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Research Article

A Quadratic High Step-Up Converter with Zero-Current Switching

Rasol Sareban[1], ***PhD student*, Mohammadreza Amini**[2]*, ***Assistant Professor*, Majid Delshad** [3], ***Associate Professor*, Mohammad Rouhollah Yazdani**[4], ***Associate Professor***

[1] Department of Electrical Engineering, Isfahan (Khrasgan) Branch, Islamic Azad University, Isfahan, Iran, rasol.sareban@iau.ir
[2] Department of Electrical Engineering, Isfahan (Khrasgan) Branch, Islamic Azad University, Isfahan, Iran, mr.amini@khuisf.ac.ir
[3] Department of Electrical Engineering, Isfahan (Khrasgan) Branch, Islamic Azad University, Isfahan, Iran, delshad@khuisf.ac.ir
[4] Department of Electrical Engineering, Isfahan (Khrasgan) Branch, Islamic Azad University, Isfahan, Iran, m.yazdani@khuisf.ac.ir

Extended Abstract:

The increasing penetration of renewable energy sources, such as photovoltaic (PV) panels and fuel cells, into modern DC microgrids has created a critical need for high-efficiency, high step-up DC-DC power converters. These sources typically generate a low DC voltage that is incompatible with the higher voltage DC buses required by many modern loads and grid-tied inverters. Conventional boost converters, while simple and inexpensive, are fundamentally limited in their voltage gain, especially under practical conditions that account for component parasitics. Furthermore, in high step-up applications, they suffer from severe drawbacks, including high voltage stress across the main power switch and diodes, significant reverse recovery losses in the diodes, and high conduction losses due to the large input current ripple. These issues collectively lead to poor conversion efficiency, reduced power density, and compromised system reliability, which are unacceptable for advanced, sustainable energy systems. To address these challenges, numerous topologies have been proposed in the literature, including cascaded or quadratic boost converters and converters with coupled inductors. However, cascaded structures often require multiple active switches and complex control schemes, while coupled-inductor-based designs introduce problems related to leakage inductance, which can cause high voltage spikes and necessitate complex clamping or snubber circuits, thereby adding cost and potentially negating the efficiency gains.

In direct response to this technological gap, the research by Sareban, Amini, Delshad, and Yazdani presents a novel, non-isolated, single-switch quadratic high step-up converter that ingeniously overcomes the limitations of existing solutions. The core innovation of the proposed topology lies in its unique and integrated approach to achieving three critical objectives simultaneously: (1) attaining a very high voltage conversion ratio with a simple, single-switch structure, (2) implementing soft-switching to eliminate the main sources of switching and diode losses, and (3) ensuring a continuous input current with low ripple, which is highly beneficial for source longevity, particularly for sensitive sources like solar panels and fuel cells. The converter architecture features two distinct coupled inductors, each serving a dedicated and crucial function. The first coupled inductor is strategically integrated into the main power path to enhance the inherent voltage gain of the quadratic boost structure without requiring an impractically high turns ratio. The second, smaller coupled inductor is dedicated to a sophisticated, lossless passive snubber circuit. This snubber is not merely a protective element; it is an active and essential part of the soft-switching mechanism.

The proposed converter operates through a carefully choreographed six-mode switching cycle within each period, enabling a full suite of soft-switching benefits. Most significantly, it achieves Zero-Current Switching (ZCS) for the main power switch at turn-on and Zero-Voltage Switching (ZVS) at turn-off. At the beginning of the switch conduction period (Mode 1), the current through the main switch ramps up from zero due to the presence of a series inductor from the snubber circuit, ensuring a soft, lossless turn-on. At the end of the conduction period, the snubber capacitor resonates with the same inductor, allowing the switch voltage to fall to zero before it turns on in the next cycle, thus enabling ZVS turn-off and eliminating the capacitive switching loss. Perhaps most critically, the design ensures that all diodes in the circuit, including the main output diode and the auxiliary snubber diode, also operate under ZCS conditions. This is a major achievement, as it completely eliminates the problematic reverse recovery phenomenon that is a primary source of loss, electromagnetic interference (EMI), and potential device failure in high-frequency, high-voltage converters. The continuous input current, a direct benefit of the input inductor (L1), further contributes to the system’s overall efficiency and source compatibility.

The paper presents a rigorous and comprehensive theoretical analysis of the proposed converter. This includes a detailed derivation of the steady-state voltage gain as a function of the duty cycle and the turns ratios of the two coupled inductors, which is validated through the provided gain curves. The analysis further extends to calculating the voltage stress across all semiconductor devices (the switch and all diodes), which is shown to be significantly lower than in a conventional hard-switched boost converter for the same voltage gain. This reduced voltage stress allows for the selection of lower-rated, lower-cost, and more efficient components. The design procedure for the key magnetic components—the main inductors and the snubber inductors—is also clearly outlined, based on permissible current ripple specifications. To validate the theoretical claims and analytical models, the authors undertook a meticulous experimental verification process. They first developed a 60 W simulation model of the converter in the PSPICE software environment. The simulation results provided detailed waveforms that confirmed all the key operational claims: the ZCS turn-on and ZVS turn-off of the main switch, and the ZCS operation of all diodes, as evidenced by their current waveforms reaching zero before commutation.

Following the successful simulation, the authors constructed a physical 60 W hardware prototype of the proposed converter. The experimental waveforms, captured from the prototype, were found to be in excellent agreement with the simulation results, thereby providing robust empirical validation of the converter’s operation. The final and most compelling proof of the converter’s superiority is its measured efficiency. Under full-load (60 W) conditions, the prototype achieved a remarkable efficiency of 96%. This performance represents a substantial 6% absolute improvement over a comparable hard-switched quadratic boost converter, which would have operated at only 90% efficiency under the same conditions. This efficiency gain is directly attributable to the elimination of hard-switching losses, diode reverse recovery losses, and the reduction in conduction losses due to lower device stress. The efficiency comparison curve also reveals that the proposed soft-switching converter maintains its performance advantage across a wide load range, with a notably flatter efficiency curve, while the hard-switched counterpart suffers a more significant drop in efficiency at partial loads, likely due to the fixed losses associated with its passive clamping circuits.

In conclusion, this research presents a significant and practical advancement in the field of high step-up DC-DC power conversion. The proposed single-switch quadratic converter is not just another incremental improvement but a holistic solution that elegantly integrates high voltage gain, soft-switching for all active and passive semiconductor devices, low voltage stress, and a continuous input current. The successful validation through both detailed simulation and a fully functional hardware prototype, culminating in a demonstrable 6% efficiency gain, provides strong evidence of its technical viability and commercial potential. This converter topology is exceptionally well-suited for a range of applications where efficiency, reliability, and power density are paramount, including interfacing low-voltage renewable energy sources to DC microgrid buses, battery charging systems, and electric vehicle powertrains. The work stands as a valuable contribution to the ongoing effort to develop the efficient and reliable power electronic building blocks necessary for a sustainable energy future.

Keywords: High Step-Up Converter, Continuous Input Current, Coupled Inductor, Zero-Current Switching (ZCS)

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*** Corresponding Author:** Dr. Mohammad Reza Amini

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