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고전압비와 낮은 전압 스트레스를 가진 단일 스위치와 전압 체배 회로를 이용한 새로운 비절연형 DC-DC 컨버터

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A Novel Non-Isolated DC-DC Converter using Single Switch and Voltage Multipliers with High Step-Up Voltage Gain and Low Voltage Stress Characteristics

Tran Manh Tuan[1], Saghir Amin[1], and Woojin Choi†

Abstract

High voltage gain converters are essential for distributed power generation systems with renewable energy sources, such as fuel cells and solar cells, because of their low voltage characteristics. This paper introduces a novel nonisolated DC-DC converter topology developed by combining an inverting buck-boost converter and voltage multipliers. In the proposed converter, the input voltage is connected in series with the output, and the majority of the input power is directly delivered to the load. The voltage multipliers are stacked in series to achieve high step-up voltage gain. The voltage stress across all of the switches and capacitors can be significantly reduced. As a result, the switches with low voltage ratings can be used to achieve high efficiency and low cost. To verify the validity of the proposed topology, a 360-W prototype converter is built to obtain the experimental results.

Key words: High voltage gain, High efficiency, IBB(Inverting Buck-Boost) converter, Low voltage stress, VM(Voltage Multipliers)

1. Introduction

In recent days, the renewable energy sources are becoming an essential part of modern society and are progressively dropping the dependence on fossil fuels. It is well known that the fossil fuels will be depleted in the near future and the need for the grid infrastructure powered by renewables is increasing [1],[2]. Since the outputs of the renewable energy sources such as fuel cells and solar cells are DCs and low in voltage, typically two stage power conversion is required to produce the AC power with a suitable voltage level. Therefore, the use of a high voltage gain DC-DC converter to step up the low voltage of the renewable source is essential to provide a suitable DC link voltage for the rear-end DC-AC inverter [3],[4]. For example, in a two-stage single-phase DC-AC system, the DC link voltage required for the grid-connected inverter is as high as 380V DC when the RMS (Root Mean Square) output voltage is AC 220V. However, since the output voltage of a photo voltaic module or a fuel cell stack with a small power rating (less than 300W) ranges from 25 to 45 V, typically 1:10 voltage gain is required for the front-end DC-DC converter. One simply way to cope with this issue can be the use of an isolated DC-DC converter topology but it would not be a good option for the small power system of which volume and cost are critical factors. The classical non-isolated DC-DC converter such as the non-isolated boost converter

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can be a candidate for those applications. However, its gain is limited to a certain value due to the parasitic component of the inductor. Since the duty cycle approaches to unity as the voltage gain is increased, the current ripple of the inductor and the turn-off current of the power device become large, resulting in large conduction losses and switching losses. In order to overcome the limited voltage gain of the non-isolated boost converter several topologies with coupled inductors are introduced. However, the additional snubber circuits are essential to absorb the energy stored in the leakage inductor which causes the voltage spike on the active switch voltage. Therefore, the system becomes complex and expensive[3]. Other methods to get the high voltage gain with no magnetic coupling include the converters utilizing the switched-capacitors (SCs) and the voltage multipliers (VMs). Though the converters with SCs can achieve high gain it has pulsating input current and poor regulation. To cope with above mentioned problems, many kinds of different non-isolated high boost topologies have been developed by employing SCs or VMs. Though the voltage gain and the voltage regulation characteristics are dramatically improved[4]-[7], it has disadvantages in terms of efficiency, complexity, component stresses, and discontinuous current, which requires further improvements.

In this paper a novel non-isolated high step-up Inverting Buck-Boost (IBB) converter with voltage multipliers is proposed as shown in Fig.1. The proposed converter can be derived by connecting the positive and negative voltage multiplier (Fig. 2(b) and (c)) at the top and bottom of the IBB converter (Fig. 2(a)), respectively. As shown in Fig. 2(b) and (c), the output voltage of the proposed converter can be multiplied by connecting the voltage multiplier to the IBB converter represented by the square wave source (Vosc1 and Vosc2) either in positive or negative way. The output of the proposed IBB converter is connected in series with the capacitors of the voltage multipliers, thereby achieving a high step-up voltage gain. In addition, the voltage stresses of all semiconductor devices and capacitors can be reduced. It is also advantageous in that its power conversion efficiency can be improved since the majority of the input power is delivered directly to the load.

The resulting continuous input current characteristics can be considered as an additional advantage of the proposed converter. In order to achieve the even higher voltage gain, the proposed converter can be easily expanded by employing more VMs at the top and bottom of the output of the IBB.

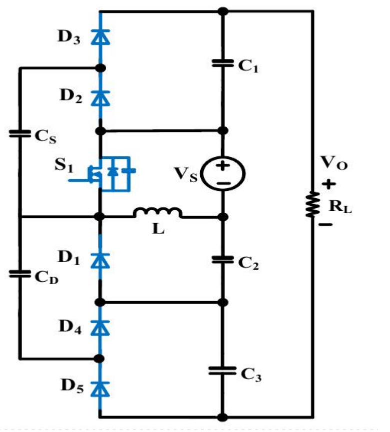

Fig. 1. Proposed high step-up boost converter.

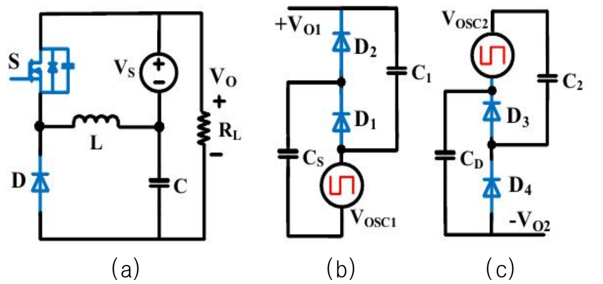

Fig. 2. (a) Proposed IBB converter, (b) Positive voltage multiplier, (c) Negative voltage multiplier.

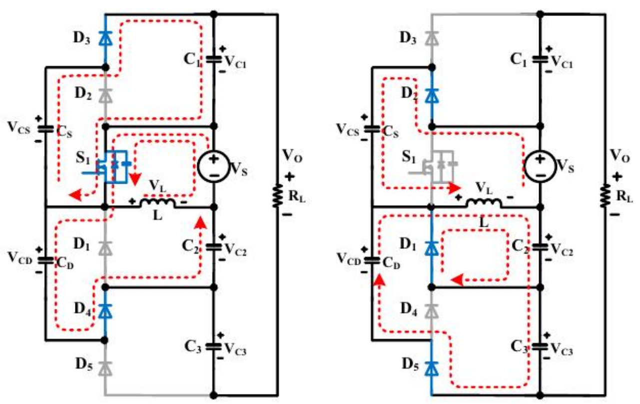

Fig. 3. Operation principle of the proposed non-isolated buck-boost converter.

2. Operating Principle of the Proposed Converter

In this section, the operating principle of the proposed converter in the continuous conduction mode (CCM) is described. As shown in Fig. 3 one

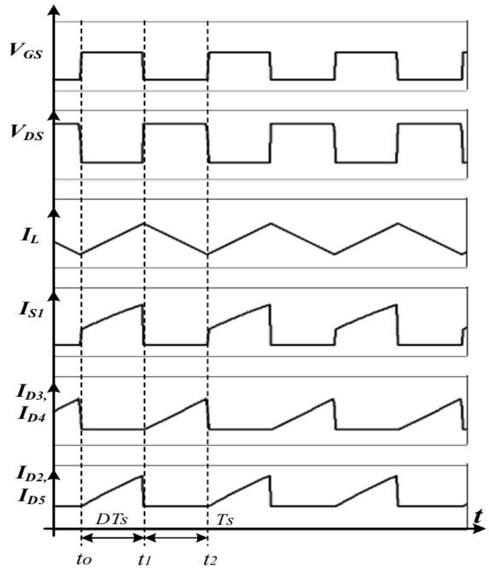

Fig. 4. Key waveforms of the proposed non-isolated buck-boost converter.

switching cycle is divided into two states based on the status of the main switches.

2.1 Switch On-State (Fig. 4: t_0 = 0, t_1 = DT_s)

The circuit operational mode is presented as shown in Fig 3(a). During the switch ON state, the input voltage is applied to the inductor L. Hence, the inductor L is charged, and the current I_L is linearly increased. The diodes D_3 and D_4 are forward biased while D_2, D_1 and D_5 stop conducting. Assuming that all capacitors get fully charged at the steady state and the diode voltage drops are neglected. The following equations can be obtained.

$$V_L = V_S, V_{CS} = V_{C1}, V_L = V_{CD} - V_{C2} \tag{1}$$

2.2 Main Switch Off State (Fig. 4: t_1 = DT_s, t_2 = T_s)

As shown in Fig. 3(b), the switch S_1 is turned OFF, the energy stored in L is discharged linearly. D_2, D_1 and D_5 start to conduct while the diodes D_3 and D_4 are reverse biased. Then the following relationships can be obtained.

$$\begin{aligned} &V_L = -V_{C2} = V_S - V_{CS}, V_{CD} = V_{C3} \\ &V_o = V_{C1} + V_S + V_{C2} + V_{C3} \end{aligned} \tag{2}$$

2.3 Voltage Gain Derivation

In the steady state, according to the voltage-second principle of the inductor L, the average voltage across

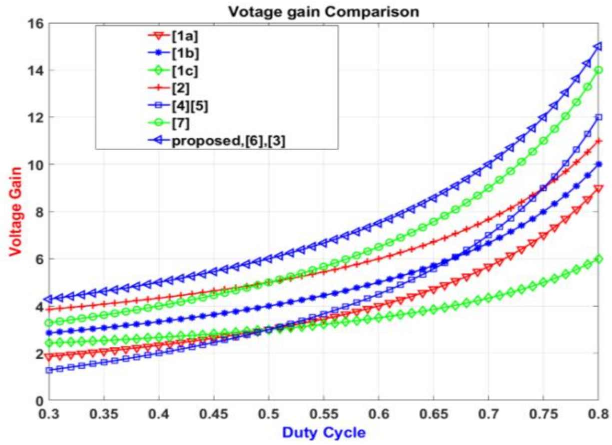

Fig. 5. Voltage gain vs. duty cycle curves of the various kinds of the high voltage gain non-isolated converters.

the inductor in a switching period is zero and the following equations can be obtained from Eqs. (1) and (2).

$$\begin{aligned} &V_L = DV_S - (1-D)V_{C2} = 0 \\ &V_L = DV_S - (1-D)(V_S - V_{CS}) = 0 \\ &V_L = D((V_{CD} - V_{C2}) - (1-D)V_{C2} = 0 \end{aligned} \tag{3}$$

By using the Eqs. (1), (2) and (3), the voltage across the capacitor and the voltage gain of the proposed converter can be derived as Eq. (4).

$$\begin{aligned} &V_{C2} = DV_S/(1-D), V_{C1} = V_{C2} = V_{CD} = V_{C3} = V_S/(1-D) \\ &\frac{V_o}{V_S} = 3/(1-D) \end{aligned} \tag{4}$$

Fig. 5 shows the voltage gain vs. duty cycle plots of the various kinds of high voltage gain non-isolated DC-DC converters. It can be found that the voltage gain of the proposed converter is higher than those of others.

2.4 Voltage Stress of the Components

In proposed converter, it should be noticed that the voltage across the switch and diodes are clamped by the capacitors. Therefore, the low voltage stress for all semiconductor devices and passive components can be achieved. The voltage stress of all the components can be derived as shown in Eqs. (5), (6), and (7).

$$V_{C1} = V_{CS} = V_{CD} = V_{C3} = V_O/3 \tag{5}$$

$$V_{C2} = DV_O/3 \tag{6}$$

$$V_{S1} = V_{D1} = V_{CD} = V_{C3} = V_O/3 \tag{7}$$

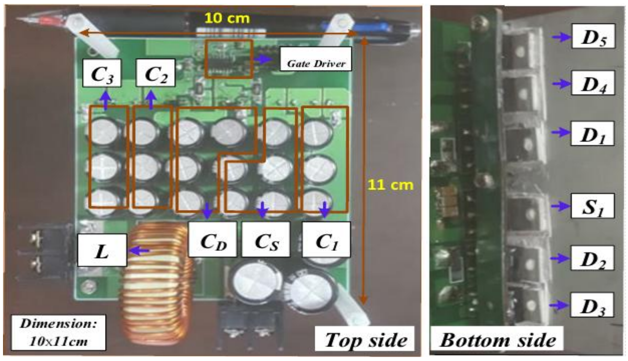

Fig. 6. Prototype of the proposed converter.

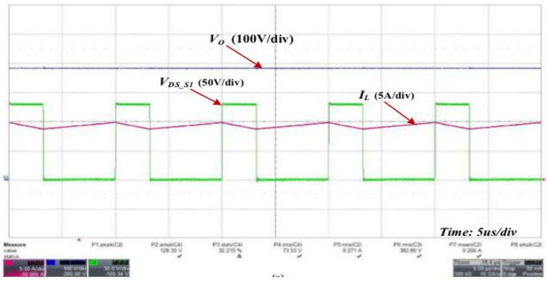

Fig. 7. Key experimental waveforms of the proposed converter at 100% load.

3. Experimental Result

In order to verify the validity and the performance of the proposed high step-up boost DC-DC converter, a 360W prototype circuit is built for a photovoltaic module (Hyundai RI Series 360W-72 Cell Solar Module) with the specification in Table I (Fig. 6).

In the experiment, the gate signals is generated by DSP TMS320F28335 and the capacitors (C_S, C_D, C_1, C_2, and C_3) are implemented by paralleling the multiple number of electrolytic capacitors to reduce ESRs. The semiconductor devices are mounted with heat sink and located at the bottom of the printed circuit board as shown in Fig.6.

The experimental results in Fig. 7 show the measured waveforms of the prototype converter at full load including the output voltage V_O, voltage across the switch S_1 and the inductor current. The prototype converter operates in CCM mode with a duty cycle of 0.685 and the input and output voltage is 40V and 380V, respectively. As shown in Fig. 8, the voltage across the switch is clamped to 120V during the off time. The voltage stresses across the switch and diodes are equal to $V_O/3$ as already shown in the Eq. (7). Fig. 9 shows the measured efficiency plot of the proposed converter when the output V_O = 380V and f_{SW} = 100 kHz at different input voltages varying from 35V to 45V. It can be found from Fig. 9 that the maximum efficiency of 96% is obtained at 250W with an input voltage of 45V.

TABLE I
SPECIFICATION OF THE PROPOSED DC-DC CONVERTER

Parameter	Manufacturer	Symbol	Value
Input	-	V_S	36-45 V
Output	-	V_O	380 V
Power	-	P_O	360 W
Switching Frequency	-	f_{SW}	100kHz
Inductor	CH400125	L	280 uH
Mosfet	IRFB260NPBF	S1	200V/56A
Diodes	STPSC806D	D1-D5	600V/8A
Capacitors	EPCOS/TDK	C1,C2,C3,CD,CS	47uF/150V

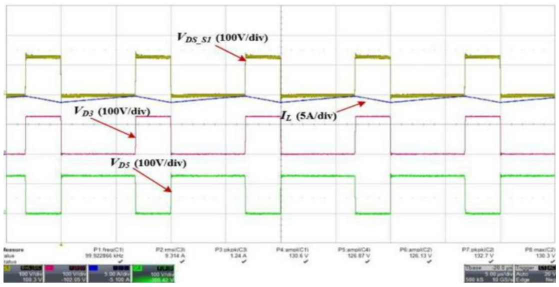

Fig. 8. Voltage stress across the main switch and the diodes at 100% load.

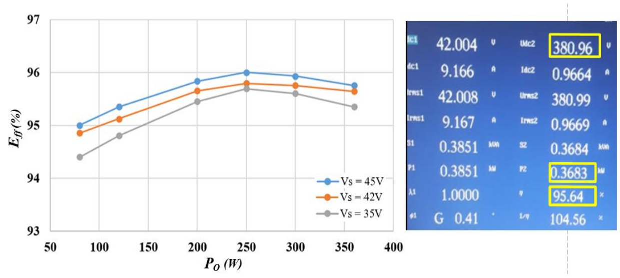

Fig. 9. Measured efficiency of the proposed converter.

4. Conclusion

In this paper a novel non-isolated high step-up boost converter with single switch and single inductor which exhibits a high voltage gain and a high efficiency characteristic is proposed. Its validity and feasibility have been proved by the experiments with a prototype 360W converter. The proposed converter can achieve the relatively higher voltage gain as compared to the other non-isolated high voltage gain boost converters and the maximum efficiency of 96% can be obtained. In addition, the voltage stresses of the switches and the passive components are lower than those of other high voltage gain non-isolated converters. It is also advantageous in that the voltage gain of the proposed can be further increased by adding more number of voltage multipliers. The proposed converter is suitable for the distributed power generation systems with renewable energy sources, which requires a high voltage gain without using a transformer.

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