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Experimental verification of an improved soft-switching cascade boost converter

Naci Genc*, Yavuz Koc

Yuzuncu Yil University, Engineering and Architecture Faculty, Electrical and Electronics Engineering Department, Zeve Kampusu, 65080 Van, Turkey

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ABSTRACT

A soft switching cascade DC–DC boost converter is proposed in this paper. The proposed cascade single-switch converter has a higher step-up voltage gain and a wider turn-of period compared to classical boost converters, which tend to have a problem of narrow turn-of periods at higher output voltages. To reduce the switching losses, an auxiliary circuit was also added to the converter. It has a simple structure with only one main switch, one auxiliary switch and the minimum number of diodes. The proposed soft switching method enables the main switch to turn on at zero-voltage-transition (ZVT) and turn off at zero-voltage-switching (ZVS). Furthermore, the auxiliary switch and diodes are soft-switched thanks to this method. All semiconductor components operate under soft-switching, safe from any additional voltage and current stresses. The study presents the design considerations for the proposed converter, along with principle operations of the topology in a single switching period. Finally, experimental results, which were obtained on a laboratory prototype rated at 300 W, are also presented in the paper. The results show that the proposed cascade boost converter can be operated successfully in soft-switching operation for a variety of input voltages and a relatively wider load range, even at higher voltage outputs.

1. Introduction

There are many industrial applications where DC–DC converters require high step-up voltage gain, like in the auxiliary power supplies for cars, uninterruptible power supplies (UPS) for computers, portable electronic devices, and renewable energy systems [1–3]. Furthermore, non-conventional and renewable energy sources, like photovoltaic (PV) panels and fuel cells (FC), generally require a high step-up converter due to their low DC output voltages. A conventional boost converter cannot provide such high voltage gains because of the narrow duty cycle available to them. Boost converters with higher voltage gains can theoretically be realized with an extreme duty-cycle design and application. Such high voltage gains, however are hard to achieve for many reasons, like the voltage stress on the power switches, large current ripples of inductance, conduction losses, reverse recovery problem of diodes, and electromagnetic interference (EMI) noise phenomenon [4,5].

Many boost type converters — like cascade, quadratic, coupled-inductor, multilevel and multiple-phase types- have been proposed in literature to obtain higher voltage gains. Although a relatively higher step-up voltage gain can be achieved via these types of converters, they all seemingly come with drawbacks that hinder their feasibility. For instance, while the higher step-up voltage gains can be obtained by using a two-stage structure of "cascade and quadratic boost topology" proposed in Refs. [6–8], these structures cause a significantly lower efficiency and a lot more complexity in the system. Another disadvantage of these topologies is the reverse recovery loss of the output diode. Coupled-inductor type converters have been proposed to obtain the higher step-up voltage gains in Refs. [9–11], but higher voltage stress due to induced energy leakage and EMI are the main problems for these topologies. Multilevel DC–DC converter [12] and multi-phase boost converter types [13] have also been proposed for industrial applications where the higher voltage gain is needed. The circuit complexity is the main drawback of these type converters.

The switching losses of the power devices are also still a disadvantage for the DC–DC boost converter structures discussed in literature. Hard switching PWM converters are generally operated with higher switching frequencies in order to obtain higher

Abbreviations: DC, direct current; ZVT, zero voltage transition; ZVS, zero voltage switching; ZCS, zero current switching; UPS, uninterruptible power supply; PV, photovoltaic; FC, fuel cell; EMI, electromagnetic interference; PWM, pulse width modulation; CCM, continuous conduction mode; DSP, digital signal processing; PI, proportional-integral.

* Corresponding author.
E-mail addresses: nacigenc@yyu.edu.tr, nacigenc@yahoo.com (N. Genc), yavuzkoc@yyu.edu.tr (Y. Koc).

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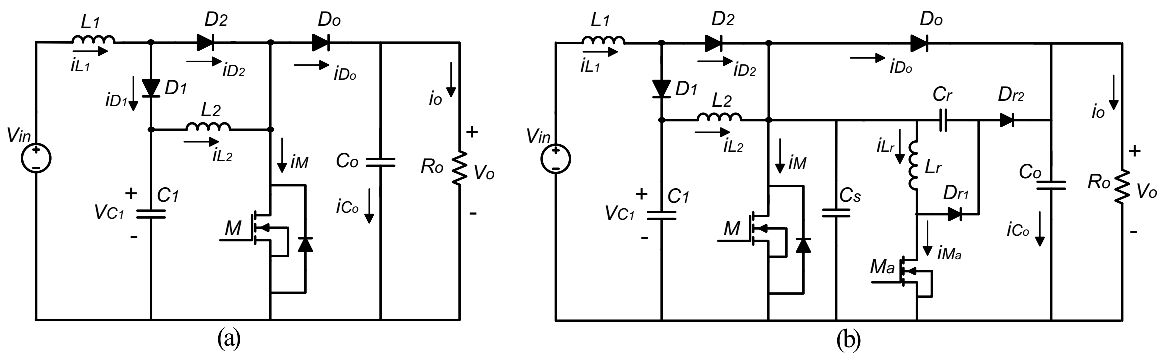

Fig. 1. Circuit topologies of; (a) cascade boost converter, (b) proposed ZVT cascade boost converter.

power densities and faster transient responses. This, however, causes increased switching losses and higher EMI noise. Since the switching losses of boost converters increase power dissipation, the efficiency and power density of a converter improves when switching losses are reduced. Passive and active snubbers for soft-switching techniques are generally used to reduce switching losses and voltage/current stresses, particularly in high voltage and current stress levels. Since the passive snubbers do not need any additional active switches, the driver circuits of the converters with passive snubbers are relatively simple in design. They are bulky, however, and have relatively higher voltage stresses on switches. Even though the design on Ref. [14] improves the converter efficiency, the power switch in it has a large current stress, and the main diode has a large voltage stress. In addition, the inductor used in the auxiliary circuit of this topology is large and needs a bulky circuit. Active snubber approaches presented in the literature improve the converter efficiency. Yet still, many of the active snubbers used for soft-switching have some drawbacks. While the topology with an active snubber approach proposed in Ref. [15] has a main switch which operates in ZVS without any additional current and voltage stress, the auxiliary switch used in this converter operates under hard switching condition which causes higher levels of EMI noise and lower overall efficiency. Both main and auxiliary switches used in the circuit proposed in Ref. [16] are soft switches, yet the auxiliary switch has large amounts of current stress. Although there are many studies with an active-snubber approach in DC–DC boost converters [17–22], the number of studies which use active snubber circuit for cascade boost topology is very few in the literature [23,24]. The topology presented in Ref. [23] was not verified with an experimental study. The auxiliary switch of the cascade topology introduced in Ref. [24] does not have a common mode with the main switch, which causes complexity on the driving circuit. Main and auxiliary switches of the cascade topology introduced in Ref. [25] operate under ZVS. These switches, however, do not have a common drain point. This causes the need for a complex driver circuit to operate the switches.

With all these in mind, an active-snubber based soft-switching cascade boost converter with a high voltage conversion ratio is proposed in this paper. Only one main switch was used in this converter in order to achieve a high-voltage gain for the cascading operation. In addition, an active snubber cell was inserted to the converter to provide the zero voltage transition (ZVT) for the main switch. Furthermore, the auxiliary switch and the output diode of the topology were designed to operate with soft-switching. The study also presents a steady-state analysis, detailed information on operational principles, and design considerations of the proposed cascade boost converter. Finally, a laboratory prototype of the proposed design with a 50 kHz switching frequency, 300 W rated power output, and 300 V of voltage output for the 30–50 V input voltage range was tested to demonstrate the topology performance.

2. Analysis of the circuit operation

The study presents an active-snubber based soft-switching cascade boost converter (Fig. 1b). The converter is composed of a single-switch cascade boost conversion unit (Fig. 1a) and an active auxiliary circuit unit. The proposed circuit components L_1, D_1, D_2, C_1 and M displayed in Fig. 1a are used to create a boost converter unit, while the second unit houses the circuit components C_1, L_2, M, D_3 and C_o. The voltage conversion ratio is $V_o/V_{in} = 1/(1-d)$ for each boost converter stage, where V_{in} is the input voltage, V_o is the output voltage and d is duty cycle of the converter. As a result, total voltage conversion ratio becomes $V_o/V_{in} = 1/(1-d)^2$ for the cascade boost converter. When a turn on signal is sent to power switch M of the cascade boost converter, D_2 will be in "on" state, and D_1 and D_o will be in "off" state. The currents through L_1 *and* L_2 increase linearly and the voltage on C_1 *and* C_o decreases. During the on-time interval dT_s, related currents and voltage equations can be expressed as;

$$\frac{\Delta i_{L_1}}{\Delta t} = \frac{I_{L_1,\max} - I_{L_1,\min}}{d \cdot T_s} = \frac{V_{in}}{L_1} \tag{1}$$

$$\frac{\Delta i_{L_2}}{\Delta t} = \frac{I_{L_2,\max} - I_{L_2,\min}}{d \cdot T_s} = \frac{V_{C_1}}{L_2} \tag{2}$$

where, T_s is switching period and d is duty cycle of the converter.

When a turn off signal is sent to power switch M of the cascade boost converter, D_1 and D_o will be in "on" state and D_2 be in "off" state. The currents through L_1 *and* L_2 decrease linearly and the voltages on C_1 and C_o increase at the same duration. During the off-time interval $(1-d)T_s$, related currents and voltage equations can be expressed as;

$$\frac{\Delta i_{L_1}}{\Delta t} = \frac{I_{L_1,\min} - I_{L_1,\max}}{(1-d) \cdot T_s} = \frac{V_{in} - V_{C_1}}{L_1} \tag{3}$$

$$\frac{\Delta i_{L_2}}{\Delta t} = \frac{I_{L_2,\max} - I_{L_2,\min}}{(1-d) \cdot T_s} = \frac{V_{C_1} - V_o}{L_2} \tag{4}$$

The relation between voltage of the capacitor C_1 and input voltage V_{in} can be expressed as Eq. (5) by using Eqs. (1) and (3). In addition, the relation between voltage of the capacitor C_1 and output voltage V_o can be expressed as Eq. (6) by using Eqs. (2) and (4).

$$V_{C_1} = \frac{V_{in}}{(1-d)} \tag{5}$$

$$V_o = \frac{V_{C_1}}{(1-d)} \tag{6}$$