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Development of a Single-Switch Quasi-Resonant High Voltage Gain Dc–Dc Converter with Coupled Inductor

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ABSTRACT: This paper conducts topology transformation based on the Buck/Boost converter. The front-end unit adopts an interleaved structure and passive clamp branches to enhance voltage transformation capability. This setup ensures a smoother input inductor current, mitigating current ripple and improving overall converter performance. At the same time, a dual-coupling structure is introduced, and a voltage multiplier cell is formed by using the secondary side of the dual-coupled inductor connected in series with the diode-capacitor (D-C) branch. It can once again enhance the voltage and suppress the impact force, use generalized quasi-resonance to achieve the zero-current-switching (ZCS) of the loop, and reduce the voltage stress of the devices. An interleaved quadratic Boost converter is proposed, a detailed theoretical analysis of its working principle and performance characteristics is carried out, and various indicators are compared horizontally in different converters.

KEYWORDS: diode-capacitor (D-C), zero-current-switching (ZCS), DC–DC, Converter With Coupled Inductor, Single-Switch Quasi-Resonant

I. INTRODUCTION

Techniques associated with the generation of electrical energy have been improved to address the challenges associated with climate change and contribute to sustainable development. In this sense, production of electrical energy from renewable resources, such as wind, solar and biomass, is not an alternative anymore but a necessity. Considering photovoltaic (PV) and fuel cell (FC) systems, the voltage levels are usually low and in the form of direct current (DC), diverging from the usual alternate current (AC) system that prevails in the distribution of electricity in most segments [2]. Thus, in order to adapt the voltage levels while taking into account technical and economic aspects, electronic energy processing is mandatory, from which low cost and high efficiency are expected. In this sense, high-step-up DC–DC converters are widely employed in applications where the primary energy source is characterized by a voltage level much lower than that required for the end use [10].

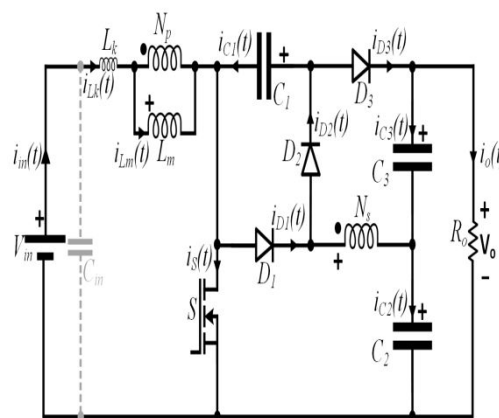


Fig 1: Quasi-Resonant Single-Switch High-Voltage-Gain DC-DC Converter with Coupled Inductor



Providing energy to a DC distribution system or conditioning the voltage as an intermediate stage of a DC–AC conversion system are some applications of DC–DC converters. One of the main challenges in the use of such converters is to avoid expressive switching and conduction losses. Therefore, using circuits with a reduced number of components, featuring low-voltage stress on the semiconductors and with the ability of recycling the leakage energy are key to improving the overall system efficiency. However, achieving all these characteristics is not an easy task. One classic example is the boost converter, which is indeed a simple circuit but exhibits poor performance under high-voltage-gain conditions [10]. Addressing the limitations of the boost converter by the use of techniques to improve the voltage gain has been extensively investigated in the literature [8]. Among the several techniques discussed in [13], one can be highlighted: boost-based solutions using a single active switch, a single coupled inductor and voltage multiplier cells (VMCs), such as the boost-flyback and the boost associated with VMCs introduced in [9] and [12], respectively, in addition to other solutions recently reported in the literature [15]. In all these examples, voltage gain is dependent on the duty cycle (D) and on the number of turns ratio (n) of the coupled inductor. As a result, higher voltage conversion ratios can be achieved without extreme duty cycle values, and therefore a higher efficiency is expected, since conduction and switching losses are lower compared to the conventional step-up converters.

Converters employing a single active switch and reduced number of diodes and capacitors are usually not suited for applications where the power processed is higher than a few hundred watts. However, these circuits are interesting for processing energy from PV modules rated in the range of 200–600 W. In this sense, this work introduces a high-voltage-gain DC–DC converter based on the boost configuration using coupled inductor and voltage multiplier cells, as depicted in. The key features of the proposed circuit that make it suitable for PV applications are: high efficiency; reduced number of components; low voltage stress on the semiconductors; and voltage distribution among the output capacitors. In addition, quasi-resonant characteristics guarantee ZCS operation for diodes D_2 and D_3 , thus contributing to improving the system efficiency [6]. In addition, a high voltage conversion ratio can be achieved if compared with similar topologies, even though a relatively low number of turns ratio of the coupled inductor is adopted. Therefore, weight, volume and magnetic losses can be minimized.

II. BACKGROUND OF WORK

The current promotion of energy transformation has become a global consensus. In recent years, the proportion of renewable energy use has been increasing annually. This has led to the advancement and research of DC-DC converters, which have shown excellent application performance in emerging industries such as photovoltaic power generation technology and new energy vehicles. As a result, there is a growing need for more efficient and high-gain converters.

Converter topologies can be built by adding voltage multiplier structures and cells to the original basic converter type. Traditional DC-DC converters can directly incorporate switched capacitors or switched inductors, but are prone to severe hard switching conditions and duty cycle loss. To address this, propose switched capacitor inductor units^{5,6} and the switched capacitor inductor network. Moreover, the active-passive inductor cells proposed in⁸ can work with multi-switches for cascade expansion with the continuous input current, however, this approach involves challenging control, excessive surge of switch structures, and serious hard-switching conditions, leading to a significant overall loss that reduces the converter efficiency. Given the losses caused by hard switching, auxiliary switches can be added in the traditional converter to form unidirectional or bidirectional cells that can be used to achieve zero-voltage-switching (ZVS), but the gain cannot be improved. The introduction of coupled inductors is an effective means to increase converter gain. The most common is the double-winding structure, three-winding structures can also be used^{12,13,14}, and the impedance source structure is gradually developed. In practical applications, device size and leakage inductance need to be considered. By adding active/passive clamping branches to reduce device voltage stress and utilizing leakage inductance energy, the soft-switching design of the device can be realized to improve efficiency.

The topology can also be reconstructed based on different multi-level connection methods. For the quadric converter with the better gain effect, a single switch design is adopted in, but the hard conduction problem of the switch is serious. The quadratic Boost converter uses a single-switch integrated Cuk structure to improve the gain further, but it still does not solve the problem of hard turn-on of the switch and the input current ripple is large. The quadric converter is controlled by the same frequency dual switches¹⁹, based on the quasi-resonance principle, which reduces the turn-off current of the switches and realizes the ZCS of the diodes. The quadratic converter with interleaved three-switch control integrates a gain expansion unit with a floating capacitor to achieve a higher fourth-power gain.



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III. METHODS

The proposed high-step-up DC–DC converter depicted in contains a VMC composed of the winding N_s of the coupled inductor associated with the pairs D_2/C_2 and D_3/C_3 . Since this topology is able to impose high voltage levels on the capacitors, adopting a number of turns ratio close to one is possible without the need for overly high values of duty cycle. The steady-state analysis of the proposed converter is carried out for deriving a mathematical model that allows the proper choice of every component contained in the circuit. In this sense, the following assumptions are made: During the second and third stages, which correspond to the intervals Δt_2 and Δt_3 , respectively, switch S is turned on, the magnetizing inductance L_m stores energy, and capacitors C_2 and C_3 provide energy that has been stored during the previous stages to the system. These intervals are characterized as linear stages, since resonance between the leakage inductance L_k and the capacitors contained in the circuit is not expressive. This operational condition is finished when S is turned off.

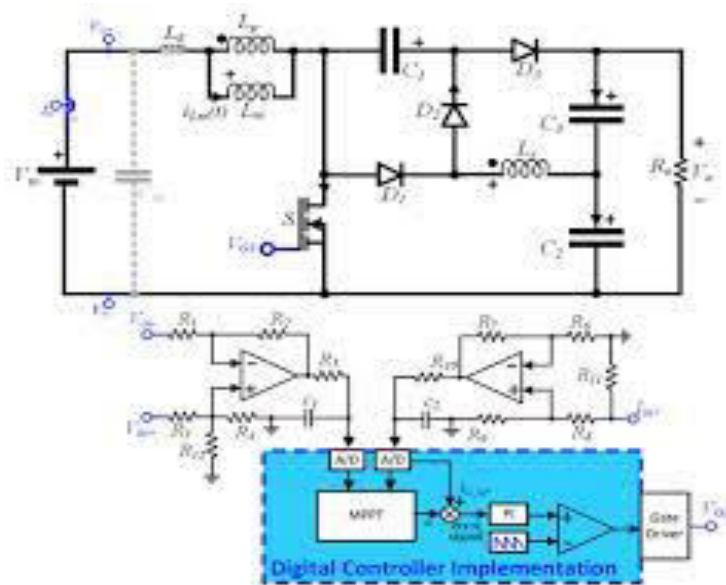


Fig 2: Quasi-Resonant Single-Switch High-Voltage-Gain DC-DC Converter

The fifth and sixth stages, defined by the intervals Δt_5 and Δt_6 , occur when S remains in the off state. During these stages, energy stored in L_m is provided to the circuit. Resonance between L_k , C_1 and C_3 becomes expressive during the fifth stage. In this sense, if it is guaranteed that the resonant frequency is higher than the switching frequency, D_2 operates with ZCS, thus contributing to increasing the system efficiency. It is noteworthy that the fifth stage plays a crucial role in defining the voltage gain of the converter. Regarding the sixth stage, the converter returns to a linear operating characteristic. As a consequence, if the same duty cycle is adopted, a higher number of turns ratio is required to reach the same voltage gain, and therefore weight and cost of the coupled inductor are also increased. It is also noteworthy that the snubber required for proper operation increases the losses of the circuit, which has an impact on the overall system efficiency. The converters proposed in present similar constructive and operational characteristics. The highest efficiencies are verified in the proposed converter and in the circuit introduced in. However, the proposed converter has a higher voltage gain and was tested with a higher switching frequency

Based on the Buck/Boost topology, this paper proposes a high-gain dual-coupled inductor interleaved quadratic converter and realizes a quasi-resonant soft switching design. Its working principle and performance indicators were analyzed in detail, and a 400 W prototype was built for experimental verification. The proposed topology combines the advantages of the interleaved and quadratic types and also introduces other technologies such as coupled inductance and quasi-resonant ZCS soft switching. The converter has good overall performance, achieving a balance between high gain and high efficiency, and is suitable for various applications such as distributed photovoltaic power generation systems. Has the following advantages: (a) The interleaved of the input realizes the quadratic voltage boost effect; (b) A dual coupling structure is introduced to flexibly control the voltage boost by adjusting the turn ratio n . The interleaved input cooperates with double coupling to reduce the current ripple when the input current is continuous; (c) Flexible utilizes multiple groups of D-C branches as clamps for switches to control voltage stress; absorb leakage



inductance energy to achieve soft-switching of the device; together with the secondary side connected in reverse series, forming the voltage multiplier cell; (d) Using the quasi-resonant circuit to reduce the turn-off current of the corresponding switch while realizing ZCS, effectively reduces the instantaneous impact and the loss of the device; (e) Based on the cooperation of the quasi-resonant circuit and the D-C branch, the leakage inductance energy is fully utilized to suppress the voltage and current surges in the circuit, further alleviating the reverse recovery problem of the diode; (f) Through the coordination of devices, the performance can be effectively improved, the number of devices can be controlled, and the size of the equipment can be reduced. Sum, high voltage gain, adapting to a wide input voltage range; high efficiency, using advanced topology to improve energy conversion efficiency; suitable for space-constrained scenarios. These characteristics make it a key component in new energy, the Internet of Things, automotive electronics, medical equipment, etc.

IV. RESULT ANALYSIS

As known, PV and FC systems require a proper control system to ensure maximum power point tracking (MPPT) operation. In such a system, the DC–DC converter stage is directly responsible for MPPT realization by means of controlling the input voltage or current. In this paper, a control strategy aiming at controlling the input current is adopted, in accordance with the schematic depicted in. In the proposed scheme, input voltage and current are measured using the digital signal processor TMS320F28377S, in which an input current compensator is implemented. First-order filters with a cutoff frequency of 1 kHz are used for signal conditioning and analog-to-digital conversion is performed with a sampling frequency equal to 100 kHz. In this work, a proportional–integral (PI) controller with proportional and integral gains of 0.005 and 15, respectively, is used to adjust the input current, which in turn allows MPPT to be realized. It is noteworthy that the small-signal analysis of the proposed circuit is very extensive due to the high number of operating stages and quasi-resonant operation, and therefore it will not be detailed in this paper. Nevertheless, closed-loop operation will be investigated to demonstrate the suitability of the proposed converter for PV and FC applications.

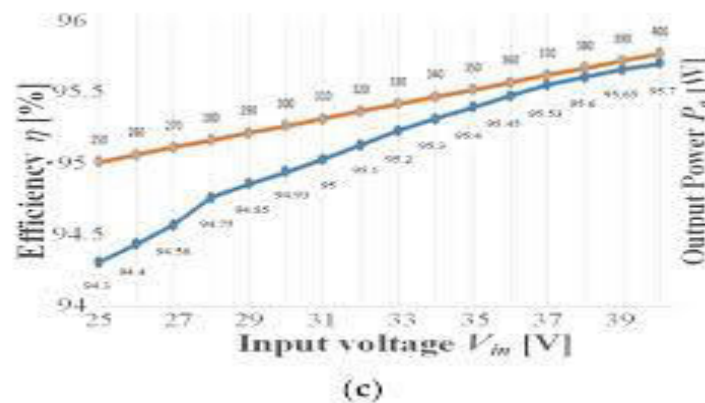


Fig 3: Quasi-Resonant Single-Switch High-Voltage-Gain DC-DC Converter with Coupled Inductor

The proposed converter is compared with the high-voltage-gain topologies proposed in, as summarized in Table 3. In this comparative analysis, only circuits containing a single active switch and one coupled inductor with two windings are considered. In addition, it is assumed that the leakage inductance of the coupled inductor is much smaller than its magnetizing inductance. As can be concluded from Table 3, both the voltage gain M and the voltage stresses on the semiconductors are usually related to the number of diodes and capacitors contained in the circuits. The circuits proposed in contain only two diodes and two capacitors, although in the voltage stress on the switch and on the diode D2 is equal to the entire output voltage level. As a result, higher conduction and switching losses are expected. The converters introduced in exhibit the higher voltage gains, but more diodes and capacitors are employed. The boost-flyback converter proposed in presents the lower voltage conversion ratio, and also requires the use of an auxiliary snubber to prevent potentially destructive voltage spikes on D3.

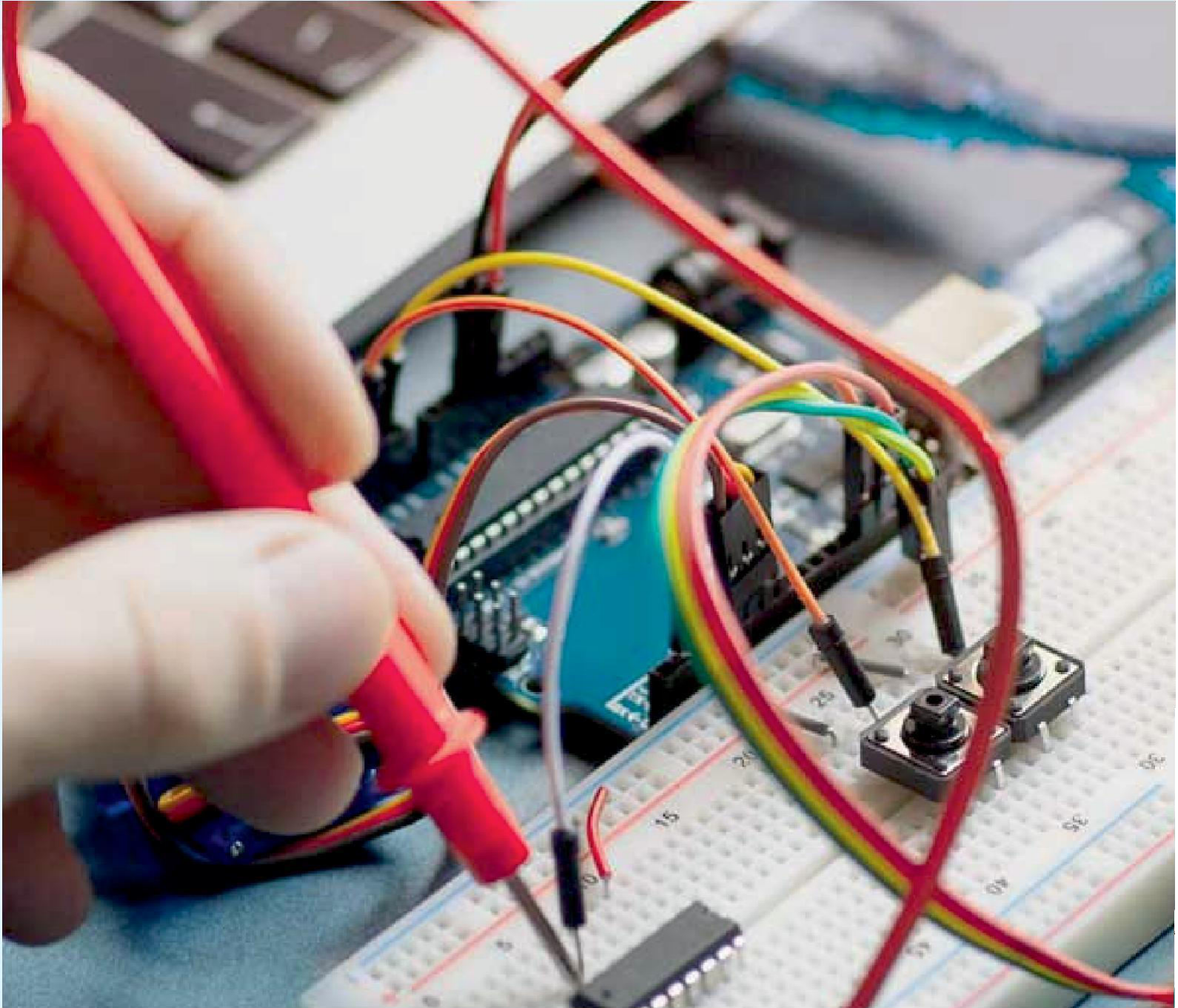


V. CONCLUSION

A novel high-step-up DC–DC converter based on the boost converter employing one coupled inductor and voltage multiplier cells was proposed in this paper. The circuit contains a single active switch, three diodes and three capacitors, and is capable of achieving a high conversion ratio even when a low number of turns ratio is adopted. It was demonstrated that using a low number of turns ratio minimizes the influence of the leakage inductance on the voltage gain. In addition, the resonant characteristic of the circuit provides ZCS operation for two of its diodes, thus reducing the switching losses and improving the system efficiency. A detailed efficiency analysis was performed in the laboratory, and the results demonstrate that the proposed converter is a viable solution for applications with a power rating on the order of a few hundred watts, since it is capable of providing high voltage gain with a reduced number of component

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