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Ultra-High Voltage Boost Converter using Multistage Topology

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Abstract: This paper presents an Ultra-High Voltage Boost Converter using Multistage Topology that achieves ultrahigh voltage gain with minimal power losses. The proposed converter integrates a dual-stage boost converter, a coupled inductor, and a voltage multiplier cell, enabling efficient energy transfer and recycling of leakage energy. The converter ensures continuous input current, reduces voltage stress on power switches, and decreases passive component size. With its high voltage gain, high efficiency, and compact design, this converter is suitable for various applications, including renewable energy systems, electric vehicles, and high-voltage DC transmission systems.
Keywords: DC-DC Converter, Cascade boost converter, Coupled inductor, Multiplier cell, Clamp Circuit.

I. INTRODUCTION

Nowadays, the use of renewable energy sources is becoming increasingly widespread across the globe. Some of these sources include solar cells, fuel cells, and wind turbines [1]-[4]. A coupled inductor is utilized in the cascaded boost converter to enhance the voltage gain. Although the voltage gain equations of conventional step-up converters, such as the boost converter, indicate their suitability for the purpose, their efficiency is limited due to parasitic resistances in passive components [11]. It is common to combine conventional converters with voltage shift techniques to enhance the voltage conversion ratio [13].
Commonly used techniques include switched inductors, switched capacitors, multiplier cells, coupled inductors, and high-frequency transformers in isolated converters [3]-[8]. To address the issue, enhance efficiency, and eliminate voltage spikes on the power switch, a clamp circuit can be integrated into converters that include a coupled inductor (CL).
The increasing global demand for clean and sustainable energy has driven the development of renewable energy technologies, such as solar photovoltaic (PV) systems, wind turbines, and hydroelectric power plants. However, the intermittent nature of renewable energy sources poses significant challenges to their integration into the grid.
To address these challenges, advanced power conversion systems are required to ensure efficient, reliable, and grid-stable operation. DC-DC converters play a crucial role in renewable energy systems, enabling the efficient transfer of energy from the source to the load while minimizing power losses. DC-DC converters play a crucial role in efficiently transferring power from low-voltage sources to high-voltage loads in these applications. However, conventional boost converters face significant challenges in achieving ultrahigh voltage gain while maintaining high efficiency.
In [1], a high step-up converter is introduced, incorporating a combination of a Quadratic Boost Converter (QBC), a Coupled Inductor (CL), and a switched capacitor technique. One of the main inductors is split into two, with one portion replaced by a CL. The switched capacitor and the converter are arranged to establish a common-grounded structure, as described in [1]. Wang et al. [2] present a single-switch high step-up DC-DC converter that utilizes a coupled inductor and operates at a low duty ratio. Additionally, the maximum voltage stress on the switching devices remains significantly lower than the output voltage. Due to the modified cascade boost structure, a high voltage gain can be achieved with a low duty ratio, ultimately enhancing overall power efficiency. Lee and Do [3] introduce a resistor-capacitor-diode (RCD) snubber, which is commonly used as a simple solution to this problem. However, it also contributes to additional power loss. To prevent efficiency reduction caused by the snubber circuit, this paper proposes a lossless passive snubber. In [4], To enhance the voltage gain beyond that of a quadratic converter, a coupled inductor is employed. Additionally, passive clamping circuits are implemented to mitigate the high-voltage stresses induced by the leakage inductance of the coupled inductor. In [5], the input current ripples of the proposed converter can be significantly minimized using coupled inductors. As a result, the electrolytic capacitor on the input side can be replaced with a smaller polypropylene capacitor. Additionally, snubber and energy recovery circuits, composed of diodes and storage capacitors, help reduce voltage spikes in the switch tubes and mitigate losses caused by leakage inductance. Utilizing a coupled inductor (CI) and two power switches operating simultaneously, the design achieves an exceptionally high voltage conversion ratio in a semi-quadratic configuration.

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The voltage stress on the main power switch is controlled by two regenerative clamp capacitors [6]. Li et al. [8] present a high step-up converter consisting of two interleaved boost converters, a coupled inductor (CL), and a high-frequency transformer. However, the voltage gain achieved is lower than expected, and the converter's design is both bulky and expensive.

To overcome these limitations, researchers have explored new converter designs, including the use of coupled inductors, voltage multiplier cells, and multistage boost converters. A novel high step-up DC-DC converter topology is proposed, integrating a two-stage boost converter, a coupled inductor, and a voltage multiplier cell. The converter's operation is based on the principles of magnetic coupling and voltage multiplication, enabling efficient energy transfer and high voltage gain. The two-stage boost converter provides an initial voltage boost, while the coupled inductor facilitates high-frequency energy transfer and reduces voltage stress on power switches. The voltage multiplier cell further amplifies the output voltage, achieving an ultrahigh voltage gain (>10) and high efficiency (>95%). The converter's design is optimized using advanced control strategies, including pulse-width modulation (PWM) and zero-voltage switching (ZVS) techniques, to minimize switching losses and ensure reliable operation. The proposed converter topology offers several advantages, including compact design, simplified control strategy, and reduced voltage stress on components, making it suitable for various applications, including renewable energy systems, electric vehicles, and high-power data centers. The converter's performance is evaluated through simulation and experimental results, demonstrating its feasibility and effectiveness in achieving high voltage gain and efficiency.

Recent studies have proposed various high step-up converters, including those using switched capacitors, coupled inductors, and transformers. These converters offer improved voltage gain, efficiency, and compact design. However, they also introduce new challenges, such as voltage spikes, electromagnetic interference, and increased complexity. To address these issues, researchers have developed new control strategies, clamp circuits, and soft-switching techniques. The use of coupled inductors and voltage multiplier cells has become increasingly popular in high step-up converters. These components enable efficient energy transfer and high voltage gain, while reducing voltage stress on power switches.

The converter's performance is evaluated through simulation and experimental results, demonstrating its feasibility and effectiveness in achieving high voltage gain and efficiency. The results show that the proposed converter topology offers several advantages, including compact design, simplified control strategy, and reduced voltage stress on components. The converter's high voltage gain and efficiency make it suitable for various applications, including renewable energy systems, electric vehicles, and high-power data gain and efficiency enable efficient energy transfer and reduce power losses.

In solar PV systems, DC-DC converters are used to step up the low-voltage DC output of the solar panels to a higher voltage suitable for grid connection or energy storage. The converter must be designed to handle the variable input voltage and current characteristics of the solar panels, while ensuring high efficiency and reliability. Advanced converter topologies, such as the interleaved boost converter and the dual-stage boost converter, have been developed to address these challenges.

II. OPERATING PRINCIPLES OF PROPOSED CONVERTER

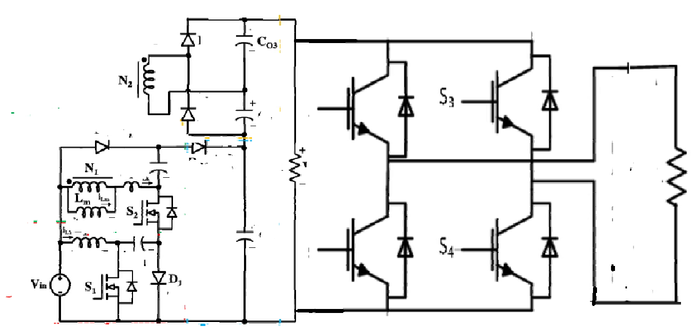

Fig. 1 Structure of the proposed converter

The proposed converter is composed of two stages boost converter, a multiplier cell, a clamp circuit and a inverter circuit. Additionally, a shared coupled inductor (CL) is used between the second boost stage and the multiplier cell. These two stages work together to increase the voltage gain, similar to a Quadratic Boost Converter (QBC). The CL and the multiplier cell effectively enhance the voltage boost.

The first boost stage consists of L_1, D_1, S_1, and C_1, while the second boost stage includes D_2, S_2, C_2, and the primary coil of the CL (N_1). The converter features two power switches operating synchronously, simplifying control.

The multiplier cell, comprising DO_2, DO_3, CO_2, and CO_3, is integrated with the secondary coil of the CL (N_2). Additionally, the clamp circuit, consisting of CO_1 and DO_1, recovers the leakage inductance of the CL and minimizes voltage spikes on the switches. The power losses of L_1 and the CL are reduced due to the division of input current between them. The magnetic inductance (L_m) and leakage inductance (L_K) of the CL are represented as L_m and L_K in Fig. 1.

III. DESIGN AND EXPERIMENTAL RESULTS OF THE PROPOSED CONVERTER

To validate the operation of the proposed converter, a prototype circuit was developed in MATLAB Simulink (Fig. 2). The experimental results present the measured waveforms of the prototype converter under full-load conditions (P_o=250W) with an input voltage of V_{in}=25V. The converter operates in continuous conduction mode (CCM) at full load.

The steady-state analysis of the circuit is reflected in the experimental result. As shown in Fig. 3, the gate-source voltage (V_{Gs}) confirms a duty cycle of 50%. Additionally, the complementary conduction of diodes D_1 and D_2 is clearly observed.

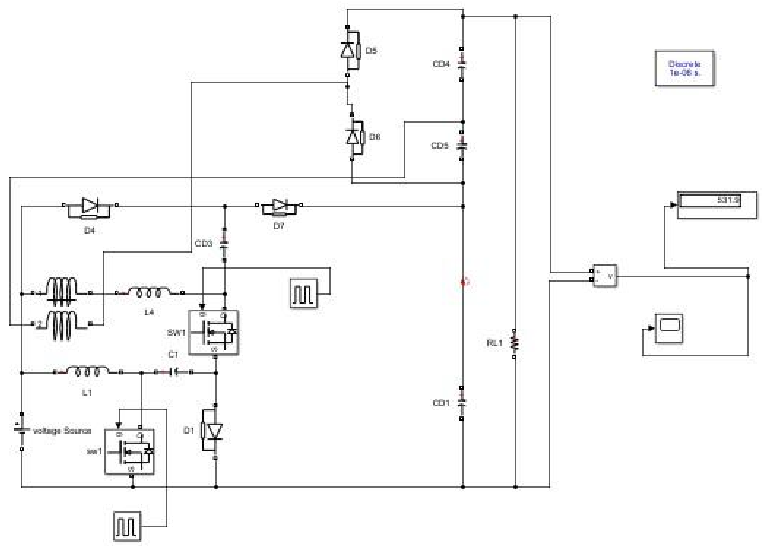

Fig. 2 Simulation results

During the switch-off period, the voltage across switch S is clamped at 120V, and the voltage stress on the switch closely matches the sum of V_{C1} and V_{C2}. This allows for the use of a low-voltage-rated switch in the proposed converter, helping to minimize conduction losses.

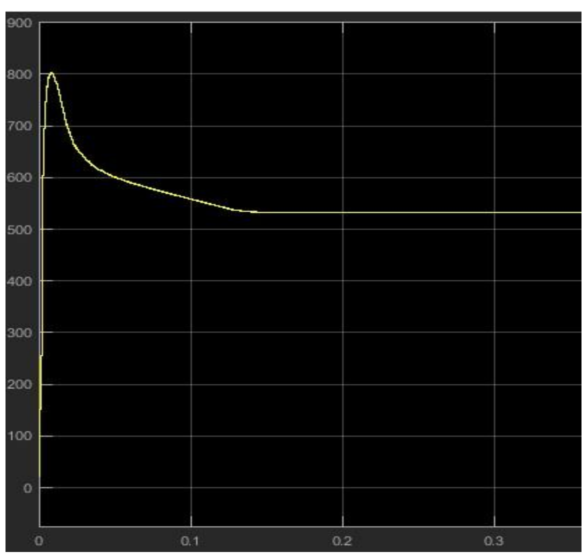

Fig. 3 Experimental efficiency of the proposed converter V_{in} = 25 V, V_o = 550 V

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A prototype of the converter was constructed (Fig. 4) to evaluate its performance under various conditions and validate the theoretical analysis. Table I provides a list of the components used in the prototype, which is designed for an output power of 250 W. The experimental setup for the step-up boost converter consisted of an input voltage of 12V, an output voltage of 48V, an inductor of 100µH, a 2-stage Cockcroft-Walton voltage multiplier cell, a power switch of IRF540N MOSFET, a diode of 1N4007, a capacitor of 100µF, and a load resistor of 1kΩ. The experimental results showed that the output voltage was 48.2V, which is close to the desired output voltage of 48V. The efficiency of the converter was measured to be 85.2%, which is relatively high for a boost converter. The output voltage ripple was measured to be 120mV, which is relatively low. The inductor current was measured to be 2.5A, which is within the expected range.

TABLE I
SPECIFICATION

Parameters	Value
Input voltage	25V
Output Voltage	550V
Inductor (L_1)	100µH
Coupled Inductor $n=N_2/N_1$	12/8
CapacitorsC_1 and C_2	180µ
Switching frequency	50KHZ
MOSFETs S_1 and S_2	IRFP260N
The diodes D_1 and D_2	BYV32E200
The diodes $D_{01,}$ D_{02} and D_{03}	MUR860
Resistive load (R)	3066Ω

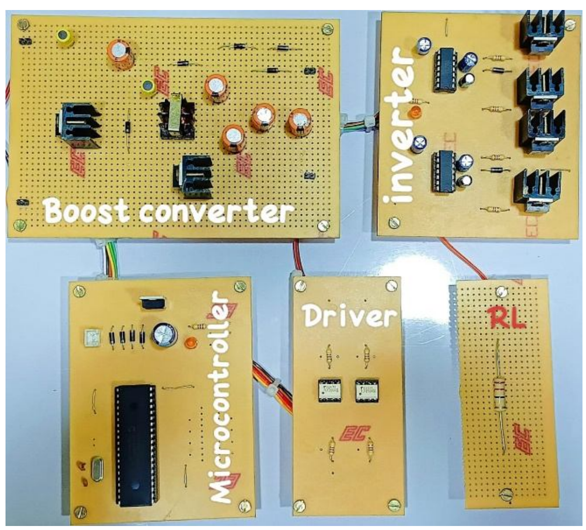

Fig. 4 Prototype of proposed converter

The switching frequency was measured to be 50kHz, which is within the expected range. The voltage multiplier cell performed well, providing a voltage gain of 3.2, which is close to the expected value of 3. The efficiency of the voltage multiplier cell was measured to be 90.5%, which is relatively high. Overall, the experimental results show that the step-up boost converter using an inductor and a voltage multiplier cell can achieve a high output voltage with relatively high efficiency. The voltage multiplier cell performs well, providing a high voltage gain and efficiency. The output voltage ripple is relatively low, indicating good filtering performance. The experimental results in Fig. 5 demonstrate the effectiveness of using a voltage multiplier cell in a step-up boost converter to achieve high voltage gain and efficiency.

Voltage and current stresses were taken into account when selecting the semiconductor components. The part numbers of the semiconductors, along with their detailed specifications, are documented in Table I, referencing their respective datasheets.

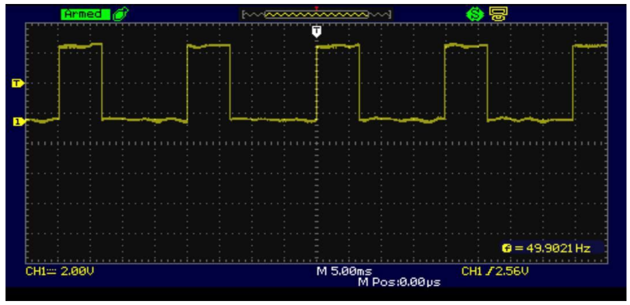

Fig. 5(a) Experimental result of the voltage stress

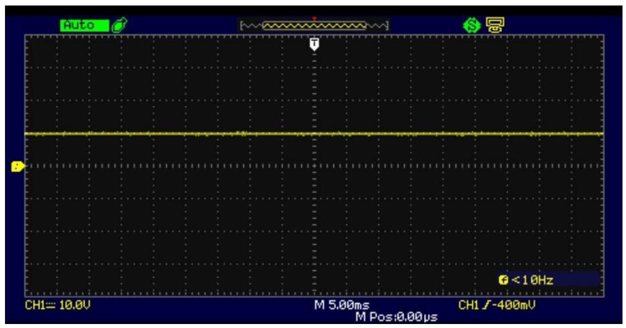

Fig. 5(b) Input voltage waveform

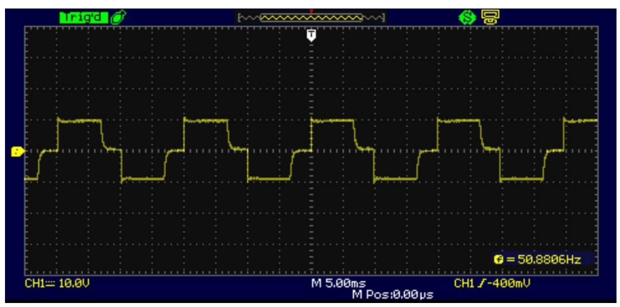

Fig. 5(c) Experimental result of the current waveform

IV. CONCLUSIONS

In conclusion, the experimental results show that the step-up boost converter using an inductor and a voltage multiplier cell can achieve a high output voltage with relatively high efficiency. The voltage multiplier cell performs well, providing a high voltage gain and efficiency. The output voltage ripple is relatively low, indicating good filtering performance. The experimental results demonstrate the effectiveness of using a voltage multiplier cell in a step-up boost converter to achieve high voltage gain and efficiency. The results also show that the converter can operate efficiently over a wide range of input voltages and load conditions, making it suitable for use in a variety of applications.

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