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DESIGN AND INVESTIGATION OF FOUR-SWITCH INTERLEAVED BOOST CONVERTER FOR RENEWABLE INTEGRATION

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Abstract
The primary goal of this research work is to build a DC-to-DC interleaved boost converter having low voltage stress and high voltage gain. The low voltage stress is particularly focused on the switching components, making the converter suitable for low voltage sources like photovoltaic (PV) modules and fuel cells. DC converters, including boost converters, are crucial for reliable performance in various applications. These applications, such as PV systems and fuel cells, often require stepping up the voltage up to 500 V. Conventional converter topologies are not capable of achieving significant voltage gain. High voltage gain of this magnitude cannot be obtained using traditional boost converters, as they require operation at high duty cycles, which leads to issues such as reverse recovery in rectifier diodes. Converters designed with a high voltage conversion ratio tend to suffer from larger voltage drops, resulting in increased switching losses. Furthermore, they also experience losses in parts of the filters which negatively impact the power conversion efficiency. Additionally, smaller filter inductors necessitate minimizing input and output current ripples. This research work aims at obtaining an increased voltage gain while avoiding drawbacks associated with excessively high duty cycles and the reverse recovery issue. The objectives include minimizing the voltage stress on switches, reducing input and output current ripples, and improving overall power conversion efficiency. The study will involve a detailed examination of existing methods, followed by the development of new techniques to meet these goals.

INTRODUCTION

The growing environmental concerns have driven researchers to focus on low-voltage green energy sources like the Solar Energy System and others, as they offer promising solutions to the energy deficit. To convert the DC output of PV systems and fuel cells into AC, power electronic circuits are essential, and boost converters are needed to elevate the DC voltage to higher levels. A boost converter, comprising of three main elements as shown in Figure 1, is designed so that the output voltage exceeds the input voltage. When the switch is closed, the inductor's current increases, and when opened, the current flows via the diode D to the capacitor and resistor, storing energy in the "on" state and transferring it to the output in the "off" state. Depending on the inductor current, operation occurs in either continuous conduction mode (CCM), where current never reaches zero, or discontinuous conduction mode (DCM), where the inductor fully discharges before the cycle ends, often under light load conditions as shown in Figure 2 and Figure 3. Power electronic converters therefore play a vital role in enabling the effective interfacing of PV generators and in integrating renewable energy into the national grid. However, while high duty cycles allow high voltage gains, they also introduce challenges such as increased current ripple, higher distortion, reverse recovery issues, EMI, and high voltage stress on switching components. The aim of this research is to overcome these issues by reducing the duty cycle while retaining high voltage gain, potentially through multiple switches rather than a single switch, thereby shortening each switch's on-time, lowering stress and losses, and improving overall efficiency.

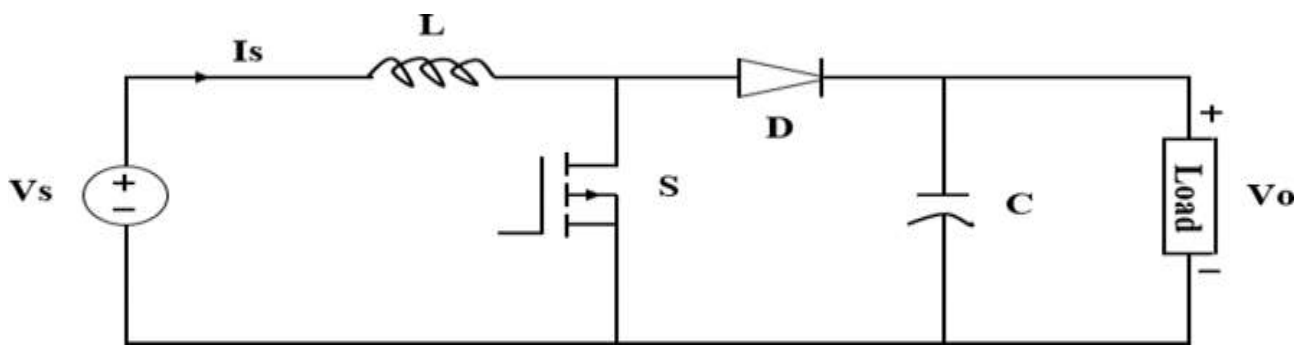

Figure 1: Conventional Boost Converter

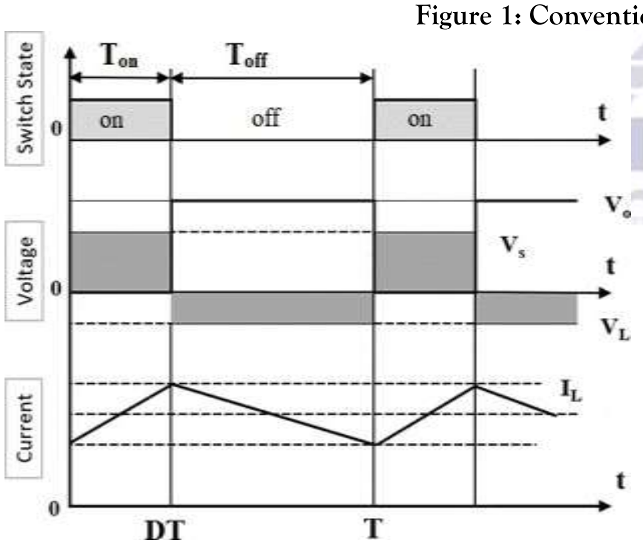

Figure 2: Continuous Conduction Mode

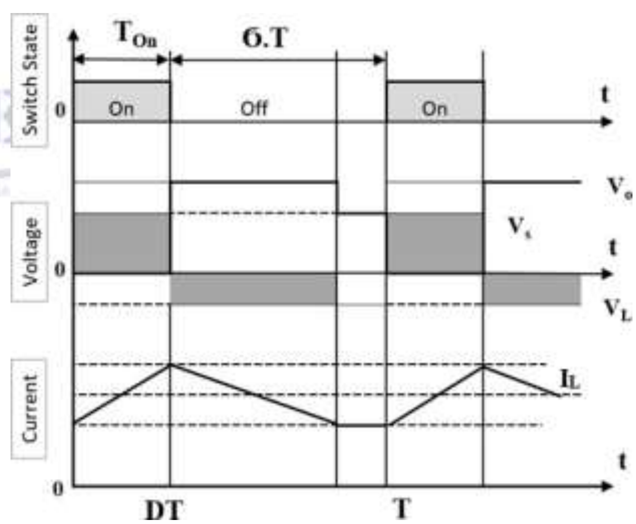

Figure 3: Discontinuous Conduction Mode

Literature Review

In recent years, DC–DC boost converter topologies have been extensively explored for applications in electric mobility, renewable energy systems, and fuel-cell-powered vehicles. Various designs have been proposed to achieve high voltage gain, reduced current ripple, and improved efficiency, each with its own operating advantages and inherent limitations.

The quasi-Z-source interleaved DC–DC converter was developed for fuel cell vehicle applications, incorporating two parallel boost converter stages operated with a 180° phase shift in their switching pulses. This configuration produces a relatively stable output voltage with high gain, low input current ripple, and reduced switching stress compared to conventional boost converters. However, despite these improvements, the converter still experiences output voltage and input current ripple. A significant transient overshoot at startup, along with an inability to operate at duty cycles above 0.5[1], limits its applicability in certain systems.

For fuel-cell electric vehicles (FCEVs), a ZVT interleaved boost converter has been presented, using a zero Voltage-transition cell to enable soft switching for all semiconductor devices in both active and passive states. This design improves power density and allows higher switching frequencies, aided by a dual-loop control strategy and a feedforward mechanism to mitigate peak switching currents [2], [3], [4]. While optimal efficiency is achieved at duty ratios above 0.5, performance degrades when the duty cycle is reduced below this threshold, compromising soft-switching benefits.

Another topology, the CCTT-core split-winding integrated magnetic converter, introduces a multi-phase voltage enhancer with a novel magnetic core structure to reduce stray inductance and leakage flux. Using ferrite materials and an optimized flux path improves efficiency and compactness [5-8]. Although the design achieves lower winding losses and reduced near-field emissions compared to conventional cores, it requires specially manufactured magnetic components, increasing production cost.

A high Voltage-gain interleaved boost converter employing coupled inductors with a voltage multiplier stage has also been investigated. This structure delivers a greater step-up ratio than standard boost converters, balances capacitor voltages, and minimizes input current ripple [9-10]. Nonetheless, the complexity of controlling multi-stage interleaved systems increases conduction and switching losses, particularly at higher frequencies, offsetting some efficiency gains.

Soft-switching multiphase interleaved boost converters have been proposed to reduce switching losses by integrating auxiliary resonant networks. Each phase operates with synchronized PWM signals and identical duty cycles, enabling efficient multiphase performance [11-14]. While switching losses are minimized, they are not eliminated, and the increased control complexity, as well as the additional passive components, can lead to larger and heavier systems, which is a drawback in weight-sensitive applications.

A high step-up forward–Flyback interleaved converter has been developed for high Voltage applications, using three-winding coupled inductors and a lossless passive clamp to recycle leakage energy [15-16]. The configuration reduces voltage stress on switches and improves efficiency, but elevated direct currents in the coupled inductors necessitate air gaps to prevent core saturation, raising cost and reducing performance under certain conditions.

Non-isolated interleaved step-up converters with magnetic coupling have also been reported, designed to reclaim stray flux energy and reduce electrical stress on switches. By removing the isolation transformer, these designs achieve higher power density [17-18]. However, the absence of galvanic isolation introduces safety and compatibility challenges, especially when interfacing with systems at different potential levels, and can result in higher output voltage ripple.

A four-switch floating interleaved boost converter has been experimentally evaluated for applications requiring a wide input voltage range and high voltage gain. The design uses averaged PWM modeling and small-signal AC analysis for control [19-22], but its performance is highly dependent on precise dead-time management and switching coordination, making implementation challenging.

To address fault tolerance, multi-switch interleaved boost converters with redundant floating topologies have been explored for renewable energy sources such as solar arrays and fuel cells [23-26]. Fault detection using Park's vector method enables degraded operation during component failures, although reconfiguration can increase stress on remaining switches, affecting long-term reliability.

Finally, coupled-inductor-based interleaved boost converters, particularly those in the floating-interleaving family, have been shown to reduce input current ripple and improve efficiency while allowing for smaller passive components [27-28]. Increasing the number of switches can further reduce ripple, but it also raises the requirement for magnetic components. Using coupled inductors instead of discrete ones can lower cost and size while improving performance, yet careful design trade-offs remain essential for optimal operation.

Methodology

This section discusses my designed model of four-switch interleaved boost converter.

Circuit Description

This section presents a new four-switch interleaved boost DC-DC power converter design with improved flexibility, performance, and cost benefits over conventional boost converters. The study focuses on its application in renewable integration. Also, it will act as a critical link between an electric vehicle's battery storage and its AC motor drive system. Traditional boost converters face limitations such as higher switching losses, reduced power conversion efficiency, increased expenses, and reliability concerns due to aging component technologies. The development of this enhanced converter requires a methodical approach to transition from theoretical concepts to practical implementation. Initial research involves analyzing switching losses, duty cycle behavior, voltage/current ripple effects, and efficiency metrics in standard converters to establish a baseline for my design.

The methodology is organized as follows:

a) Theoretical Analysis – Examines different operating modes based on duty cycle variations, dividing the switching period into eight distinct modes. Derives key equations for input current and inductor current ripple.

b) Simulation Study – Compares simulated current waveforms with calculated values, specifically analyzing inductor ripple currents in the four-switch interleaved boost converter. The combined inductor currents determine the input current ripple.

c) Performance Evaluation – Determines the optimal ratio of input current ripple to inductor current ripple, supported by graphical comparisons of theoretical, simulated, and experimental results. The study identifies the most efficient duty cycle range by evaluating operational modes with minimal input current ripple relative to inductor currents.

The goal is to validate a high-efficiency, cost-effective converter design suitable for real-world renewable applications.

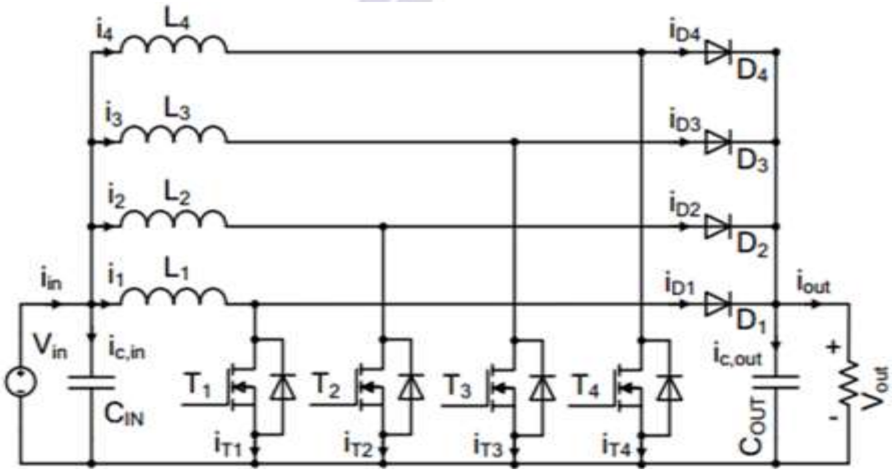

Figure 4: Suggested Interleaved Boost Converter

Functionality of Designed Converter

The switching cycle of my converter is divided into eight modes over one switching period T_s, with specific intervals defined by t_0=0, t_1= DT_s-3/4, t_2=T_s/4, t_3=DT_s-T_s/2, t_4= T_s/2, t_5=DT_s-T_s/4, t_6=3/4T_s, t_7= DT_s, and t_8=T_s. In Modes 1, 3, 5, and 7, all four switches (S_1–S_4) are conducting, keeping all diodes (D_1–D_4) reverse-biased, and the supply voltage energizes inductors L_1–L_4 without transferring energy to the output. In Modes 2, 4, 6, and 8, one switch turns off in each case, causing the corresponding diode to become forward-biased and conduct, allowing its associated inductor to deliver energy to the output capacitor and load while the remaining inductors continue to store energy from the input. This sequential switching ensures balanced inductor charging, regulated output voltage, and controlled energy transfer throughout the cycle.

Related Formulas

Voltage Gain:

The output-to-input voltage ratio of this converter is governed solely by the duty cycle according to:

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

Where Vin represents the input voltage, V_{DC} the output voltage, and D the duty ratio between 0 and 1.

Duty Cycle:

The equation of duty cycle design for switching can be designed based on equation (1)

$$D = 1 - \frac{V_{in}}{V_{DC}} \quad (2)$$

Where D is Duty cycle, Vin is Voltage input and V_{DC} is Voltage output.

Input current:

By following relationship, we can calculate:

$$I_{in} = \frac{P_{in}}{V_{in}} \quad (3)$$

with Pin denoting input power and Vin, the input voltage.

Inductor current ripple (peak-to-peak):

The peak-to-peak variation in inductor current is characterized by:

$$\Delta I_{Lpp} = \frac{V_{in}D}{f_{sw}L} \quad (4)$$

Selection of inductor and capacitor:

The required inductance value is calculated by:

$$L = \frac{V_s D}{\Delta I_L f_{sw}} \quad (5)$$

The output capacitor value is determined by:

$$C = \frac{V_0 DF}{R \Delta V_o} \quad (6)$$

where: V_o = Output voltage (V), V_s = Source voltage (V), ΔI_L = Peak-to-peak inductor current ripple (A), f_{sw} = Switching frequency (Hz), D = Duty ratio, F = Frequency (Hz), R = Load resistance (Ω), ΔV_o = Allowable output voltage ripple (V)

Comparative Analysis with Conventional Boost Converter

Traditional boost converter and my work simulation was conducted through MATLAB/Simulink utilizing identical operational parameters given in Table 1, Simulink simulates the circuit diagram of the suggested converter displayed in Figure 4. The simulation circuit for this suggested converter is being created in the MATLAB Simulink.

Table 1: MATLAB/Simulink Simulation Parameters

Sr. No	Description	Parameters
1	Input Voltage	100 V
2	Output Voltage	500 V
3	Switching Frequency	10 kHz
4	Duty Cycle	80 %
5	Filter Inductor	8.195 µH
6	Filter Capacitor	40.17 µF
7	Load Resistance	500 Ohms

Simulation Work

Pulse-width modulated signals applied to the four switches in our converter, with a 90° phase shift, as shown in Figure 6 to achieve the current ripple cancellation effect. The simulated waveforms of the input current for each switch are observed, displaying larger ripples per switch (6% peak-peak). Figure 7 presents the input current simulation waveforms after ripple cancellation, showing reduced ripple (less than 1% peak-peak) as a result of the current ripple cancellation effect among the switches. The simulated waveforms of the 100 V input source and the 500 V output at an 80% duty cycle are shown in Figure 8. The output voltage shows minimal ripple (1.18% peak-to-peak), attributed to the multi-switch cancellation effect across the four switching elements.

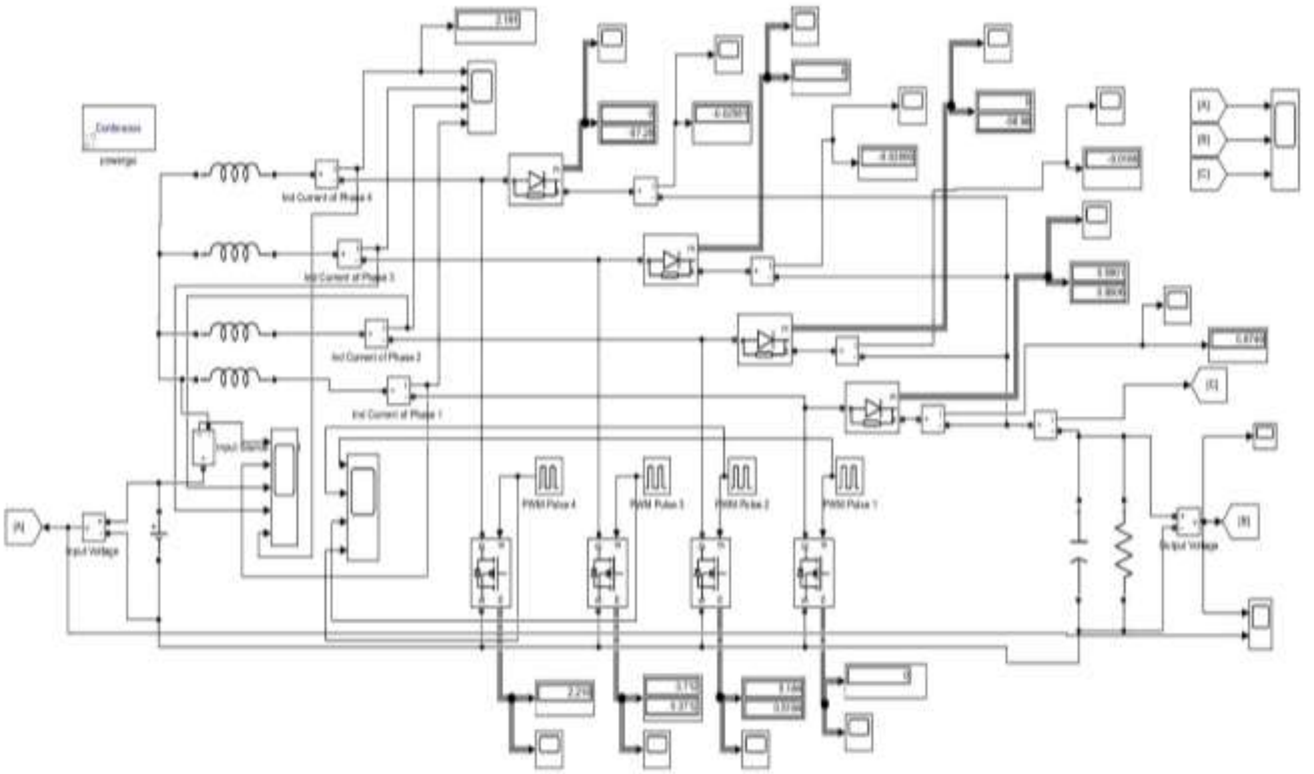

Figure 5: Four-Switch Interleaved Boost Converter MATLAB/Simulink Circuit

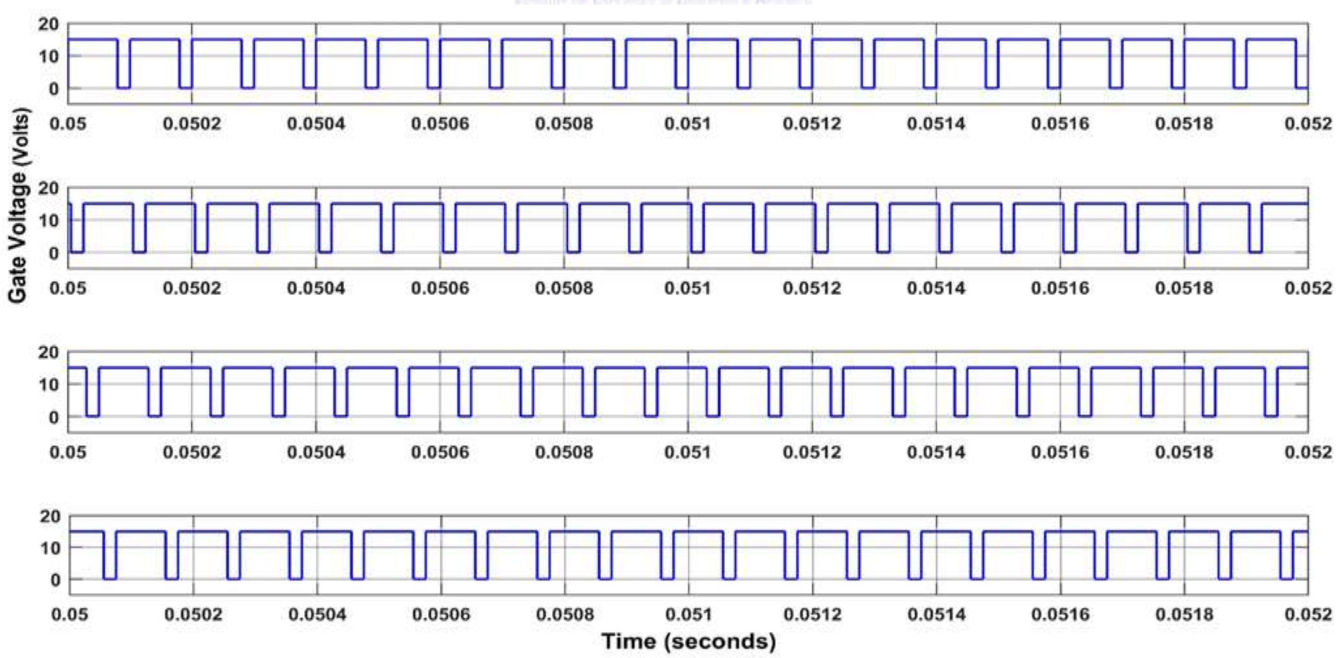

Figure 6: 90° Phase-Shifted Gate PMW pulses

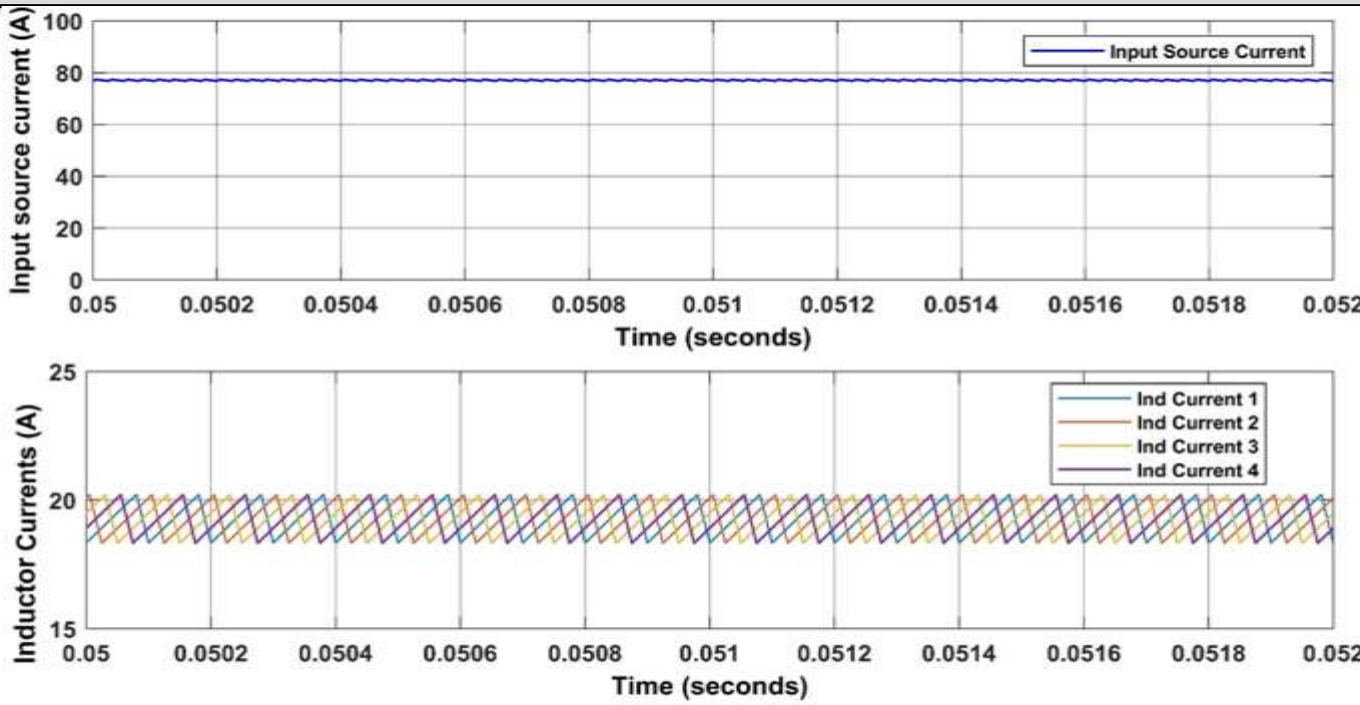

Figure 7: Simulated Inductor Currents Waveform

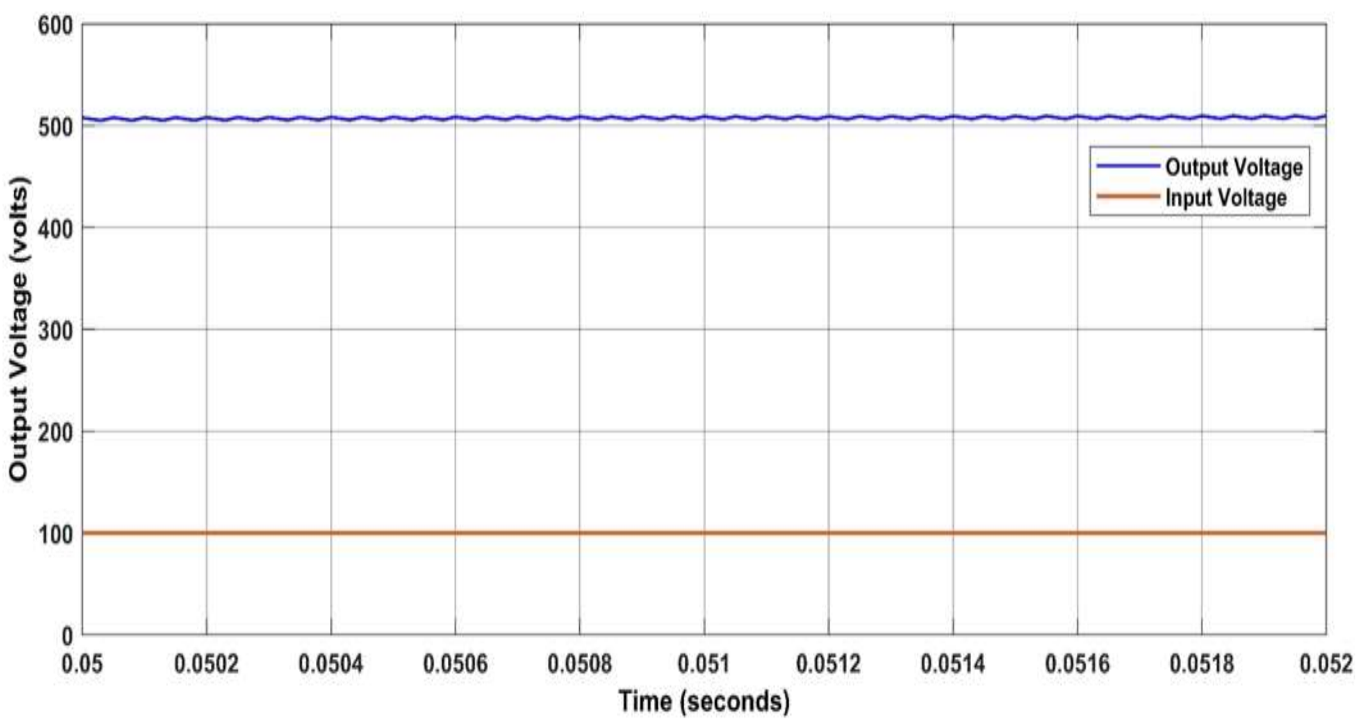

Figure 8: Simulated Input & Output Voltage Supply with D=0.8

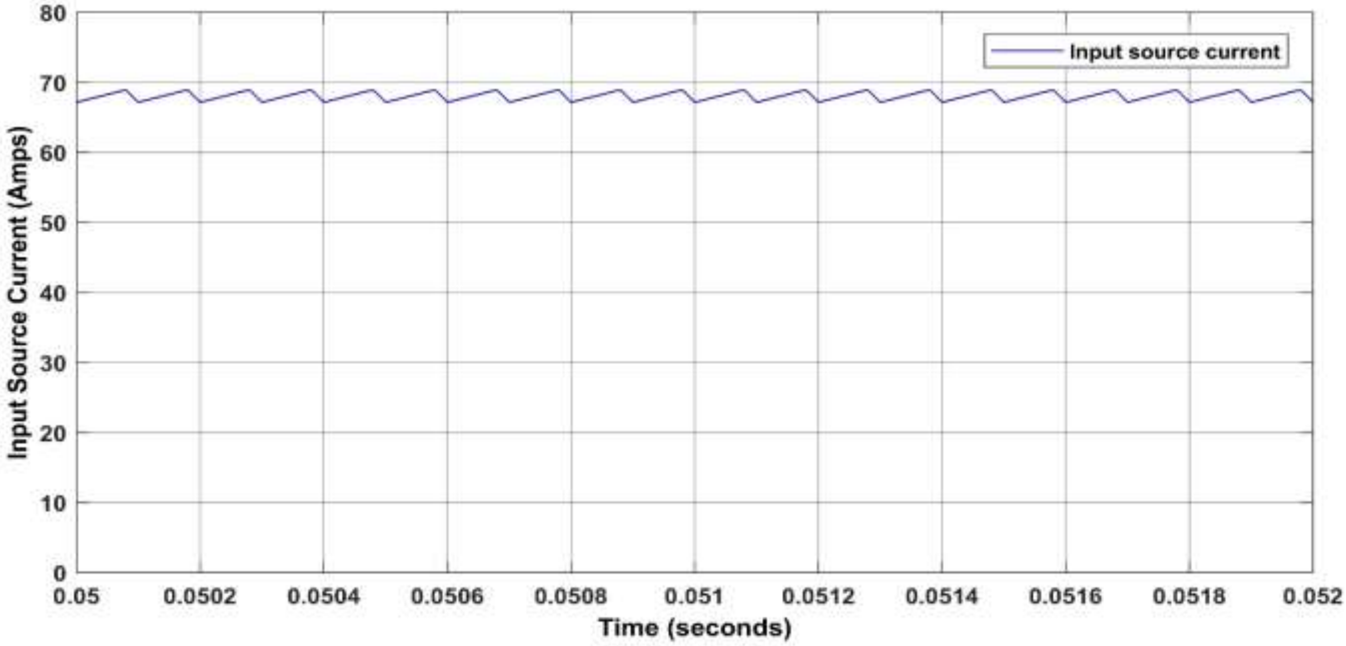

Figure 9: Simulated Conventional Boost Converter Input Current

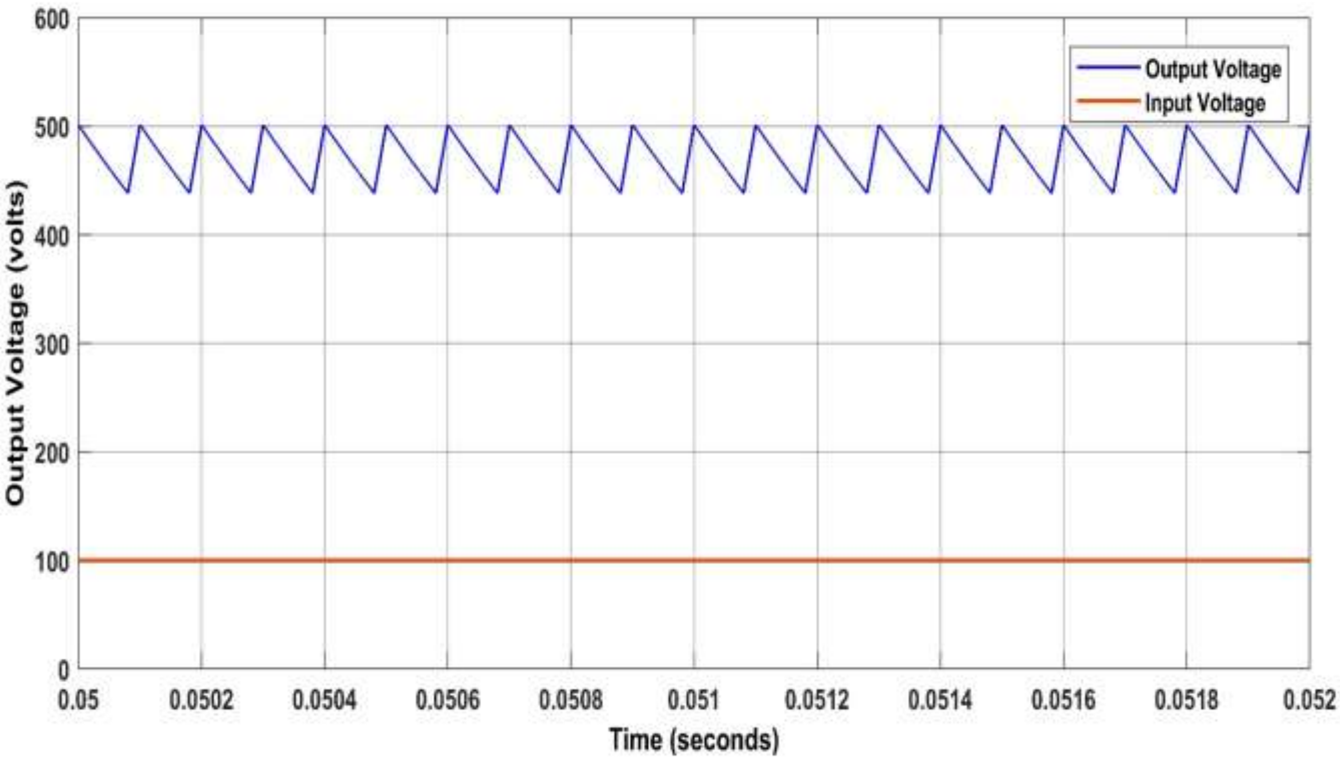

Figure 10: Simulated Conventional Boost Converter Input and output Voltage

Results Comparison

Parameter	Conventional Boost Converter	My Work
Average Output Voltage (V_{DC})	450 V	520 V
Voltage ripple (ΔV_{pp})	40 V	6 V
Voltage Ripple ($\%V_r$)	8.89 %	1.15 %
Average Input Current (I_{in})	68 A	77 A
Current Ripple (ΔI_{pp})	4 A	0.8 A
Current Ripple ($\%I_r$)	5.88 %	1.04 %

Table 2: Results comparison between my work and Conventional Boost Converter

Results Discussion

Based on the comparison, the suggested design delivers a higher average output voltage of 520 V compared to 450 V for the conventional boost converter, while significantly lowering the voltage ripple from 40 V to just 6 V. This corresponds to a reduction in percentage voltage ripple from 8.89% to 1.15%, indicating much improved output stability. On the input side, although the average input current increases from 68 A to 77 A, the current ripple is greatly reduced from 4 A to 0.8 A, with the ripple percentage dropping from 5.88% to 1.04%. These results highlight the design's ability to deliver a more stable and cleaner output while minimizing current fluctuations

Comparative Analysis with Existing work

This section signifies the comparative analysis between input/output voltages and currents of the voltages and currents of the Quasi-Z-Source Interleaved DC-DC Converter for fuel cell vehicles [1] with my work. A MATLAB Circuit was build using the data given in [1]. Input and Output voltages and currents were observed. A Duty Ratio of D=0.4 was taken for this converter and D=0.8 was taken for my converter to get the desired output. The rest of the parameters are taken same for both converters.

Input & Output Supply Characteristics

In this section, the input and output voltages of both converters are observed and analyzed. Both converters operate with the same input voltage of 100 V, while their respective output voltages are labeled as shown in Figure 11. Also, the input source currents are observed for both converters. Both the Input source currents are labelled as shown in Figure 12.

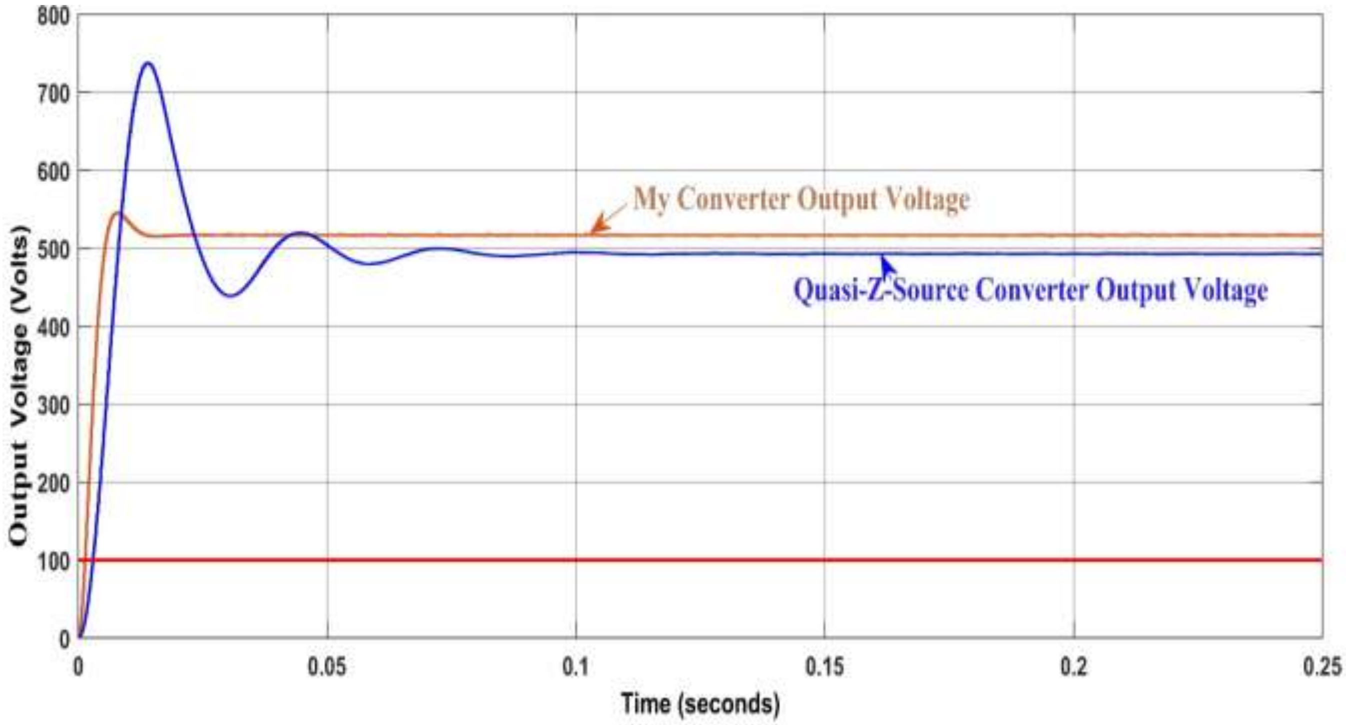

Figure 11: Output Voltages comparison of both converters

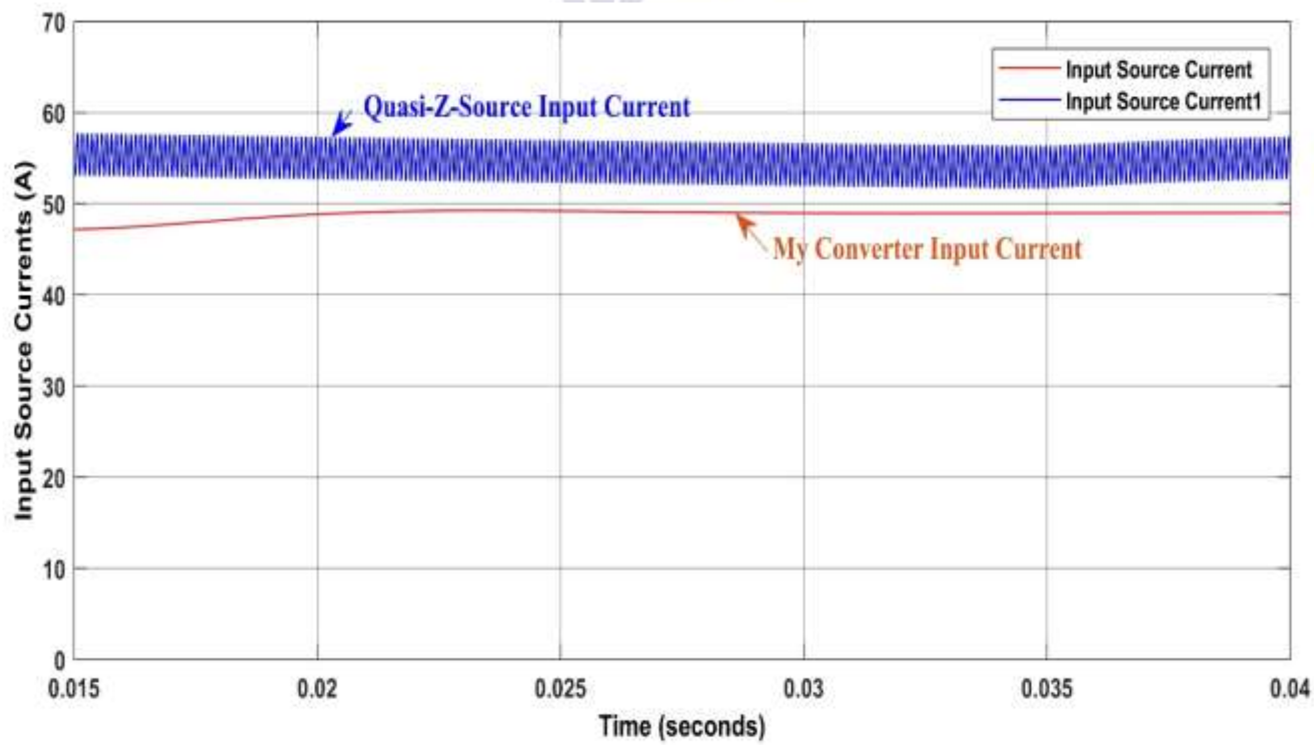

Figure 12: Input Source Currents of both converters

Results Comparison

Table 3: Results Comparison between Existing Work and my Work

Parameter	Existing Work	My Work
Output Voltage (V_{DC})	500 V (upto ~750 V overshoot)	520 V (upto ~540V overshoot)
Setting Time(s)	0.07 s	0.02 s
Average Input Current (I_{in})	56 A	48 A
Current Ripple (ΔI_{pp})	6 A	2 A
Percentage Current Ripple ($\%I_r$)	11 %	5 %
Duty Cycle Limitations	0<D<0.5	0<D<0.9

Results Discussion

From Table 3, it is clear that my work demonstrates improved voltage stability, with output overshoot reduced from 750 V to 540 V and a higher steady-state voltage of 520 V. It achieves a faster response, with settling time improved by 77.5% from 0.07 s to 0.02 s. The average input current (I_{in}) decreases from 56 A to 48 A, while the percentage current ripple ($\%I_r$) is reduced by 67%, from 6 A to 2 A, corresponding to a ripple percentage decrease from 11% to 5%. Additionally, my design offers enhanced control flexibility, providing a wider duty cycle range of 0<D<0.9 compared to the existing work with 0<D<0.5.

Conclusion

The primary objective of this research involves design and investigation of an interleaved step-up DC-DC converter optimized for low-voltage renewable energy applications, including fuel cells and photovoltaic (PV) modules. The converter addresses a critical need in applications requiring voltage elevation to 500 V for stable operation, where Existing converters face limitations due to high duty cycle requirements, excessive peak-to-peak ripples, increased size and cost, reduced efficiency. The four-switch interleaved topology achieves high voltage gain without extreme duty cycles, significantly reduces current and voltage ripples, minimizes conduction losses for improved efficiency, and enables a more compact converter design. Through rigorous analysis of existing methodologies and innovative interleaving techniques, the converter's performance has been validated via MATLAB/Simulink simulations. These advancements hold substantial promise for renewable energy systems, particularly in solar applications, by enhancing power conversion efficiency and system reliability. This work contributes to the sustainable utilization of energy resources, supporting future clean energy transitions.

Recommendations for Further Study

In the future, this work can be extended in several ways. One important area is the detailed study of the filter capacitors. By carefully analyzing their sizes and configurations, it may be possible to improve the overall performance of the converter, increase efficiency, and further reduce the ripple. Another area is the use of adaptive control techniques that can automatically adjust to changes in the input voltage. This would help keep the output voltage stable at 500 V, even if the input voltage varies, such as fluctuations around 100 V. Cost reduction is also an important consideration. Future studies could look into alternative converter designs or the use of more affordable components that still provide the same benefits in terms of efficiency and ripple reduction.

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