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Recent Advances High Gain DC-DC Boost Converter Topologies

Shahadev Pal[1] and Prof. Madhu Upadhyay[2]
Department of Electrical and Electronic Engineering[1,2]
NRI Institute of Information Science and Technology, Bhopal, India,
devshahaeee@gmail.com

Abstract*: With the shortage of the energy and ever increasing of the oil price, research on the renewable and green energy sources, especially the solar arrays and the fuel cells, becomes more and more important. How to achieve high step-up and high efficiency DC/DC converters is the major consideration in the renewable grid-connected power applications due to the low voltage of PV arrays and fuel cells. The topology study with high step-up conversion is concentrated and most topologies recently proposed in these applications are covered and classified. The advantages and disadvantages of these converters are discussed and the major challenges of high step-up converters in renewable energy applications are summarized. This paper would like to make a clear picture on the general law and framework for the next generation non-isolated high step-up DC/DC converters.*

Keywords: Coupled Inductors (CL), Double Dual Boost (DDB), Voltage Source Inverter (VSI), Three Winding Coupled-Inductor (TWCI), etc..

I. INTRODUCTION

The use of renewable sources as a suitable alternative for producing electric energy has been currently encouraged due to the pollution containment policies worldwide [1]-[3]. Among these renewable sources, photovoltaic and wind are cited as the most promising [4], however, unfortunately, the low output voltages they provide do not comply with the requirements for grid-connection [5]. In this scenario, the development of efficient topologies to provide high output voltages from low voltage input sources is an essential step toward to the integration of photovoltaic and wind energy to the conventional electric grid. For this purpose, the literature presents several techniques to derive high gain step-up dc-dc converters, usually classified as isolated or non-isolated structures [6]. In isolated topologies, the voltage gain can be easily lifted by the increase of the turn ratio of the transformer [7], nevertheless, the power switches of these structures may be subjected to voltage spikes, due the leakage inductances [8]. In order to mitigate this drawback, passive or active clamping circuits are inserted in the converters, which can deteriorate the efficiency and raise the complexity [7]. The non-isolated topologies are commonly derived from the usage of different techniques applied to increase the static gain of basic converters (boost, buck-boost, Ćuk, zeta, SEPIC) [9]- [11], such as: switched-inductors (SL) [12]-[14], switched capacitors (SC) [10], [15]-[17], coupled inductors (CL) [18]- [20], cascaded and stacked connections [21] or a combination of them [22]. When compared, all the cited techniques present advantages and disadvantages. For example, while the power switches of converters based on switched-inductors or coupled inductors can also be subjected to voltages spikes, as in the isolated topologies, the power switches of switched-capacitor converters, which require large number of storage elements, must be oversized due to the high peaks of current. In addition, the efficiency of cascaded- or stacked-based converters may be degraded by high number of components (including power switches) they need [22]. In a recent work [9], the authors classified the dc-dc converters accordingly with the principle applied to provide the high static gain and give to the reader’s important insights concerning the voltage lifting techniques. Nevertheless, [9] does not mention the possibility of connecting basic dc-dc converters to derive high gain step-up dc-dc converters, topic explored in the present paper. The use of the differential connection between converters to generate novel topologies is not new and has been studied in the literature over time. The conventional voltage source inverter (VSI), for example, can be understood as the differential connection of two dc-dc buck converters. When their voltages are subtracted due to the differential connection, the dc components are cancelled, thus, a pure sinusoidal ac component is provided the inverter output [23]-[25]. Another example, now for dc-dc converters, is the double dual boost (DDB) converter [26]-[27], which can be derived from the differential connection between a conventional boost converter and its mirrored version (also known in the literature as floating output boost [28]-[29]). As will be demonstrated, the proposed methodology can be classified as new voltage lifting technique able to be applied to any group of two converters with the same output voltage polarity (positive or negative) and with common reference between both, input and output voltages. This method can be employed for synthesizing new and already known high gain step-up dc-dc converters. Besides this introduction, section II describes the proposed concept and the general characteristics of the converters generated from it. Section III details the derived topologies, while the experimental results are evaluated in section IV. The main conclusions are drawn in section V.

Hasanpour, Sara, et al.(2021) - In this article, a new nonisolated full soft-switching step-up dc/dc converter is introduced with a continuous input current for renewable energy applications. The use of a three-winding coupled inductor (TWCI) along with a voltage multiplier, enables the proposed converter to enhance the voltage gain with lower turns ratios and duty cycles. Also, a lossless regenerative passive clamp circuit is employed to limit the voltage stress across the power switch. In addition to zero current switching performance at the turn-on instant of the power switch, the turn-off current value is also alleviated by adopting a quasi-resonance operation between the leakage inductor of the TWCI and middle capacitors. Moreover, the current of all diodes reaches zero with a slow slew rate, which leads to the elimination of the reverse recovery problem in the converter. Soft-switching of the power switch and all the diodes in the proposed converter significantly reduces the switching power dissipations. Therefore, the presented converter can provide a high voltage gain ratio with high efficiency. Steady-state analysis, comprehensive comparisons with other related converters, and design considerations are discussed in detail. Finally, a 160 W prototype with 200 V output voltage is demonstrated to justify the theoretical analysis[1]. Hasanpour, Sara, et al.(2021) - This article proposes a new configuration of quasi-resonant high-gain high-efficiency single-ended primary inductor converter (QRHGHE-SEPIC)-based dc–dc converter with continuous input current. The presented single-switch topology uses a coupled-inductor (CI), a voltage multiplier integrated with a regenerative passive lossless clamp circuit to enhance the voltage conversion ratio. In the proposed converter, the main power switch turns on at zero current switching. Moreover, by adopting a quasi-resonance (QR) operation between the leakage inductor of the CI and the middle capacitors, the current value of the main switch at turn- off moment is alleviated. In addition, the leakage inductance slows down the turn- off slope of all diodes and hence there is no reverse recovery problem in the proposed converter. Due to soft-switching operation in all switching components, the power dissipations in the converter are significantly alleviated. Thus, the proposed QRHGHESEPIC can provide high voltage gain while achieving a high efficiency. Steady-state analysis, comprehensive comparisons with other related converters, and design considerations are discussed in detail. Finally, to verify the validity of the theoretical analysis, a 160 W/200 V sample prototype is demonstrated at the switching frequency of 60 kHz and with voltage gain of 10[2]. Mahmood, Arshad, et al.(2021) - High gain DCDC converters are increasingly being used in solar PV and other renewable generation systems. Satisfactory SteadyState and dynamic performance, along with higher efficiency, is a pre-requirement for selecting the converter for these applications. In this paper, a non-inverting high gain DC-DC boost converter has been proposed. The proposed converter has only one switch with continuous input current and reduced voltage stress across switching devices. The operating range of the duty cycle is wider, and it obtains a higher gain at a lower value of the duty cycle. Moreover, the converter has higher efficiency at a lower duty cycle while drawing a continuous input current. The continuous input current is a desirable feature of the dc-dc converter making it suitable for solar photovoltaic applications. The converter's operation has been discussed in detail and extended to include the real circuit parameters for a practical performance evaluation. The proposed converter has been compared with other similar recently proposed converters on various performance parameters. The loss analysis for the proposed converter has also been carried out. Finally, the simulation has been validated with results from the experimental prototype [3].

II. DESCRIPTION OF THE QRHGHE-SEPIC MODELING

The equivalent circuit of the proposed QRHGHE-SEPIC is shown in Fig. 1. The converter is composed of a CI with turns ratios of n, a single power switch (S), an input inductor (Lin), four diodes (D1– D3 and Do), and five capacitors (C1–C4 and Co). Series interconnection between the input inductor and input dc voltage source leads to low input current ripple, which improves the RESs performance. Moreover, the maximum voltage rate across the single switch is restrained by a regenerative passive lossless clamp circuit including C2, C3, and D2 as shown in Fig. 1.

Therefore, a switch with low static drain-to-source on resistance (RDS(ON)) can be used, which reduces the conduction power losses. The combination of the secondary side of the CL along with capacitors C2 and C4, and diodes D1, D2, and D3 form a VM to increase the voltage gain in the low turns ratio of the CI. Moreover, the current waveform of the switch and the diode D3 change in sinusoidal form because of a QR operation among the leakage inductance of the CI, C1, C3, and C4. This also helps to reduce the switch turn-off and the reverse recovery losses. To simplify the converter analysis in continues conduction mode (CCM) condition, the following assumptions are considered. 1. All switching components of the converter are ideal without parasitic components. 2. All capacitors are large enough so that their voltages are constant.

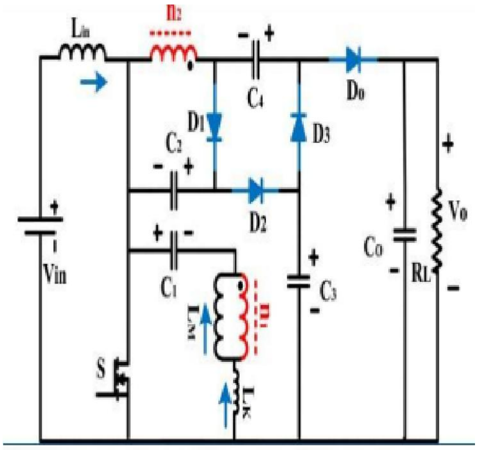

Fig. 1. Proposed QRHGHE-SEPIC-based dc–dc converter

Mode II [t1–t2]: In this time interval, the power switch S along with the diode D1 remain on. The current of the input and magnetizing inductors increase linearly like in Mode I. The capacitor C2 receives energy from the magnetizing inductor. This stage ends when the current of the diode D1 reaches zero at LRR condition. Moreover, at the end of this mode, the energy of the output capacitor Co starts transferring to the output load.

- Mode III [t2–t3]: At time t2, the diode D3 starts conducting at ZVS condition. Thus, a resonance between the leakage inductor Lk and the capacitors C1, C3, and C4 occurs in the form of QR, which discharges the energy of the capacitor C3 into the balancing capacitor C4. With the help of this resonant tank, the current in the switch S, the diode D3, andthe leakage inductance has a sinusoidal shape

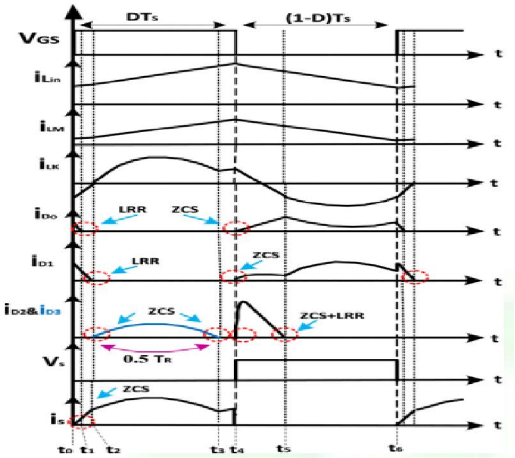

Fig. 2. Typical waveforms of the proposed QRHGHE-SEPIC. (ZCS = zero current switching, LRR = low reverse recovery.)

It is noteworthy that, to eliminate the reverse recovery loss of the diode D3 and decrease the switch turnoff loss, it is necessary that the resonant time (TR) is less than the pulse width of the switch (TR/2≤D×Ts), as shown in Fig. 2. Same as the previous modes, the input and the magnetizing inductors receive energy from the input source and capacitor C1, respectively. Mode V [t4–t5]: At time t = t4, single power switch S is turned off and the clamp diode D2 is forward biased as shown in Fig. 3(e). Therefore, the voltage rate across the single power switch is restricted by capacitors C2 and C3. Moreover, in this stage, the output diode Do along with diode D1 start to conduct. Owing to the existence of the leakage inductor, the current of the diodes Do and D1 increase slowly under ZCS condition. Moreover, the capacitor C2 receives energy from the magnetizing inductor. Furthermore, the clamp capacitor C3 begins to charge from the input inductor current until the current of the D2 reaches zero. Also, the capacitor C4, the magnetizing inductor of CL, and the input inductor transfer their energy to the output capacitor.

III. DERIVATION OF DC-DC CONVERTERS

For formalizing the methodology that allows deriving high step-up dc-dc converters from differential connections, it is necessary to classify the topologies accordingly with the polarity of the output voltage regarding the input voltage. This classification results in two groups: the positive group includes the converters that the input and the output voltages present the same polarity (e.g. buck, boost, SEPIC and zeta) while the negative group includes the converters in which the input and output voltages are inverted (e.g. buck-boost and Ćuk). The premises to implement the proposed methodology requires: (i) the selection of two converters from the same group (converters that provide either positive or negative voltages); (ii) the selected converters have to present common reference between the input and output voltages; (iii) one of the converters must be drawn on its conventional form [see Fig. 3 (a)] while the another must be mirrored, as exemplified in Fig. (1) (b), (iv) the load is differentially connected between the outputs of the selected converters, as detailed in Fig. 2, and (v) both inverters are fed by the same input voltage (Vin). The mirrored boost in Fig.3 (b) is also named in the literature as floating boost output [28]-[29]. In addition, the resulted topology from differential connection of two boost is already known in the literature either as floating-output double-boost converter [28]-[29] or DDB [26], [27]. Although Fig. 3 has applied the connection of a conventional boost and a mirrored boost converter, a generalized representation (for any other topologies) is seen in Fig. 3. In additional, the two selected converters may be either equal (for instance: two boost) or different (for instance: a boost and a mirrored buck-boost), and they can use different kinds of gain cells.

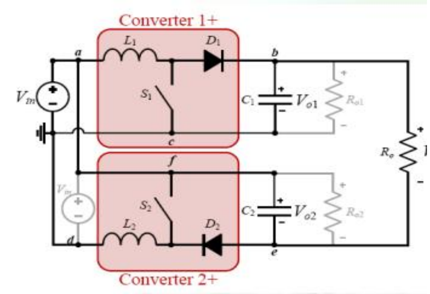

Fig. 3 (a) Conventional boost and (b) mirrored boost.

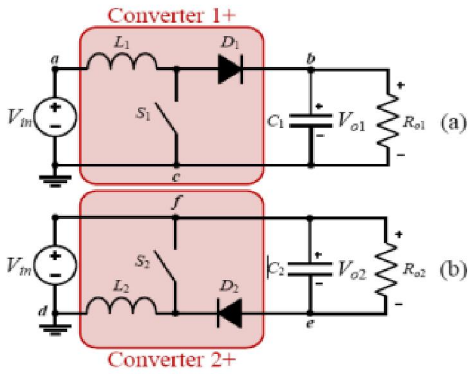

Fig. 4. Boost + mirrored boost + differential load connection

For convenience, the converter drawn on its conventional form is herein named as Converter 1 and its mirrored version as Converter 2. Hence, (a) shows converters of the positive group and (b) depicts converters of the negative group, both using the differential connection. Conversely, in the negative group, the Converters 1 and 2 process less power than the load requires (partial power processing), since the power generated by the input voltage is directly delivered to the load.

3.1 Converters based on the Differential Connections

The converters based on the differential connections may be generated in accordance with the following criteria: 1) Converter 1 equal to Converter 2; 2) Converter 1 different to Converter 2; 3) Converter 1 and Converter 2 with the same input and/or output type (current or voltage); 4) Converter 1 and Converter 2 with the different input and/or output type (current or voltage). possible connections among basic converters, following the items from 1 to 4 early cited. illustrate the connection between two equal converters: boost with mirrored boost and Ćuk with mirrored Ćuk. The differential connection of two converters with same input and output types is illustrated depict the connection of two converters with different input and output types.

3.2 Modulation applied to Differential Converters

In general, the modulation strategy applied to differential converters can be developed considering both converters operate with equal or different duty cycles. In the first case, there is no possible to ensure that both converters will deliver the same amount of power (50%) to the load, while in the second case, this condition can be assumed as truth. C. Practical Considerations Regarding the Voltage Control Fig. 3 (a) Conventional boost and (b) mirrored boost. Fig. 4. Boost + mirrored boost + differential load connection. A. Converters based on the differential connections The converters based on the differential connections may be generated in accordance with the following criteria: 1) Converter 1 equal to Converter 2; 2) Converter 1 different to Converter 2; 3) Converter 1 and Converter 2 with the same input and/or output type (current or voltage); 4) Converter 1 and Converter 2 with the different input and/or output type (current or voltage). possible connections among basic converters, following the items from 1 to 4 early cited. illustrate the connection between two equal converters: boost with mirrored boost and Ćuk with mirrored Ćuk. The differential connection of two converters with same input and output types is illustrated depict the connection of two converters with different input and output types. B. Modulation applied to differential converters The control of the differential voltage can be achieved in three ways, depending on the employed modulation strategy, as show Fig.5, When the duty cycles are equal (D1 = D2), independently of the phase (φ) between the triangular carriers, the three control strategies can be applied. On the other hand, when the duty cycles are unequal (D1 ≠ D2), only the strategies described by can be employed.

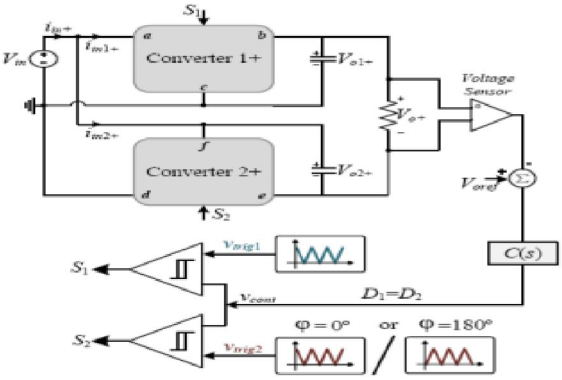

Fig. 5 Control strategy considering D1 = D2 and φ = 0º or φ = 180º.

The first control alternative is directly controlling the differential output voltage of the converter (Fig. 11). In this case, only a voltage sensor (to measure Vo+) is used. This voltage is compared to a reference (Voref) value and the error signal is applied to the controller C(s). The unique control signal (vcont) is applied to the modulators of both converters (Converters 1+ and 2+) resulting in the duty cycles signals that drive the switches. In this control strategy, the intermediary voltages Vo1+ and Vo2+ may fluctuate, as long as their sum is equal to voltage Vo+, thus the power division between the converters cannot be assured.

Integration of gain cells When ultra-high static gains are required, it is possible to integrate gain cells in the differential converters to further increase their output voltages. Figure 10 depicts how the gain cells can be inserted considering the differential converters in their reduced forms (D1=D2Figure 6 (a) illustrates a differential connection of a traditional boost and a mirrored boost version, both integrated with a switched-capacitor (SC) cell. Using D1 = D2, the components reduction can be applied, as seen in Fig. 6 (a). We highlight that the component reduction causes voltage spikes on the switches, however, these peaks already will occur in this structure due to the ASL cell placed on the entrance. In other words, regardless of the reduction or not of the SC cell, techniques to decrease voltage spikes are already inevitable in this structure. The component reduction technique promotes the same static gain, and it can decrease the weight, size and number of components and, consequently, increases the efficiency. Thus, this is a case in which the advantages related to the components reduction may overcome the drawbacks of using D1 = D2

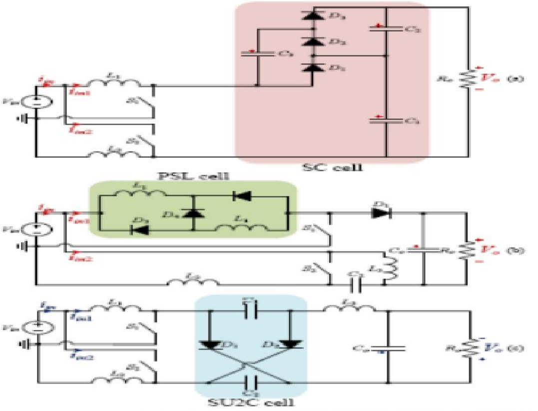

Fig.6 Differential converters with gain cells: (a) boost with mirrored boost and SC cell

V. CONCLUSIONS AND FUTURE WORK

A The limitations of the conventional boost converter in high step-up renewable energy applications are analysed and a lot of topologies, which are published in previous papers, are summarized and classified. From the above analysis, the major challenges in high step-up DC/DC converters are the following: 1. How to extend the voltage gain and avoid the extreme duty cycle to reduce the current ripple and the conduction losses; 2. How to reduce the switch voltage to make low voltage MOSFETs available; 3. How to realize soft switching performance to reduce the switching losses; 4. How to alleviate the output diode reverse recovery problem; 5. How to increase the power level easily and reduce the passive component size. The conceptual solution for high step-up conversion is proposed and some topologies satisfied the major challenges in high step-up DC/DC converters are given. A clear picture on the general law and framework for the next generation non-isolated high step-up DC/DC converters is made in this paper.

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