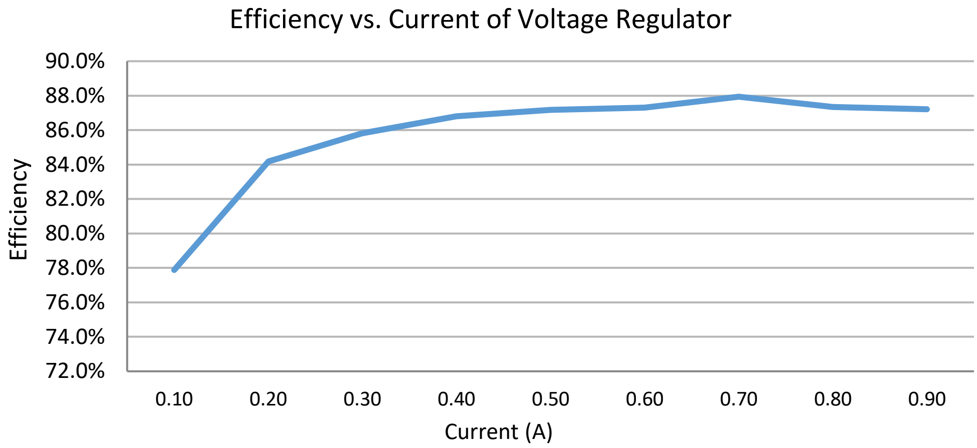


Figure 7. Input power and output power vs current at different input voltages of the proposed boost converter

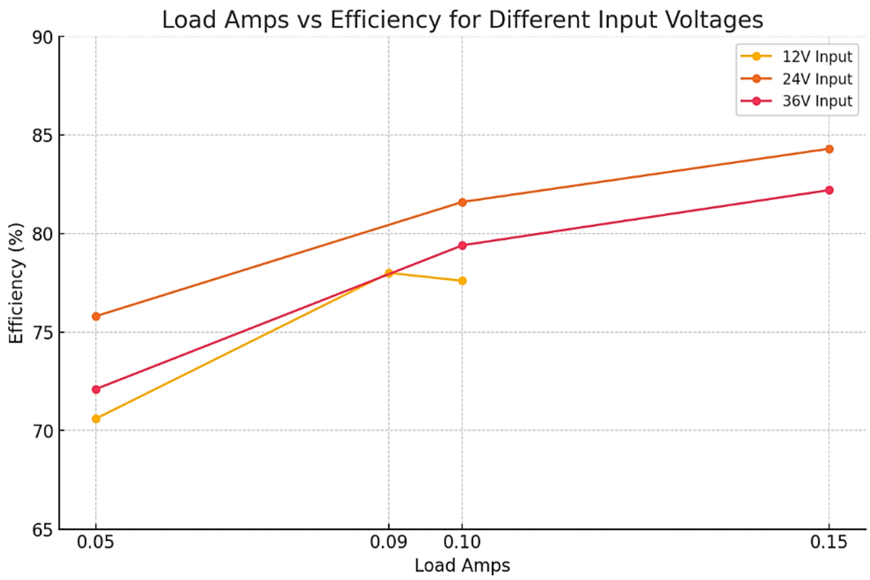
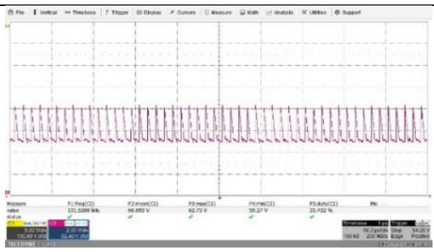
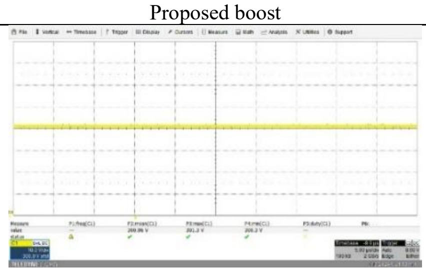
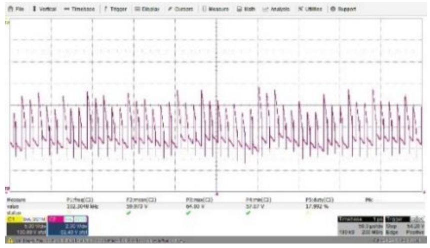
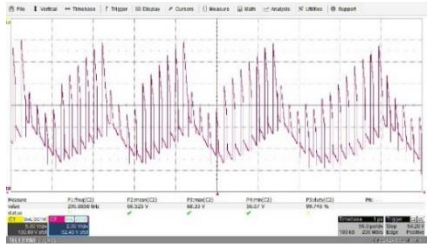
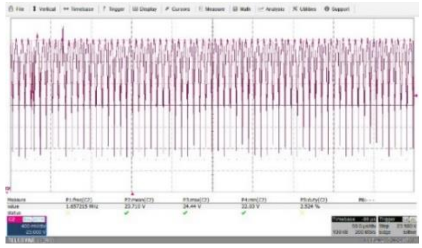
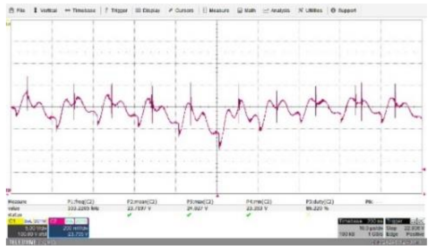
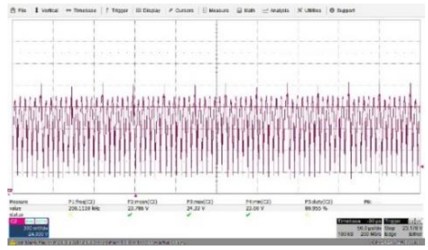
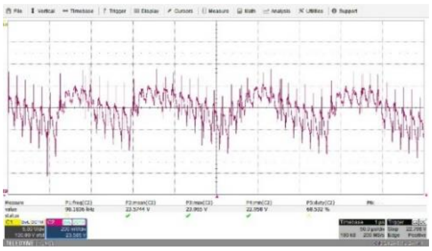


Figure 8. Efficiency vs load current of the proposed boost converter

Table 3 details the experimental results regarding the input and output voltage ripple characteristics of both the conventional and proposed converters under varying load conditions. At minimal output voltage loads, the conventional boost converter shows a higher output voltage ripple, mainly because its capacitor discharges more slowly. In contrast, the proposed design manages to keep the ripple lower through optimized control mechanisms. Under the thermal design current load, the proposed converter further reduces ripple by improving its energy storage and switching efficiency. Finally, at maximum load, the conventional converter experiences increased ripple due to high current demand, while the proposed design ensures better dynamic stability.

Table 3. Comparison of parameters for both types of converters

	Conventional boost	Proposed boost
Output voltage ripple at minimal load		
Output voltage ripple at thermal design current load		
Output voltage ripple at maximum load		
Input voltage ripple at minimal load		
Input voltage ripple at thermal design current load		
Input voltage ripple at maximum load		
MOSFET drain to source voltage		

For input voltage ripple, the conventional converter exhibits higher ripple at minimal loads because of reduced inductor current flow. Conversely, the proposed design achieves lower ripple through an improved inductor and a more effective control strategy. Under both thermal and maximum load conditions, the proposed converter continues to maintain lower ripple, thanks to its efficient power factor correction and optimized input current control. Regarding the MOSFET drain-to-source voltage (Vds), the conventional boost converter experiences higher voltage spikes and oscillations. These are caused by abrupt switching events, which can put significant stress on the components. In sharp contrast, the proposed flyback boost converter effectively reduces these spikes. It achieves this by improving its transient response and implementing a more controlled switching behavior, ultimately enhancing the system's reliability.

Table 4 offers a comparative analysis of the proposed boost converter against several other converters, evaluating factors such as component count, voltage stress, voltage gain, switching frequency, peak efficiency, and maximum output voltage across different input voltages. The proposed converter distinguishes itself with the lowest total number of components. A key objective for boost converters is voltage gain, and here, the proposed design excels by achieving a voltage gain of 25 at a 300 V output, surpassing alternatives recently suggested by other researchers. The proposed boost converter was tested with input DC voltages of 12, 24, and 36 V, utilizing 6 electronic components. When operating with a 12 V input, it generated a 300 V DC output, resulting in a voltage gain of 25, the highest among all tested converters. However, this configuration yielded the lowest efficiency at 78.0% and a maximum power rating of only 25 W due to increased input current at lower input voltages, leading to transformer overheating and high-power loss. It operated at 26 kHz with a 0.52 duty cycle. Conversely, with a 36 V input, it produced a 300 V DC output, yielding a voltage gain of 8.33. This setup achieved an efficiency of 82.2% and a maximum power rating of 50 W. However, higher input voltage can lead to increased primary current (due to Ohm's law and transformer design), potentially causing core saturation and, over prolonged operation, inefficiencies and circuit overheating as the magnetic flux reaches its limit. The 24 V DC input proved to be the optimum operating voltage. It delivered a 300 V DC output with a voltage gain of 12.50, operating at 26 kHz with a 0.39 duty cycle. This configuration achieved a peak efficiency of 84.3% and a maximum rated power of 50 W. In summary, the proposed boost converter successfully achieved the research objective by demonstrating greater voltage gain compared to other boost converters, albeit with a slightly lower efficiency in some operating conditions.

Table 4. A performance validation of a proposed system with almost similar research work

Parameters	Proposed boost converter 12 V input	Proposed boost converter 24 V input	Proposed boost converter 36 V input	[24]	[16]	[12]	[14]
No. of switches	1	1	1	2	1	1	1
No. of diodes	1	1	1	3	1	5	3
No. of capacitors	3	3	3	3	2	3	4
No. of inductors	1	1	1	2	1	3	2
Voltage stress	93.8 V	59.3 V	69.9 V	161 V	106 V	60 V	51 V
Voltage input	12 V	24 V	36 V	22 V	50 V	20 V	20 V
Voltage output	300 V	300 V	300 V	110 V	360 V	195 V	150 V
Voltage gain	25	12.50	8.33	5	7.2	9.75	7.5
Switching frequency	26 kHz	26 kHz	26 kHz	100 kHz	70 kHz	50 kHz	25 kHz
Duty cycle	0.52	0.39	0.34	0.54	0.51	0.70	0.61
Peak efficiency	78.0%	84.3%	82.2%	90%	82.3%	90%	96%
Maximum rated power	25 W	50 W	50 W	65 W	80 W	130 W	150 W

4. CONCLUSION

This research introduces a unique performance evaluation of a high-gain DC-DC flyback boost converter, specifically designed for low-power photovoltaic applications. Through comprehensive theoretical analysis, simulations, and experimental validation, the research unveils a distinctive converter design that achieves a remarkable voltage gain of 25, offering enhanced efficiency, scalability, and performance even under varying input voltages. A prototype of this high-gain DC-DC flyback boost converter was fabricated on a 100×100 mm board, designed to generate a voltage output of 300 V with a 50 W power rating, using input voltages between 12 V and 36 V. The proposed converter demonstrated a high voltage gain of 25 at 12 V input, though with a reduced power rating of 15 W, and reached a peak efficiency of 84.30% at 24 V input. Unlike traditional designs or those focused on higher-power applications commonly found in the literature, this research fills an important gap by optimizing converters for small-scale renewable energy systems. The converter's performance, particularly under fluctuating input conditions, provides crucial insights into its efficiency, stability, and real-world applicability in photovoltaic setups. This research offers a fresh perspective on evaluating previous models by demonstrating improved energy conversion, laying the groundwork for future advancements in power conversion systems for renewable energy. It redefines the understanding of energy conversion efficiency in small-scale photovoltaic applications and paves the way for further innovations in the renewable energy field.

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AUTHOR CONTRIBUTIONS STATEMENT

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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 state no conflict of interest.

DATA AVAILABILITY

Data availability does not apply to this paper.

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