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Transformerless Buck-Boost Converter With Positive Output Voltage and Nominal Duty Ratio

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Abstract: **This article deals with a transformerless buck-boost converter with simple structure. By inserting an additional switched network into the traditional buck-boost converter new converter is obtained. Compared with the traditional buck-boost converter, its voltage gain is quadratic of the traditional buck-boost converter. It can operate in a wide range of output voltage, that is, the proposed buck-boost converter can achieve high or low voltage gain without extreme duty cycle. Moreover, the output voltage of this transformerless buck-boost converter is common-ground with the input voltage, and its polarity is positive. The two power switches of the proposed buck-boost converter operate synchronously. The operating principles and the steady-state analyses for the buck-boost converter operating in CCM are presented. The PSIM simulations are provided to compare and validate the effectiveness of the buck-boost converter.**

Keywords: **Buck-Boost, Transformerless, Positive Output Voltage, Quadratic Gain.**

I. INTRODUCTION

Switching mode power supply is the core of modern power conversion technology, which is widely used in electric power, communication system, household appliance, industrial device, railway, aviation and many other fields. As the basis of switching mode power supply, converter topologies attract a great deal of attention and many converter topologies have been proposed. Buck converter and boost converter have the simple structure and high efficiency. However, due to the limited voltage gain, their applications are restricted when the low or high output voltage are needed. The voltage bucking/boosting converters, which can regulate output voltage under wider range of input voltage or load variations, are popular with the applications such as portable electronic devices, car electronic devices, etc. The traditional buck-boost converter with simple structure and high efficiency, as we all know, has the drawbacks such as limited voltage gain, negative output voltage, floating power switch, meanwhile discontinuous input and output currents. The other three basic non-isolated converters, Cuk converter, Sepic converter and Zeta converter which also have the peculiarity to step-up and step-down voltage, have been provided. However, the limits of the voltage gain along with other disadvantages in Cuk, Sepic, and Zeta converters are also non-ignorable.

Typical PWM dc/dc converters include the well-known buck, boost, buckboost, Cuk, Zeta, and Sepic. With proper reconfiguration, these converters can be represented in terms of either buck or boost converter and linear devices, thus, the buck and boost converters are named BCUs. The PWM converters are, consequently, categorized into buck and boost families. With this categorization, the small signal models of these converters are readily derived in terms of h parameter (for buck family) and g parameter (for boost family).Using the proposed approach, not only can one find a general configuration for converters in a family, but one can yield the same small-signal models as those derived from the direct state-space averaging method. Additionally, modeling of quasi-resonant converters and multi resonant converters can be

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simplified by adopting this approach[2]. A group of new DC-DC step-up(boost) converters six self-lift converters has been developed by applying the voltage lift technique. These converters are different from the conventional converters, and have higher output voltage and better characteristics. They will be used in consumer engineering projects and industrial applications. But the topological complexity, cost, volume, and losses are more[3]. Interleaved non-isolated high step-up DC/DC converter consists of two basic boost cells and some diode-capacitor multiplier (DCM) cells as needed. Because of the DCM cells, the voltage conversion ratio is enlarged and the extreme large duty ratio can be avoided in the high step-up applications. Moreover, the voltage stress of all the power devices is greatly lower than the output voltage. As a result, lower-voltage-rated power devices can be employed, and higher efficiency can be expected. Since the two basic Boost cells are controlled by the interleaving method, which means the phase difference between the two pulse width modulation (PWM) signals is 180 and the input current is the sums of the two inductor currents, the input current ripple is decreased and the size of the input filter could be reduced, which make it a suitable choice in the photovoltaic power generation system and hybrid electric vehicles, etc. But their operating mode, converter structure and control strategy are complicated[4]. A novel voltage-boosting converter[6], which combines a charge pump and a coupled inductor with the turns ratio. It aims to improve the intrinsic disadvantages of the traditional boost converter and buck-boost converter. In addition, the corresponding voltage gain is greater than that of the existing step up converter combining KY and buck-boost converters. Since the converter possesses an output inductor, the output current is non-pulsating, resulting in a relatively small output voltage ripple. Above all, part of the leakage inductance energy can be recycled to the output capacitor of the buck-boost converter. The converter can realize the continuous output current, positive output voltage, continuous conduction mode (CCM) operation all the time, and no right-half plane zero. Unfortunately, its voltage gain of two multiplies the duty cycle isn't sufficiently high or low in the situation where the converter needs to operate in a wide range of output voltage. A boost-buck cascade converter for maximum power point tracking of a thermoelectric generator, for a wide output voltage ranged thermoelectric generator, it is necessary to have a DC-DC converter that allows voltage boost and buck functions. Boost-buck cascade DC-DC converter is adopted to allow input voltage range from near 0 V to 25V and output voltage range from 12.3 V to 16.5 V, needed for vehicle battery charging. To ensure a smooth operating mode change, a modified maximum power point tracking controller is used to control the first stage converter duty cycle while regulating the second stage output voltage. A conventional duty cycle controller is then used to control the second stage converter while regulating the middle dc bus voltage. In order to avoid intricate relationship between two controller duty cycles, a novel aggregated modeling approach is used[7]. Nevertheless, the voltage gain of this cascade converter is also constrained. Especially, in order to obtain high voltage step-up or step-down gain, these converters must be operating under extremely high or low duty cycle, and this point is too hard to realize due to the practical constraints.

II. TRANSFORMERLESS BUCK-BOOST CONVERTER

A new transformerless buck-boost converter is obtained by inserting an additional switched network into the traditional buck-boost converter. The main merit of the proposed buck-boost converter is that its voltage gain is quadratic of the traditional buck-boost converter so that it can operate in a wide range of output voltage, that is, the proposed buck-boost converter can achieve high or low voltage gain without extreme duty cycle. Moreover, the output voltage of this new transformerless buck-boost converter is common-ground with the input voltage, and its polarity is positive.

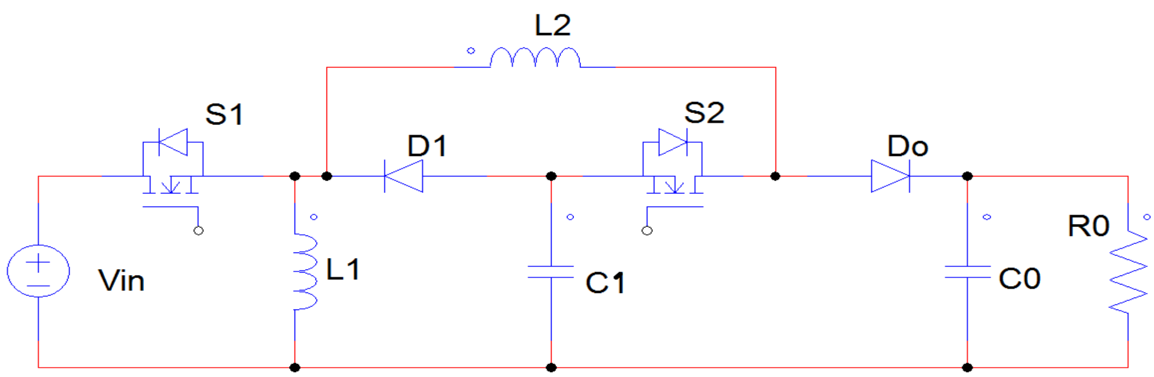

Figure1: Transformerless Buck-Boost Converter

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A. Converter Structure

The circuit configuration of the new transformerless buck-boost converter is shown in figure 1. It consists of two power switches (S_1 and S_2), two diodes (D_1 and D_O), two inductors (L_1 and L_2), two capacitors (C_1 and C_o), and one resistive load R. Power switches S_1 and S_2 are controlled synchronously. According to the state of the power switches and diodes, some typical time-domain waveforms for this new transformerless buck-boost converter operating in CCM are displayed in figure 2, and the possible operation states for the proposed buck-boost converter are shown in figures 3 and 4. Figure 3, it denotes that the power switches S_1 and S_2 are turned on whereas the diodes D_1 and D_O do not conduct. Consequently, both the inductor L_1 and the inductor L_2 are magnetized, and both the charge pump capacitor C_1 and the output capacitor C_O are discharged. Figure 4, it describes that the power switches S_1 and S_2 are turned off while the diodes D_1 and D_O conduct for its forward biased voltage. Hence, both the inductor L_1 and the inductor L_2 are demagnetized, and both the charge pump capacitor C_1 and the output capacitor C_O are charged.

B. Operating Principles

As shown in figure 2, there are two modes, that is, mode 1 and mode 2, in the new transformerless buck-boost converter when it operates in CCM operation. Mode 1 between time interval (NT<t<(N+D)T). Mode 2 between time interval ((N+D)T<t<(N+1)T).

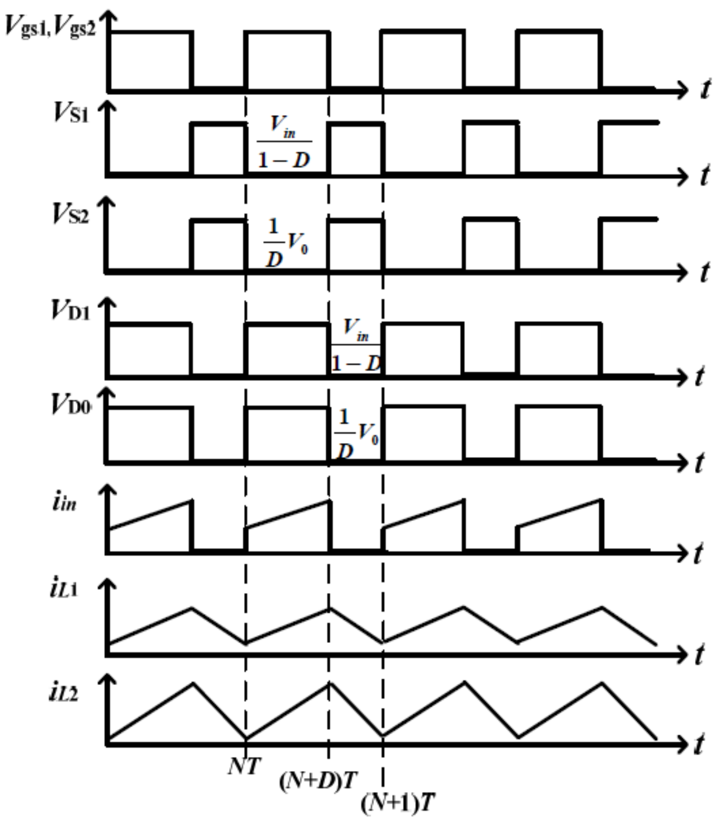

Figure 2: Typical Time-Domain Waveforms for the Buck-Boost Converter Operating in CCM.

(a). Mode 1(NT<t<(N+D)T)

Mode 1 is during the time interval (NT<t<(N+D)T). During this time interval, the switches S_1 and S_2 are turned on, while D_1 and D_O are reverse biased. From figure 3, it is seen that L_1 is magnetized from the input voltage Vin while L_2 is magnetized from the input voltage V_{in} and the charge pump capacitor C_1. Also, the output energy is supplied from the output capacitor C_O. Thus, the corresponding equations can be established as,

$$V_{L1} = V_{in} \quad (1)$$

$$V_{L2} = V_{in} + V_{C1} \quad (2)$$

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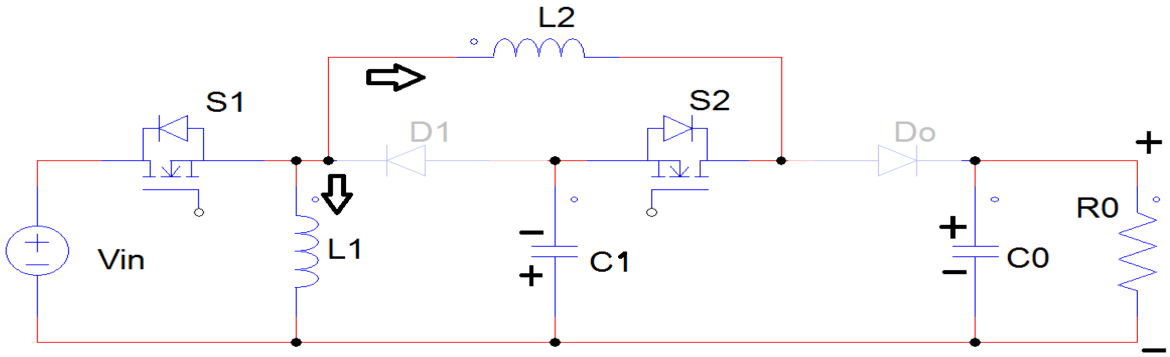

Figure 3: Equivalent circuits of the buck-boost converter in mode 1

(b). Mode 2[$t_1 - t_3$] ((N+D)T<t<(N+1)T)

State 2 is during the time interval ((N+D)T<t<(N+1)T). During this time interval, the switches S_1 and S_2 are turned off, while D_1 and D_O are forward biased. From figure 4, it is seen that the energy stored in the inductor L_1 is released to the charge pump capacitor C_1 via the diode D_1. At the same time, the energy stored in the inductor L_2 is released to the charge pump capacitor C_1, the output capacitor C_O and the resistive load R via the diodes D_O and D_1. The equations of the state 2 are described as follows

$$V_{L1} = -V_{C1} \quad (3)$$

$$V_{L2} = -(V_{C1} + V_O) \quad (4)$$

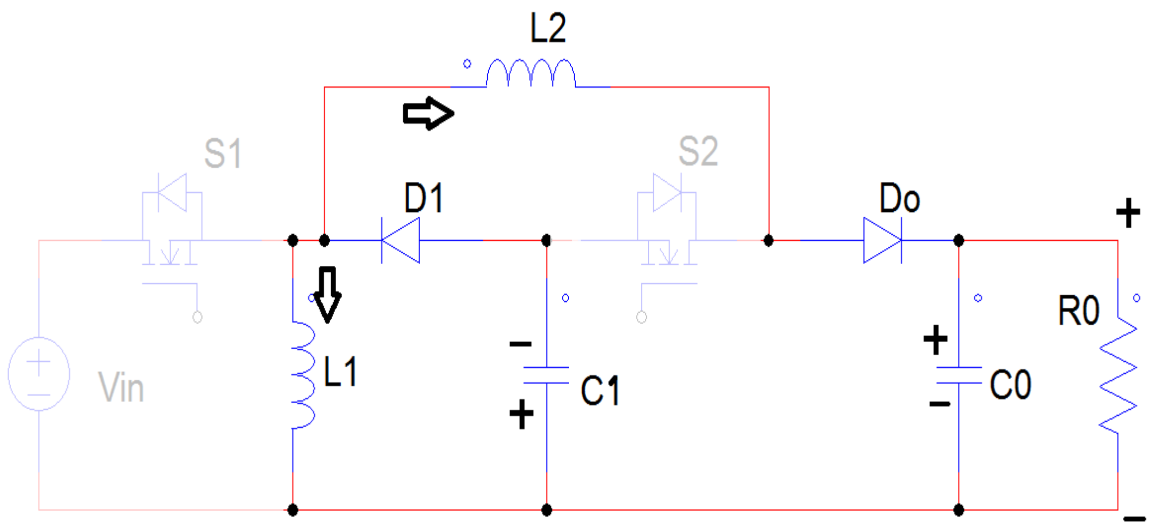

Figure 4: Equivalent circuits of the buck-boost converter in mode 2.

If applying the voltage-second balance principle on the inductor L_1, then the voltage across the charge pump capacitor C_1 is readily obtained from equations (1) and (3) as

$$V_{C1} = \frac{D}{1-D} V_{in} \quad (5)$$

Here, D is the duty cycle, which represents the proportion of the power switches turn on time to the whole switching cycle.

Similarly, by using the voltage-second balance principle on the inductor L_2, the voltage gain of the proposed buck-boost converter can be obtained from equations (2), (4), and (5) as

$$M = \frac{V_O}{V_{in}} = \left(\frac{D}{1-D}\right)^2 \quad (6)$$

From equation (6), it is apparent that the proposed buck-boost converter can step-up the input voltage when the duty cycle is bigger than 0.5, and step-down the input voltage when the duty cycle is smaller than 0.5.

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III. SIMULATION MODEL AND RESULTS

Based on the PSIM software and Fig. 1, the simulation circuit of the new transformerless buck-boost converter constructed for the PSIM simulations to confirm the above mentioned analyses. Circuit parameters here are listed in table

Table I: Simulation parameters

Input voltage V_{in}	18V
Frequency f_s	20kHz
Inductance L_1, L_2	1mH, 3mH
Capacitance C_1, C_o	10 µF, 20 µF
Resistance R	30-150Ω
Duty cycle D	0.4-0.6

A. Simulation Model

PSIM model of the converter is shown in figure 5. MOSFET's are used as switches. Output voltage and stresses across switches are analyzed from the simulation results.

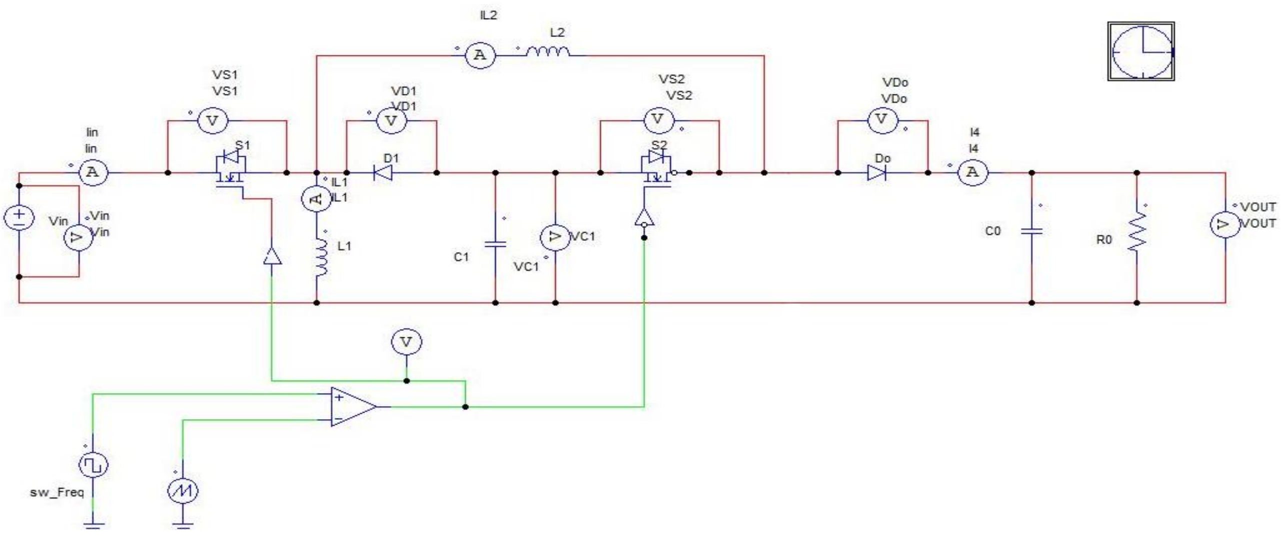

Figure 5: PSIM Model of Transformerless Buck-Boost Converter

B. Simulation Results

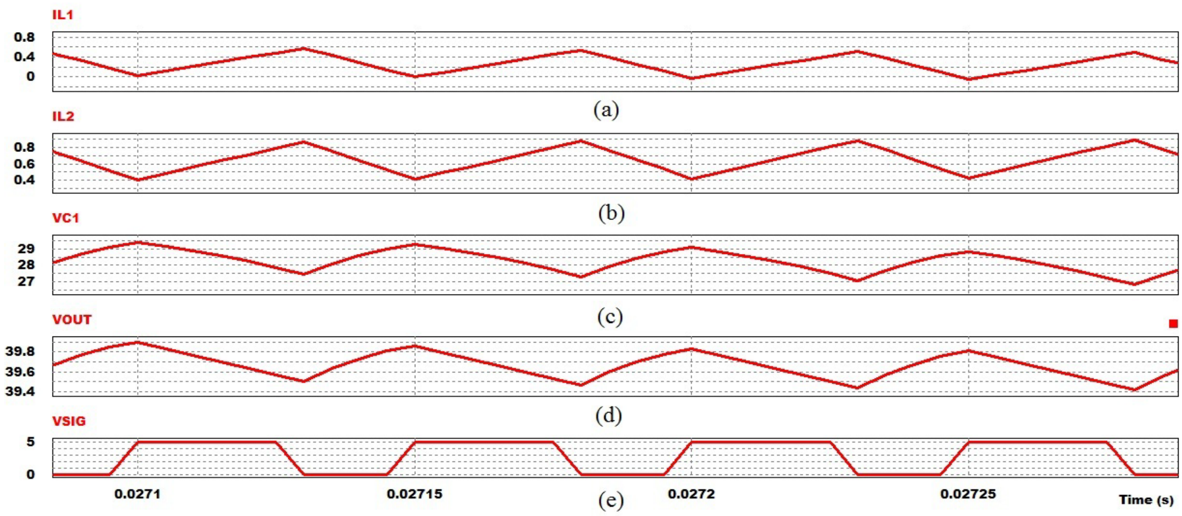

Figure 6: PSIM simulations for the buck-boost converter operating in step-up mode

Figure 6 shows the time-domain waveforms of the output voltage V_{OUT} , the charge pump capacitor voltage V_{C1}, the currents of the two inductors L_1 and L_2, and the driving signal V_{SIG} for the new transformerless buck-boost converter operating in step-up mode when the duty cycle is 0.6. Since the two power switches conduct synchronously, only one driving signal VSIG is chose. From figure , one can obtain that the charge pump capacitor voltage VC1 is within (25.8V, 27.8V), the output voltage VO is within (40.2V, 40.6V), the inductor current IL1 is within (0.07A, 0.61A), and the inductor current IL2 is within (0.45A, 0.90A). Also, the ripples of the inductor current ΔIL1 and the inductor current ΔIL2 are 0.54A and 0.45A, respectively. Additionally, the ripples of the two capacitors ΔVC1 and ΔVCO are 2V and 0.4V, respectively.

From the equations (5), (6) the theoretical results are V_{C1}=27V, V_{OUT} =40.5V, I_{L1}=0.34A, I_{L2}=0.68A, ΔI_{L1}=0.54A, ΔI_{L2}=0.45A, ΔV_{C1}=2V, ΔV_{CO}=0.4V, respectively. For the proposed buck-boost converter operating in step-down mode when the duty cycle is choosing as 0.4. figure 7 displays the time-domain waveforms of the output voltage V_{OUT} , the charge pump capacitor voltage V_{C1}, the currents of the two inductors L_1 and L_2, and the driving signal V_{SIG}. It is clearly seen that the charge pump capacitor voltage V_{C1}, the output voltage V_{OUT} , the inductor current I_{L1}, and the inductor current I_{L2} are within (11.44V, 12.32V), (7.77V, 8.04V), (-0.33A, 0.03A) and (0.34A,0.54A), respectively. Also, the ripples of the inductor current ΔI_{L1} and the inductor current ΔI_{L2} are 0.36A and 0.2A, respectively. And, the ripples of the two capacitors ΔV_{C1} and ΔV_{CO} are 0.88V and 0.27V, respectively.

Similarly, the theoretical calculations from the equations (5), (6) are V_{C1}=12V, V_{OUT}=8V, I_{L1}= -0.15A, I_{L2}=0.44A, ΔI_{L1}=0.36A, ΔI_{L2}=0.2A, ΔV_{C1}=0.89V, ΔV_{CO}=0.27V, separately.

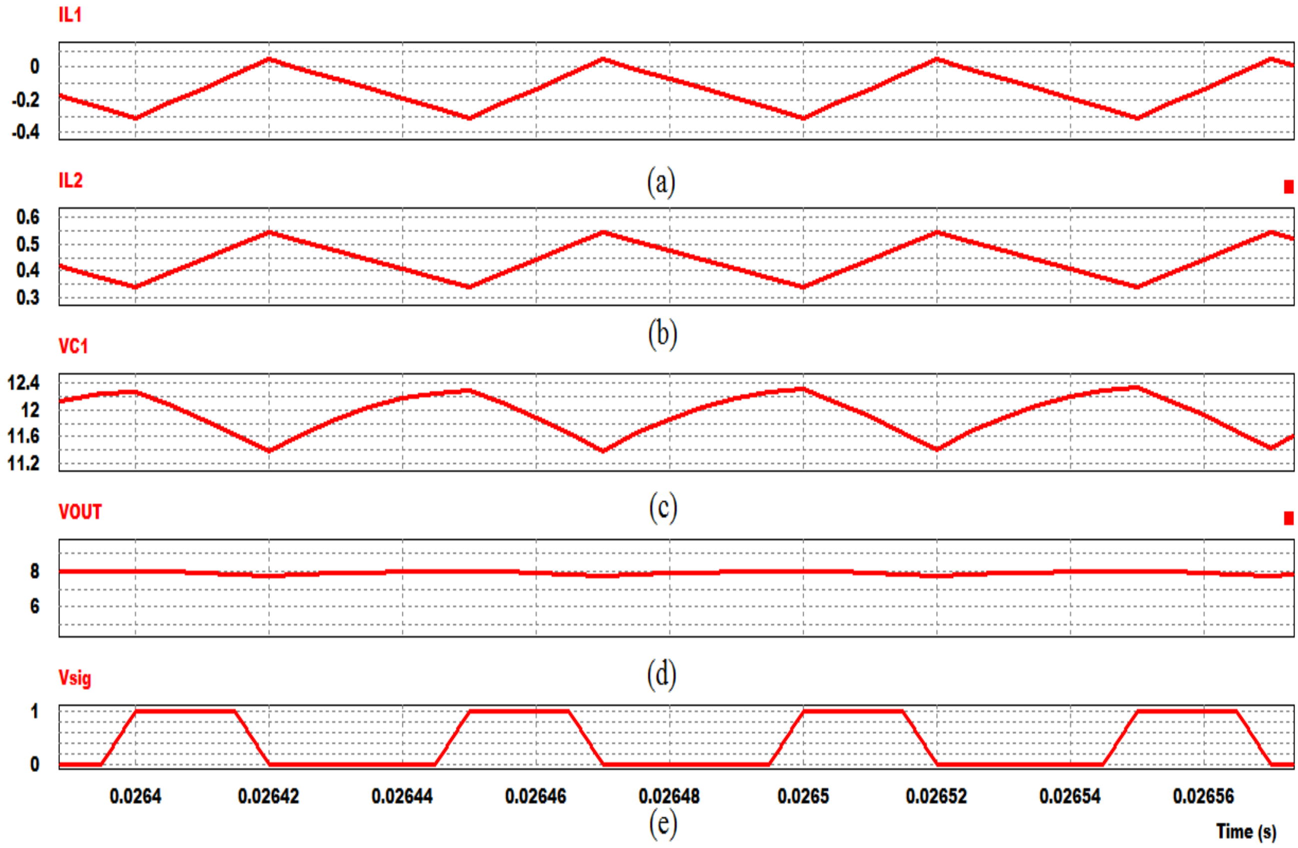

Figure 7: PSIM simulations for the buck-boost converter operating in step-down mode

C. Voltage Stress

Figure 8 shows the voltage stress of diodes and switches of the buck-boost converter. Voltage stress of the power switch S_1 and the diode D_1 are both equal to the voltage stress on the power switch in the traditional buck-boost converter with the same input voltage Similarly, under the same output voltage condition, the voltage stress of the power switch S_2 and the diode D_O are the same as the voltage stress on the diode in the traditional buck-boost converter.

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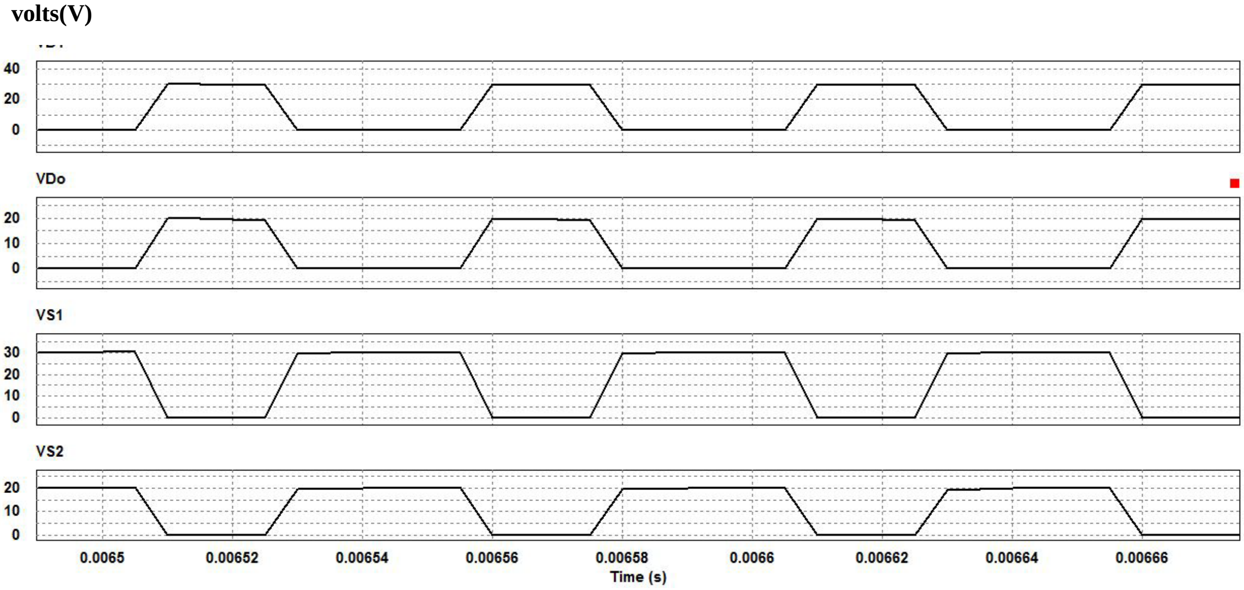

Figure 8: Voltage stress of diodes and switches

IV. CONCLUSIONS

Transformerless buck-boost converter is simulated using PSIM and analyzed. It is obtained by inserting an additional switched network into the traditional buck-boost converter. Transformerless buck-boost converter possesses the merits such as high step-up/step-down voltage gain, positive output voltage, simple construction and simple control strategy. Hence, the proposed buck-boost converter is suitable for the industrial applications requiring high step-up or step-down voltage gain. The converter operate in a wide range of output voltage without using extreme duty cycles. It provides enough gain within the duty ratio 0.4-0.6. It has simple operating modes.

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