



RESEARCH ARTICLE

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ENHANCED QUADRATIC BOOST CONVERTER FOR PV APPLICATIONS

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ABSTRACT

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This paper presents a performance analysis of an enhanced quadratic boost converter (EQBC) designed for photovoltaic applications (PV). The design topology aims for quadratic voltage gain with continuous converter current and high conversion efficiency, making the new converter adaptive to various PV operating conditions. The converter architecture is designed and simulated using LTspice based on optimized component parameters. The converter features a coupled-inductor arrangement and a quadratic boost topology, which enhance gain characteristics while maintaining operational efficiency across a wide duty-cycle range. Furthermore, a 300 W PV module is used as the input source to assess system behavior under different loads and environmental factors. Simulation results reveal that the maximum power delivered effectively to the load at a duty cycle of 0.34, providing mid-range flexibility for compensating for load and environmental variation. The voltage analysis verifies the quadratic relationship for a duty cycle of 0.5, and two slopes have been identified: one linear from 0.1 to 0.46 and another modified after that. The efficiency is high for duty cycles up to 0.54, ranging from 96% to 93%, and then reduces linearly to 84% for higher duty cycles. Therefore, EQBC records superior gain and efficiency across a wider duty cycle range compared to a conventional quadratic converter. The results reveal that the EQBC is a promising solution for PV systems that require high voltage gain, high efficiency, and operate under dynamic conditions, particularly in systems utilizing maximum power point tracking (MPPT).



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I. INTRODUCTION

Various renewable energy techniques play a crucial role in mitigating the surge in demand for power sources. The accelerated growth in demand is the natural outcome of the continuous increase in population and their essential need for energy. Photovoltaic systems are one of the most widespread renewable techniques and are particularly suitable for covering some of the domestic loads; however, PV power is generated at low voltage levels. Bringing the low voltage levels to higher values while maintaining a constant and stable voltage level with high efficiency and less complexity in the conversion process is the challenging phase of any proposed DC to DC boost converter. High-voltage gain-boosting DC-DC converters are widely utilized in various applications, including photovoltaic systems, fuel cells, electric vehicles, and power supplies for hybrid systems. The use of a traditional boost converter circuit in high-gain applications is limited by its constructional boundaries on its voltage gain capability. A variety of DC-DC converter typologies built on different voltage boosting techniques have been reviewed. The quadratic boost converter topology has gained increased interest and focus due to its quadratic performance in output voltage gain. A modified methodology for designing non-isolated DC-DC converters is developed. The suggested methodology provides quadratic enhancement of voltage conversion ratios and relief from voltage stresses on switching elements. The quadratic enhancement of voltage conversion ratios is achieved by using voltage multiplier units in the converter structure [1]. A novel type of quad DC-DC converter using a switched-inductor and two power switches is proposed in [2]. The non-isolated type of converter is used for high voltage conversion ratios by using two switched inductor elements.

The dual switch configuration optimizes the energy transfer paths between the low-voltage input and high-gain output stages. [3] [4] proposed an innovative type of transformer-less buck-boost converter. The semi-quadratic converter provides a continuous input current and includes a compact output capacitor. An enhanced type of quadratic buck-boost converter is proposed in a study for high voltage conversion ratios. The proposed converter provides a continuous current in both input and output stages and is also suitable for dual output applications for systems that require multiple voltage levels [5]. Another work proposes a non-secluded DC-DC boost converter architecture with quadratic voltage amplification capability. This proposed architecture consists of a two-phase interlinked boosting converter and a voltage raise capacitor for dual voltage gain capability. Additionally, a cubic voltage gain cell based on a floating capacitor configuration act as a secondary voltage amplification stage [6]. In another work, a new quadratic boost converter topology with common ground switches was proposed. This new topology does not require any gate drive isolation components, hence simplifying the converter topology while allowing for high voltage gain capability [7]. A high step-up non-secluded DC-DC converter can be achieved using a cross-bred switched inductor capacitor configuration. This provides a significant increase in voltage gain compared to traditional topologies [8]. The interleaved boost converter topology can be effectively used to reduce current ripple content. This is a major drawback of traditional boost converter topologies, which are known to have high current ripple content [9] [10].

A recent study proposed a novel high voltage gain DC-DC converter that uses a three-winding coupled inductor configuration along with a single switch. This provides a continuous input current source along with minimum current ripple content and voltage stress, making it suitable for renewable energy systems [11]. The research proposes a new topology for a quadratic converter based on a conventional Čuk converter. This proposed topology ensures continuous input and output currents, resulting in a significant reduction in current ripple and electromagnetic interference. This proposed topology for a quad converter is capable of operating over a wide input voltage and provides high voltage gain capability [12] [13] [14] [15] proposed a novel topology for a coupled inductor-based DC-DC step-up converter. This proposed topology is suitable for high voltage applications and provides high efficiency and high voltage gain. Furthermore, it reduces voltage stress for power switch devices. Another proposed topology is a fault-tolerant reconfigurable quadratic boost converter. This proposed topology is suitable for a DC microgrid. The proposed topology provides a two-level redundancy scheme for switch and capacitor failures. Experimental analysis is provided for the proposed topology, showing significant reduction in voltage stress for input and output capacitors during fault-tolerant operation [16]. Another idea involves a non-cascaded step-down and step-up topology with quadratic gain characteristics based on an I-IIA configuration. This topology uses dual L-C circuits and active switches working in synchronization for the reduction of the number of components and the voltage conversion factor through the control of the duty cycle [17]. An overall review of the various advancements in the field of quadratic boost converters has been conducted in [18].

This review comprehensively evaluates the various topologies associated with the overall configuration of the converters. In total, five distinct categories have been established for the overall converter architectures, which are Coupled Inductor-based Converters, Switched Inductor-based Converters, Hybrid Switched Inductor/Switched Capacitor Converters, Switched Capacitor Converters, and Soft Switching Converters [18]. In addition, for applications requiring an extended voltage gain, an improved cubic boost converter topology has been designed for mitigating the switching losses, which normally occur at higher duty ratio and result in reduced overall efficiency of the converter. The proposed topology has been designed for achieving an extended voltage gain, thereby utilizing a lower duty ratio while simultaneously reducing voltage stress on power components [19]. A novel converter design has been proposed, which not only retains the performance characteristics of conventional quadratic boost converter topologies but also reduces the overall size of the passive components of the power converter, thus minimizing the energy storage during power conversion while simultaneously reducing input current and output voltage switching ripples at rated power conditions [20]. Another study provides a comprehensive analysis and design methodology of a novel DC-DC double quadratic boost converter, which has the capability of achieving an exceptionally high voltage gain at its output. The proposed DC-DC converter topology has shown better performance by maintaining high voltage conversion ratios while keeping voltage stress on active switching devices low [21]. In ultra-high voltage DC-DC converter applications, a novel design has been proposed by modifying a conventional quadratic boost converter topology by using three winding coupled inductors.

The implemented design of the DC-DC converter has been made using a single active switch, four capacitors, two inductors, and five diodes. By selecting an appropriate winding coefficient and duty cycle, voltage gain greater than 16:1 has been achieved, and voltage stress on switches is kept at 25% of the output voltage by utilizing a low-side switch configuration [22]. Other studies have proposed a high-gain DC-DC converter based on the quadratic step-up converter with coupled inductors and active control capacitor techniques. In this proposed system, the primary winding of the coupled inductor and the quadratic boosting main inductor are integrated, while the output capacitor is divided into two parts connected in parallel, with one of them connected in parallel with the switched capacitor network. In addition, the proposed system achieves high voltage gain, reduced voltage stress for switches, and minimal inductors while maintaining continuous input currents. Moreover, increasing the turns ratio of the coupled inductors reduces voltage stress in diodes, capacitors, and switches [23]. A new design architecture is presented with a novel quadratic boost converter topology. It is characterized by the use of two power switches, two diodes, two inductors, and two capacitors. The quadratic boost converter ensures the continuity of the input current. At the same time, the ripple of the inductor current is reduced. Moreover, the voltage stress of the switching devices is minimized by the use of the PWM technique [24]. Finally, a study presents a quadratic boost converter topology. It is characterized by the minimization of the output voltage ripple. This allows the quadratic boost converter to have a compact size. The capacitance of the quadratic boost converter is directly proportional to the power rating. It is inversely proportional to the output ripple [25].

1.1 CHALLENGES AND LIMITATIONS

The enhanced quadratic boost converter has some important advantages in PV systems. However, some changes and limitations are influencing their future development [26-28].

- 1- Achieving high efficiency at high power levels and high voltage gain remains a challenge, whereas power losses become significant in switching devices, diodes, inductors, and capacitors over a wide range of operating conditions.

- 2- High-power applications impose significant electrical and thermal stress on components, even in enhanced topologies that aim to reduce voltage stress on components. This raises long-term reliability issues.
 - 3- Complex Control strategies can increase the cost and difficulty of implementation for EQBC more than for conventional boost converters. This, in turn, required higher manufacturing costs compared to conventional ones.
 - 4- Achieving optimal coupling coefficients, minimizing leakage, and avoiding core saturation are recorded as the main challenges of coupled inductor design, even when improving gain by using the linear part of the B-H curve. However, extended operation risks driving the magnetic core into a nonlinear region, which then increases losses.
 - 5- Scaling of high-power levels remains challenging due to component stress, efficiency drops, and thermal constraints.
- Addressing the inherent limitations of EQBC makes it highly suitable for interfacing low-voltage PV panels with higher-voltage loads or grid-tied inverters.

1.2 CLASSIFICATION OF QBC

The QBCs can be classified based on application requirements, circuit configuration, energy storage elements coupling mechanism, cost constraint, and control strategies. The classification is presented in the Figure 1 [18-30]. Single-switch QBCs are used for small-scale PV systems where circuit simplicity is required and cost is more important than high efficiency, due to their simple structure and easy control. However, it is not ideal for high-power or high-gain requirements due to the stress on the single switch [31]. Multi-switch QBCs are used for medium-power PV systems (200-500 W) where higher gain is required. However, affordable components are required in such a system because splitting stress across switches improves reliability [25]. Diode-capacitor QBCs are used in portable solar chargers to provide good gain with minimal complexity. However, it is not scalable to higher power levels due to the stress on the diodes and the capacitor [32]. Coupled inductor EQBCs are used for medium to high power PV systems that require high voltage conversion without extreme duty cycles. However, the magnetic coupling design is complex, which allows for higher efficiency and better voltage gain [33]. Switched capacitor EQBCs are designed for low to medium-sized PV systems (50-300 W) to achieve high gain with a simple design. However, capacitor current ripple makes them less suitable for high-power PV systems [34].

Switched inductor EQBCs are used for medium to large PV systems where reliability and efficiency are critical. Therefore, switched inductors boost gain and efficiency. However, conduction losses make them less suitable for ultra-high currents [35]. A hybrid couple inductor with switched capacitor or switched inductor EQBCs is designed for high-voltage PV systems because it can achieve a very high step-up gain with a controlled duty cycle. However, the complexity and cost are justified in an advanced PV system where space, efficiency, and performance are top priorities [36]. Interleaved EQBCs are used in high-power PV systems, where multiple phases reduce ripple and balance current between inductors. However, this system is ideal for large systems that require scalability and reliability [37]. Soft switching and resonant EQBCs are designed for high-frequency and high-efficiency PV systems because soft switching reduces switching losses, enabling high-frequency operation with small passive components. However, the cost and complexity of such a system are high [38]. MPPT-integrated EQBCs are utilized for PV systems operating under varying irradiance and temperature conditions. This system is optimized for tracking the MPP and dynamically adapting gain [39]. [40]. This system is needed when energy is shared between a PV system, an energy storage system, and the grid to cover a specific load. High-frequency EQBCs are used for portable and compact PV systems due to the reduction in size and weight of inductors and capacitors, which makes the design lighter and more compact than other designed systems [40].

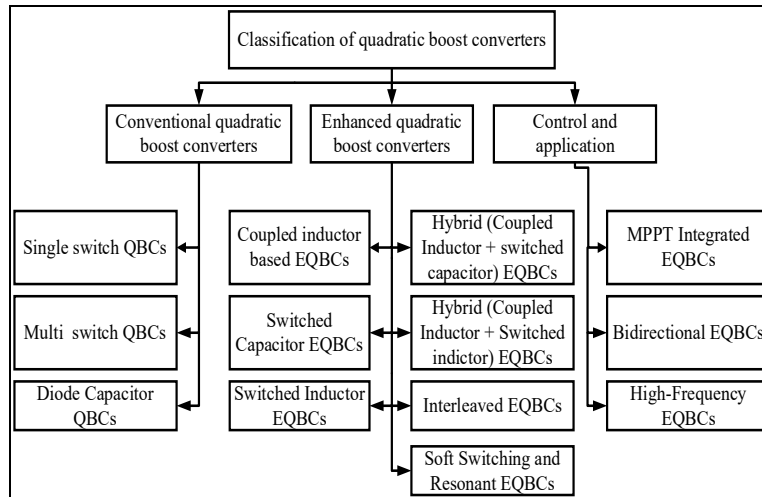


Figure 1: Classification of QBC.

Source: Authors, (2026).

II. THE PROPOSED ARCHITECTURE.

II.1 CIRCUIT DESCRIPTION.

The proposed circuit shown in Figure 2 consists of L1, the main inductor, which is considered the primary boosting element, while both the coupled inductors L2 and L3 are the secondary boosting elements. The capacitor C1 acts as an energy reservoir, charging from L1 during the OFF state of the single switching device in circuit S1, and then discharging through L2 at a constant voltage level during the ON state. This architecture should afford two boosting stages.

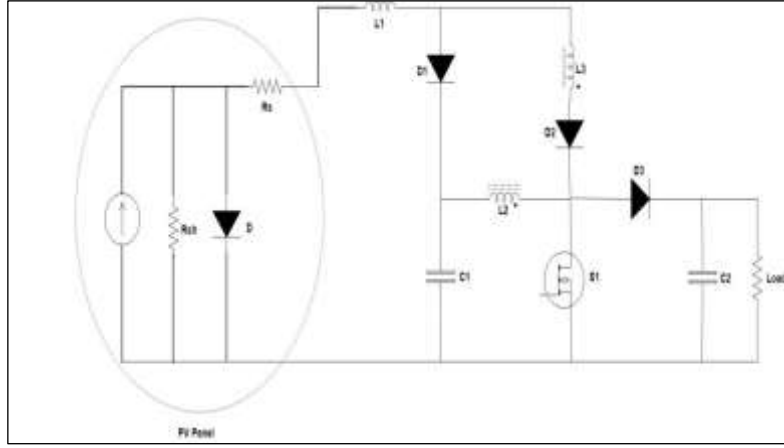


Figure 2: the proposed quad DC-DC converter circuit.
Source: Authors, (2026).

II.2 PRINCIPLE OF OPERATION

The proposed circuit operates in two operating states when the switch is turned ON. The current will flow from the source through L1 and L3. Meanwhile, the capacitor C1 is discharging through the inductor L2. The rate of the current through L2 and L3 should be affected by the coupling coefficient and the number of turns of both inductors, as shown in

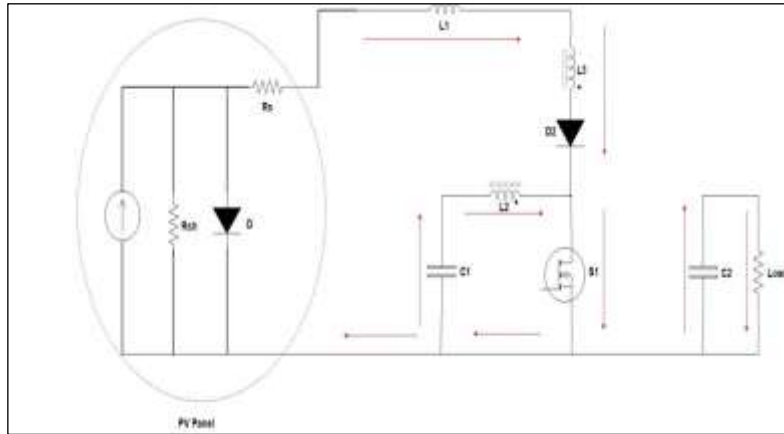


Figure 3: The power flow and current directions during the ON state of the proposed quad converter.
Source: Authors, (2026).

Increasing the current during the ON duration should energise L1 and the coupled inductors. According to equation (1)

$$E = \frac{\Delta I_1}{DT} (L1 + L3) \quad (1)$$

$$I_2 = I_{C1} = I_1 \sqrt{\frac{L2}{L3}} \quad (2)$$

Figure 4 represents the OFF state. During this state, the inherent change in the current value of I1 causes a boost in the voltage across inductor L1; this voltage simultaneously charges capacitor C1 to a voltage of VL1+E.

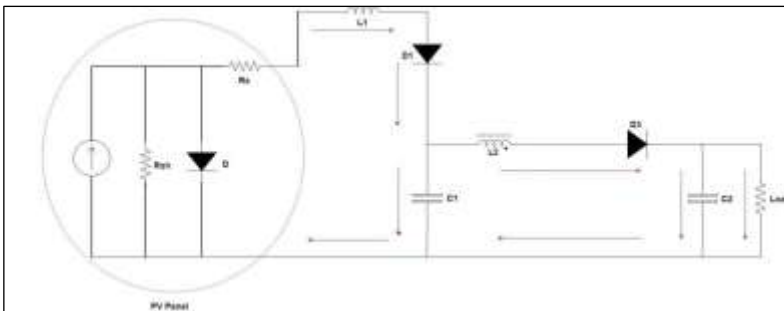


Figure 4: The power flow and current directions during the OFF state of the proposed quad converter circuit.
Source: Authors, (2026).

Likewise, the energy stored in L2, due to the inherent change in the current through the switch, should boost the voltage across L2, causing it to supply the load with a voltage equal to $V_{L1} + V_{L2} + E$. The transferred energy from L2 charges the capacitor C2 and feeds the load. Since the current flow through L2 is in continuous mode of operation, it should reduce the reverse recovery current through diode D3, thereby improving efficiency.

III. DERIVING TRANSFER FUNCTION

The following assumptions were made during the derivation of the transfer function of the proposed converter:

- 1- The circuit operates in continuous conduction mode (CCM).
- 2- All components are ideal (no losses during the conversion process for all components).
- 3- The mutual inductance coefficient is ($k=1$).
- 4- The transformation ratio (turn ratio) is ($n = N_3/N_2$), where N_2 and N_3 are the number of turns of inductors L_2 and L_3 , respectively.
- 5- The duty cycle of switch S_1 is (D) of the whole switching period (T_s).

This DC-DC converter has two operational states: The converter operates through two distinct switching states determined by the MOSFET switch S_1 's duty cycle (D) with switching period T_s :

- 1) On State ($0 < t < D \cdot T_s$):

When S_1 is closed, the circuit enters the energy storage phase:

- Diode D_2 becomes forward-biased while D_1 and D_3 remain reverse-biased
- Input voltage (V_{in}) charges the primary inductor L_1 , building magnetic energy
- Capacitor C_1 discharges through the secondary winding L_2 , transferring stored energy via magnetic coupling
- Output capacitor C_2 maintains load current during this phase

- 2) Off State ($D \cdot T_s < t < T_s$):

When S_1 opens, the energy transfer phase begins:

- Diodes D_1 and D_3 conduct while D_2 blocks
- Inductor L_1 discharges into capacitor C_1 through D_1
- The coupled inductor pair (L_2 - L_3) releases stored energy to the output stage
- Both magnetic and capacitive energy contribute to load power delivery

The converter achieves voltage transformation through this cyclical energy transfer process between inductive and capacitive elements, with the duty ratio D controlling the output voltage level. The proper timing of these switching transitions ensures that continuous power delivery is achieved along with a stable output characteristic. Starting with the inductor voltage of L_1 and the coupled inductors L_2 , L_3 during the On and Off states of the single switch converter circuit, the final formula for the DC voltage gain of the proposed converter is described below:

$$[V_{out} = \frac{4}{n(1-D)^2} V_{in}] \quad (3)$$

Where V_{in} is the input voltage, V_{out} is the output voltage of the converter at a duty cycle of (D) and turn ratio of the coupled inductors of (n).

IV. EXPERIMENTAL RESULTS

The proposed circuit is supplied from a 300-watt PV panel to feed a load of 40 Ω . The simulation is performed according to the component values shown in Table 1.

Table 1: The PV characteristic and the circuit components value.

PV Specs		Component	Value
P_m	300w	L_1	55uH
V_m	32.38V	L_2	5uH
I_m	9.26A	L_3	125uH
V_{oc}	38.55V	C_1	220uF
I_{sc}	9.47A	C_2	22uF

Source: Authors, (2026).

The input current of the converter is in continuous conduction mode, as shown in figure 5.

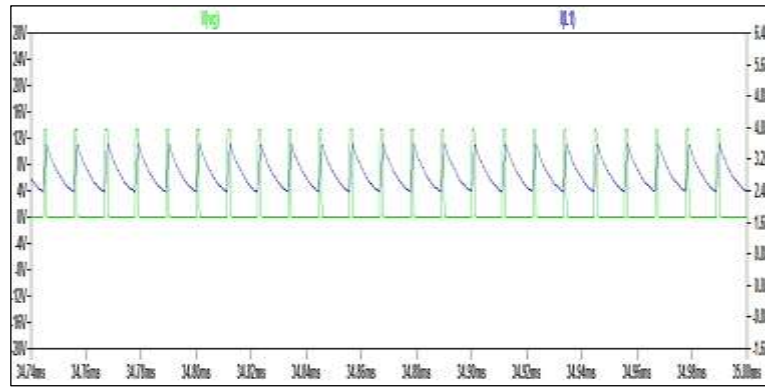


Figure 5: The current through L1 inductor with respect to the gate signal.
Source: Authors, (2026).

Figure shows the current through L2, where the switching effect of D2 is represented as a spike during the operation states. The reverse recovery current is reduced due to the effect of L2, which is connected in series with the diode. The charge and discharge of the capacitor C1 are shown in Figure.

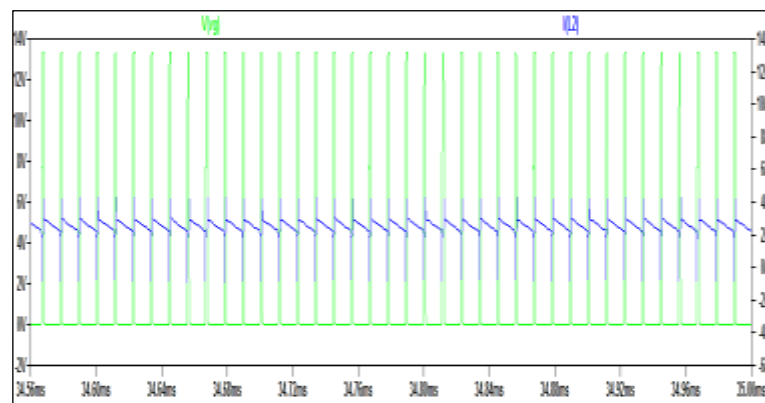


Figure 6: The current through L2 inductor with respect to the gate signal.
Source: Authors, (2026).

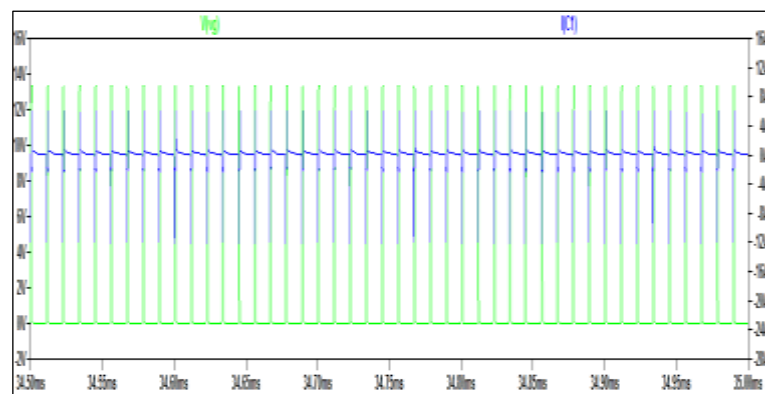


Figure 7: The current of the capacitor C1 with respect to the gate signal.
Source: Authors, (2026).

The currents of both L2 and L3 are shown in *Figure* while the summing of both currents represents the converter current output through the diode D4 as shown in *Figure*.

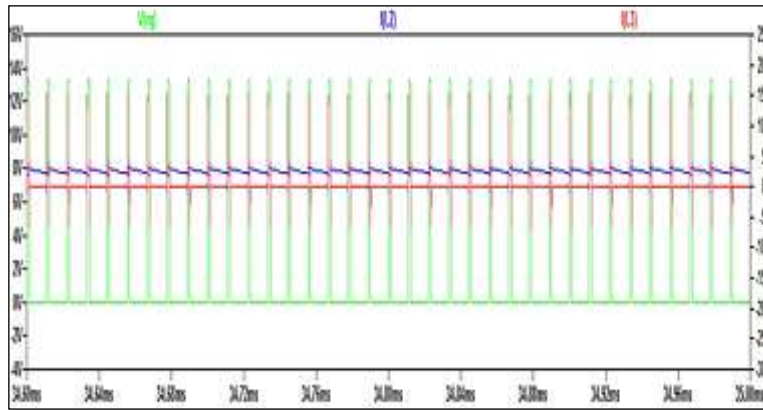


Figure 8: The current through the inductors L2 and L3 with respect to gate signal.
Source: Authors, (2026).

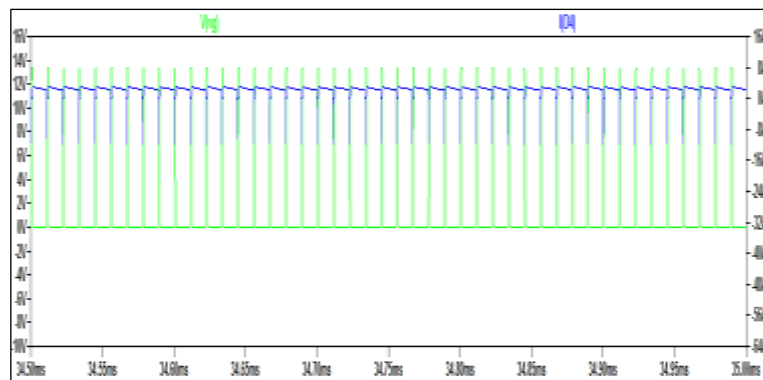


Figure 9: The current through the output diode D4 with respect to gate signal.
Source: Authors, (2026).

To minimize the output current ripple, the capacitor C2 is used. Figure shows the current through the output capacitor filter, while Figure shows the filtered output current to feed the load.

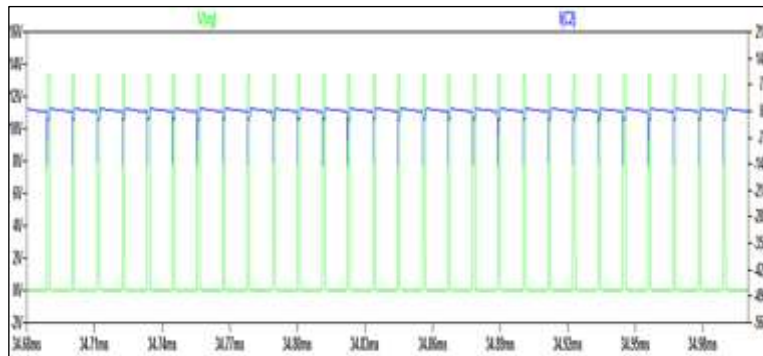


Figure 10: shows the current through the output capacitor filter C2.
Source: Authors, (2026).

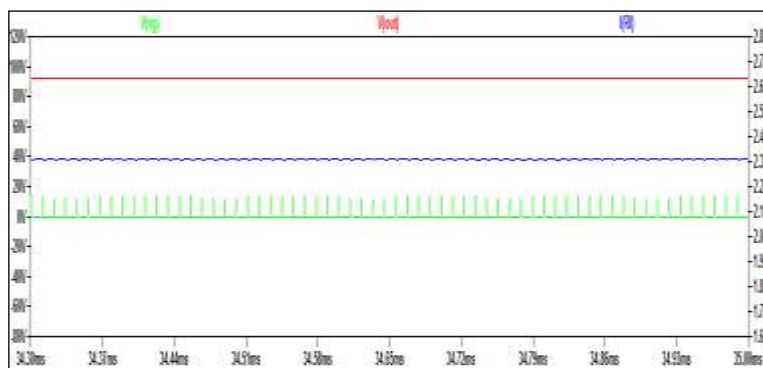


Figure 11: The converter output voltage and load current through R_1 with respect to gate signal
Source: Authors, (2026).

V. RESULTS AND DISCUSSION

The proposed circuit was simulated using LTSpice, yielding results that matched the designed values. Because the converter is dedicated to a renewable PV system, the selected voltage source is a 300-watt PV panel to test the performance. According to Figure the topology can control the power delivered to the load. The maximum power of the PV occurs at a duty cycle of 0.34. The mid-range value of the duty cycle provides a ceiling for adjustments to compensate for changes in load value or PV climate conditions, such as irradiance or temperature.

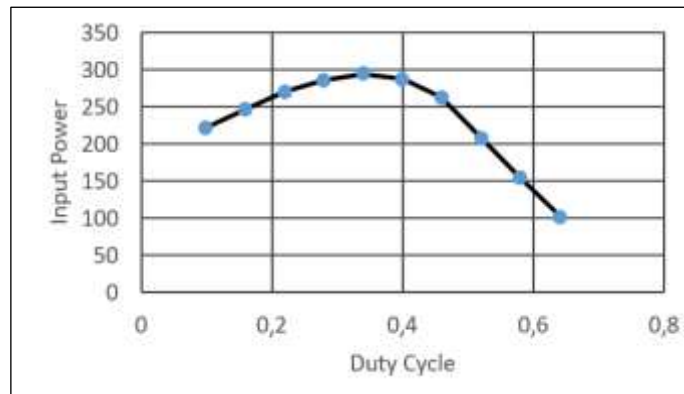


Figure 12: Input power vs Duty cycle.
Source: Authors, (2026).

The voltage gain of the converter shown in Figure illustrates that the gain is quadratic when the duty cycle is 0.5, which is identical to a quadratic Boost converter. However, the response can be intercepted into two regions according to the slope. Where the gain is linear for the range from 0.1 to 0.46 and then diverges for different slopes from the previous point value until higher duty values. Such performance is due to the coupling effect, and it utilizes the linear part of the B-H curve of the coupled inductors to achieve the gain.



Figure 13: Voltage Gain vs Duty cycle.
Source: Authors, (2026).

It is shown in Figure that the converter provides a high efficiency of 96% to 93% for a range of duty cycles up to 0.54, while it reduces linearly to 84% for higher values. Comparing Figure (13) to the conventional Boost converter, it is clear that the proposed topology offers superior performance at a high range of duty cycles, thanks to the increased current value through the inductors.

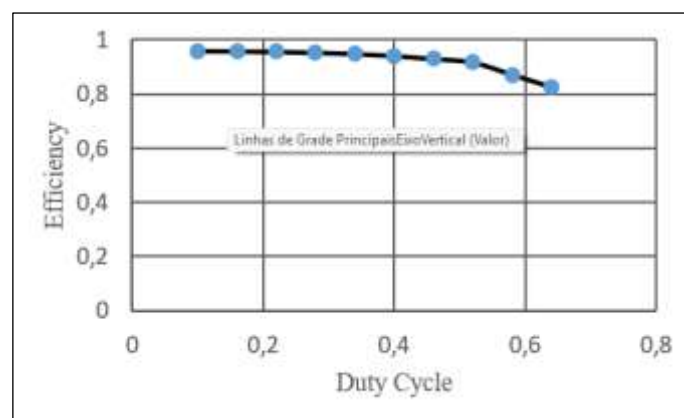


Figure 14: Efficiency vs Duty cycle.
Source: Authors, (2026).

VI. CONCLUSIONS

The results of the proposed EQBC topology showed that the converter gain is quadratic at a 50% duty cycle, decreasing to 1.1 at a 10% duty cycle. Furthermore, the converter efficiency is improved compared to a conventional boost converter, where it reaches 96% at a low duty cycle and then decreases to 92% at a 50% duty cycle. However, efficiency decreases significantly, reaching 82% at a 64% duty cycle. The converter not only amplifies voltage efficiently but also preserves performance across a wide duty cycle range by leveraging coupled inductors and operating in the linear region of their magnetization curve. From the results, the converter efficiency is improved by focusing on reducing the reverse recovery current through the diodes using the coupling technique, which verifies the proposed topology.

VII. AUTHOR'S CONTRIBUTION

Conceptualization: Saif Al-Zubaidi, Mohammed H. Alkhafaji, and Ali Hussein Al-Omari.

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Approval of the final text: Saif Al-Zubaidi, Mohammed H. Alkhafaji, and Ali Hussein Al-Omari.

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