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A Single-Switch DC-DC Converter with a High Voltage Gain Capability and Reduced Voltage Stress of the Switch for Renewable Energy Applications

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***Abstract*— The growing trend toward high-efficiency, high-gain converters that minimize component count, has spurred the development of many new step-up topologies. In this context introduces a new single-switch, non-isolated DC-DC step-up converter topology specifically designed for renewable energy applications. Key advantages of this topology include a high boost factor, continuous input current, reduced voltage stress on the switch, and a suitable number of elements relative to the achieved boost factor. These features address many of the critical design objectives. The steady-state analysis of the proposed converter is presented and discussed. Simulation and experimental results are presented to verify the theory and performance of the converter.**

***Keywords*— DC-DC converter, extended voltage gain, single-switch, reduced voltage stress**

I. INTRODUCTION

The rising importance of DC distribution networks and equipment can be attributed to several factors, including the growing adoption of renewable energy sources and distributed renewable energy generation [1,2]. Indeed, renewable energy sources such as photovoltaic (PV) panels generate power in DC form, which has led naturally to the emergence of DC microgrids [3,4]. However, a crucial component of all these systems is a DC/DC power electronic converter. As a result, the development of new DC/DC topologies has been aided in recent years.

There are several power sources, such as fuel cells and photovoltaic (PV) panels, that necessitate DC/DC converters to optimize energy extraction and adjust the DC voltage at the point of connection [5-8]. However, several of these applications necessitate the use of DC/DC converters with a boost topology, where the input current is preferably continuous [9,10]. The problem is that the traditional Boost converters, along with certain proposals, have constraints related to the practical static voltage gain. Consequently, several converters with increased voltage gains have been suggested. Several approaches have been employed. One of the strategies involves the use of a cascade connection of converters [11]. However, this solution significantly increases the number of components and reduces the efficiency. One approach that utilizes a single switch is the quadratic converter [12-15]. Other single-switch solutions have also been presented, but they typically require a higher number of passive components or offer lower gain compared to the quadratic converter [16-23]. Other approaches have been adopted to increase the static voltage gain of the converters. To mention that some proposed solutions also operate in discontinuous conduction mode (DCM) of the converter input current. This can be a disadvantage for applications that require continuous conduction mode (CCM), such as fuel cells or photovoltaic panels. However, these approaches typically require the use of more than one switch [24-31]. The described solutions have some limitations. In fact, the proposed topologies often require switches subjected to high voltage stress and/or count of passive components, or even operate in discontinuous conduction mode.

This paper introduces a novel converter design characterized by a wide voltage gain, and a simplified structure, all while requiring only a single switch with a low voltage stress. This non-isolated topology is versatile and can be employed in various applications, such as fuel cells and renewable energy generation systems. To evaluate the proposed new converter, both simulation studies and a laboratory prototype will be utilized for testing purposes.

II. DC-DC CONVERTER WITH A HIGH VOLTAGE GAIN CAPABILITY AND REDUCED VOLTAGE STRESS OF THE SWITCH

It was stated in the introduction that a category of DC-DC power converters, which is particularly important in applications like photovoltaic and fuel cells systems, are those with high static voltage gain and continuous input current. Nevertheless, the problem with the majority of the proposed DC-DC converters is that they require multiple switches and/or the switches are subject to high voltage stress. To address this, a novel quadratic Buck-Boost topology, illustrated in Fig. 1, is introduced. This novel topology offers a higher static voltage gain than traditional Boost or quadratic Boost converters, while maintaining continuous input current and low voltage stress on the switch.

The proposed converter's theoretical analysis and behavior are based on several key assumptions, including: ideal transistor and diodes, capacitors and inductors, continuous conduction mode operation, and capacitor voltages that remain relatively constant. Under these idealized conditions, the converter's operation can be divided into two distinct modes that occur within a single switching cycle:

State switch is in the ON condition: The resulting circuit configuration for this state is illustrated in Fig. 2(a). Since the switch is in the ON state, diodes D_2 and D_3 become forward-biased, while the other two diodes are reverse-biased. As a result, the currents through both inductors will rise, as they are in a magnetizing state. Meanwhile, capacitor C_2 will accumulate charge, whereas capacitors C_1 and C_o will release their energy to the inductor L_2, capacitor C_1 and load.

When the switches are in the OFF state: It results in the equivalent circuit that is shown in Fig. 2(b). Diodes D_2 and D_3 are reverse-biased, while D_1 conducts. The inductor currents decrease as they enter the demagnetization phase. Capacitor C1 discharges, while capacitors C_2 and C_3 charge, absorbing the energy stored in the inductors.

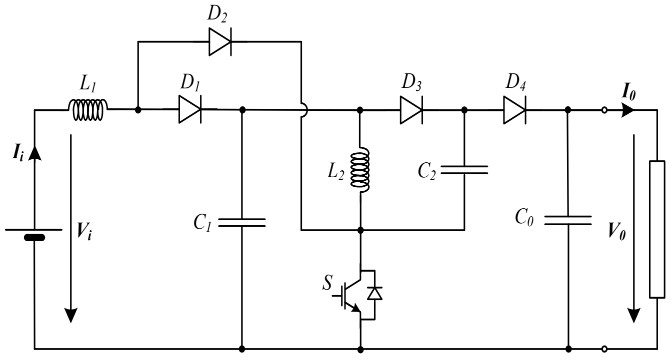
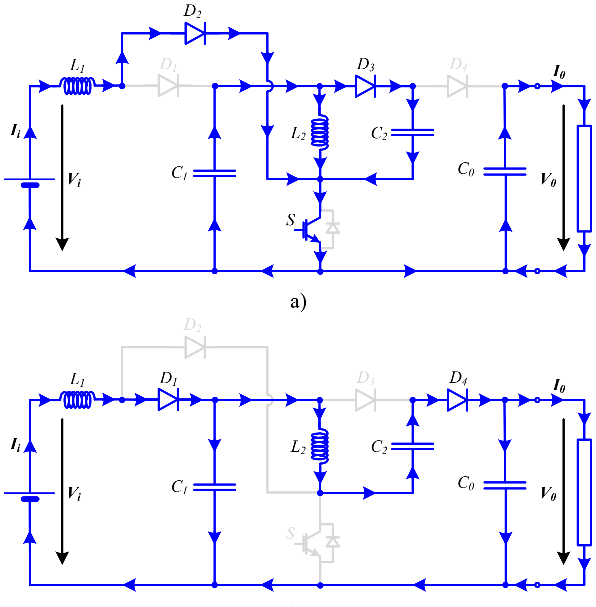


Fig. 1. Circuit diagram of proposed single-switch DC-DC converter with a high voltage gain capability and reduced voltage stress of the switch.



a)

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Fig. 2. Equivalent circuit topologies arising from: a) Simultaneous conduction of both switches b) Simultaneous non-conduction of both switches.

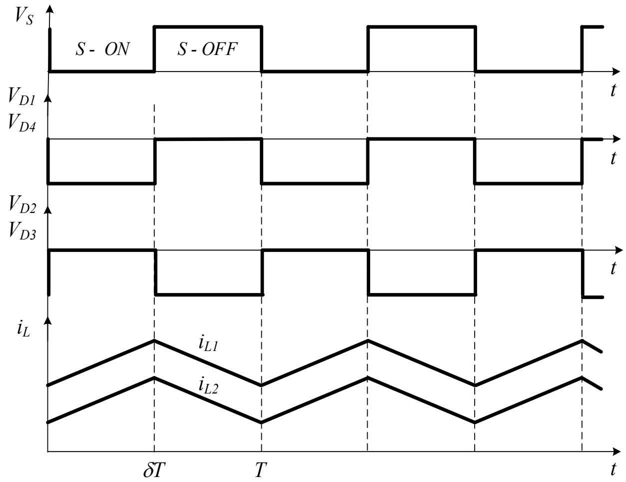


Fig. 3. Representative voltage and current waveforms illustrating the operation of the power converter circuit shown in Fig. 1 (in which $i_L = I_{in}$).

III. CONVERTER ANALYSYS

Considering that the proposed converter is intended for use in applications such as PV generators and/or fuel cells, the analysis will focus on the continuous conduction mode (CCM). The static voltage gain of the system in this mode can be derived by applying the principles of capacitor charge conservation and inductor volt-second balance. Thus, based on these principles and the circuit analysis, the following equations are derived:

$$\frac{1}{T}\int_0^T v_{L_1}dt = \frac{1}{T}\left[\int_0^{t_1} V_i\, dt + \int_{t_1}^{T}(V_i - v_{C_1})dt\right] = 0 \qquad (1)$$

$$\frac{1}{T}\int_0^T v_{L_2}\,dt = \frac{1}{T}\left[\int_0^{t_1} v_{C_1}\,dt + \int_{t_1}^{T}(v_{C_1}+v_{C_2}-V_o)dt\right]=0 \tag{2}$$

Based on the previous equations, the average voltage of capacitors C1 and C2 can be determined as a function of the duty cycle (denoted as δ, with δ being equal to t_1/T):

$$\begin{cases} V_{C_1} = \dfrac{1}{1-\delta}V_i \\ V_{C_2} = (1-\delta)V_o - \dfrac{1}{1-\delta}V_i \end{cases} \tag{3}$$

When the switches are in the ON state, the equivalent circuits reveal that capacitors C_1 and C_2 are connected in parallel. Consequently, their average voltage values are equivalent. Therefore, the mathematical expression for the output voltage of the presented converter is:

$$V_o = \frac{2-\delta}{(1-\delta)^2}V_i \tag{4}$$

This static voltage gain can also be visually represented and contrasted with the Boost and quadratic Boost configurations, as depicted in Figure 4. As evident from the analysis of this figure, the suggested converter shows that their static voltage gain is greater in comparison to the other converters. In this way, the high static voltage gain of the presented converter is confirmed.

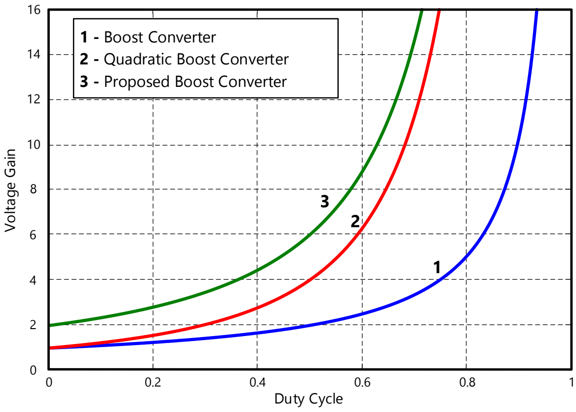


Fig. 4. Graphical depiction of the static voltage gain of the presented converter and the Boost and quadratic Boost topologies.

Regarding the voltage stress across the switch, from the equivalent circuits, it is possible to see that, it will be given by.

$$V_S = V_o - V_{C_2} = \frac{1}{2-\delta}V_o \tag{5}$$

This last expression indicates that, unlike typical topologies, the voltage stress in this one is lower than the output voltage. When considering the diodes, the equivalent circuits and capacitor voltages yield the following expressions for their voltage stress:

$$V_{D_1} = \frac{1}{1-\delta}V_i \tag{6}$$

$$V_{D_2} = \frac{\delta}{(1-\delta)^2}V_i \tag{7}$$

$$V_{D_3} = V_{D_4} = \frac{1}{(1-\delta)^2}V_i \tag{8}$$

The expressions of the diodes' voltage stress show that they are lower than the output voltage, confirming that these power semiconductors are also subject to reduced blocking voltage when compared with classical solutions.

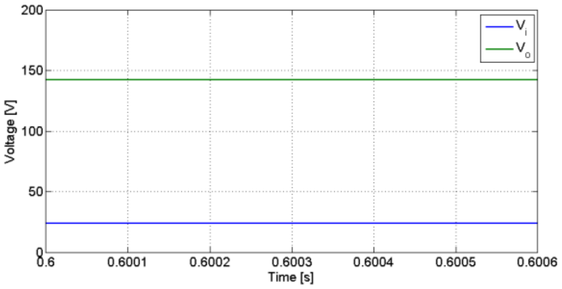
IV. SIMULATION RESULTS

An initial implementation of the proposed solution was carried out using a simulation tool with the aim of examining and verifying the theoretical assumptions. The Matlab/Simulink tool, one of the most commonly used simulation tools, was chosen for this purpose. The parameters of the converter and the overall system are detailed in Table I.

Table I: Key parameters of the converter circuit and the complete system

Parameter	Value
Inductors (L_1 and L_2)	1 mH
Capacitor (C_1 and C_2)	50 µF
Capacitor (C_o)	470 µF
Input voltage	24 V
Resistor Load	50 Ω
Switching frequency	20 kHz

The initial simulation focused on examining the characteristic of high static voltage gain. The circuit was set to operate with a duty cycle of δ = 0.5. The results of this test can be observed in Figures 5 and 6. From result presented in Fig. 5, It can be observed that a high voltage gain is achieved (around 6) and the input continuous current (the same as i_{L1}). On the other hand, it is possible to verify that all power semiconductors are subject to lower voltage stress.



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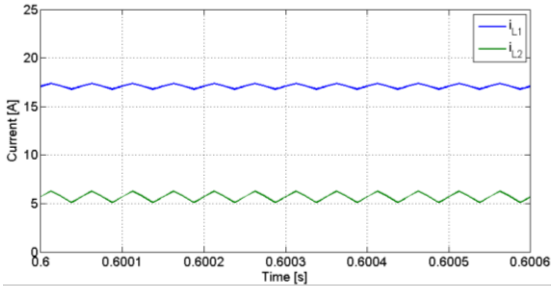

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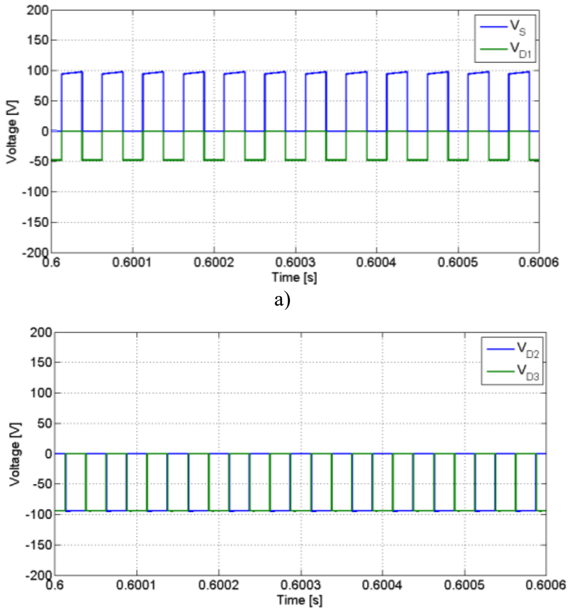
Fig. 5. Simulation results depicting: (a) input and output voltages (b) inductors L_1 and L_2 currents.



a)

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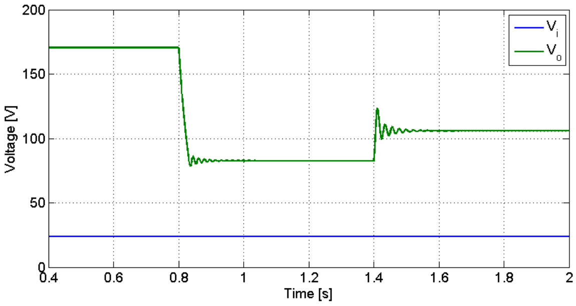
Fig. 6. Simulation results depicting: (a) voltage over the diode D_1 and switch (b) voltage over D_2 and D_3 diodes.

To examine the converter's transient response, simulations were conducted by suddenly altering the duty cycle from 0.55 to 0.3 and then to 0.4. The load was changed to 80 Ω. The outcomes of this simulation are illustrated in Fig. 7. As shown by Fig. 6 a), the converter output voltage follows the change of the duty cycle. As anticipated, the currents track the voltage gain, decreasing or increasing their amplitude in accordance with the output voltage.



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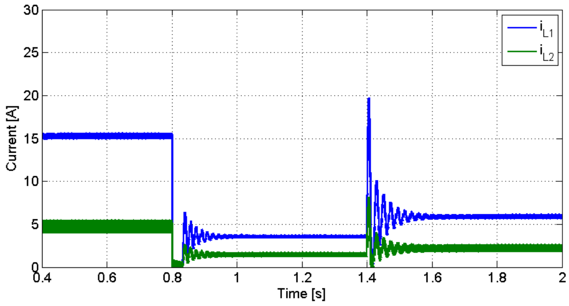


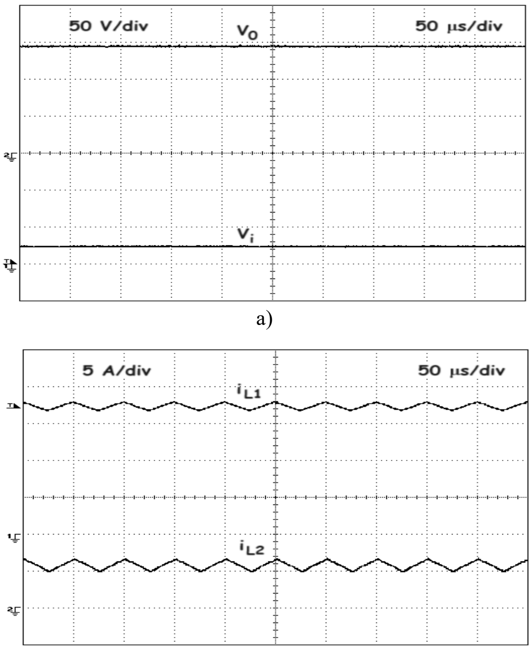
b)

Fig. 6. Simulation results for the condition of duty cycle suddenly change: a) input and output voltages b) inductors L_1 and L_2 currents.

V. RESULTS OBTAINED UNDER EXPERIMENTAL CONDITIONS

A prototype of the proposed converter with high voltage gain was built and tested in a laboratory setting to validate the simulation results. The converter was designed using the same parameters as those employed in the simulation studies. The specific parameters used, along with the system parameters, are summarized in Table I.

Adopting the same approach as the computer simulations, the converter was initially subject to steady-state condition with 50 % duty cycle. The resulting experimental data from this test are illustrated in Figs. 7 and 8. The experimental results show that the static voltage gain is similar to the theoretical prediction and simulation outcome. Additionally, the continuous conduction mode of the input current and the level of voltage stress experienced by the power semiconductors, as expected, were also experimentally verified.



a)

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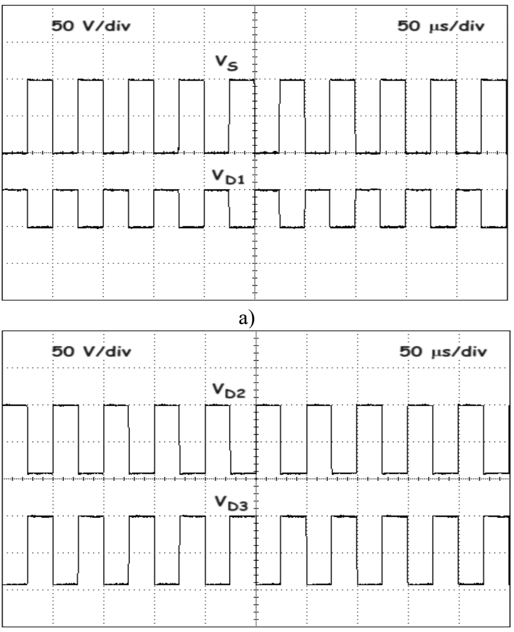
Fig. 7. Experimental results depicting: (a) input and output voltages (b) inductors L_1 and L_2 currents.



a)

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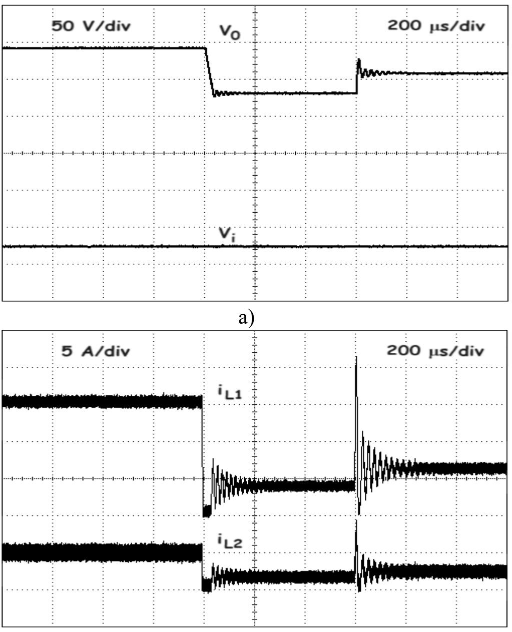
Fig. 8. Experimental results depicting: (a) voltage over the diode D_1 and switch (b) voltage over D_2 and D_3 diodes.

The laboratory prototype was also used to validate the converter's behavior under transient conditions, mirroring the simulation tests. The results obtained for the sudden changes from 0.55 to 0.3 and then to 0.4 are depicted in Fig. 9. These results confirm the static voltage gain for different duty cycles, as well as their transient behavior.



a)

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Fig. 9. Experimental results for the condition of duty cycle suddenly change: a) input and output voltages b) inductors L_1 and L_2 currents.

VI. CONCLUSIONS

This paper presented a novel single-switch non-isolated Boost DC-DC converter topology that achieves a high static voltage gain. In fact, the results showed that this topology offered improved voltage gain performance at lower duty ratios, surpassing the capabilities of traditional converter topologies. Furthermore, this converter features continuous input current and reduced voltage stress over the power switch and diodes. The unique combination of features in this DC-DC converter makes it an ideal choice for applications demanding extremely wide conversion ratio ranges, particularly in the realm of renewable energy systems. To validate the proposed converter's performance, a comprehensive testing program was undertaken, involving both simulation-based studies and hands-on experimentation using a purpose-built laboratory prototype. The experimental data gathered from the prototype validate the theoretical assumptions, confirming that the converter indeed exhibits the predicted enhancements in voltage gain and hold-off voltage capabilities.

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