High Boost DC-DC Converter: HB-LDC Converter

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Abstract: A new type of DC-DC converter has been devised: the Hybrid Boost Inductor-Diode-Capacitor (HB-LDC) converter. A novel switching structure, a diode, a capacitor and a switch were added into an elementary additional circuit, to construct the HB-LDC converter. The proposed switching structure that carries out the step-up function is composed of three inductors and six diodes. The HB-LDC converter depends mainly on charging and discharging of the inductors and capacitors to realize the step-up function. The continuous-conduction mode (CCM) operation for the HB-LDC converter is analyzed. When the HB-LDC converter works in CCM, the voltage gain is only related to the duty cycle. Theoretical analysis shows that the HB-LDC converter is characterized by high voltage gain, low switching stress, and low inductance ripple. The theoretical analysis was verified by the construction of a working device.

Keywords: HB-LDC converter, switching structure, CCM, theoretical analysis

Classification: Power devices and circuits

References

[1] R. Maurya, S. P. Srivastava, P. Agarwal: “Symmetrical and asymmetrical controlled three-phase high frequency isolated DC–DC converter,” Electrical Power and Energy Systems 52(2013) 132 (DOI: 10.1016/j.ijpeds.2013.03.042).

[2] E. Babaei, H. M. Maheri, M. Sabahi, et al: “Extendable nonisolated high gain DC-DC converter based on active-passive inductor cells”, IEEE transactions on industrial electronics, 65(2018) 9478. (DOI: 10.1109/TIE.2018.2807367)
[3] J. H. Park, Z. Maregn, Y. J. Kim: “Color transformation-based dynamic voltage scaling for mobile AMOLED displays”, IEICE electronics express, 12(2015) 1. (DOI: 10.1587/exlex.12.20150239).

[4] H. Moradzadeh, S. J. Azhari: “High performance low-voltage QFG-based DVCC and a novel fully differential SC integrator based on it”, IEICE electronics express, 5(2008) 1017. (DOI: 10.1587/elex.5.1017).

[5] K. Li, Y. Hu, and A. Ioinovici: “Generation of the large DC gain step-up nonisolated converters in conjunction with renewable energy sources starting from a proposed geometric structure”, IEEE transactions on power electronics, 32(2017) 5323. (DOI: 10.1109/TPEL.2016.269501)

[6] C. Dariush, A. Ehsan and F. Hosein: “Soft-switched nonisolated high step-down converter”, IEEE transactions on industrial electronics, 66(2019) 183. (DOI: 10.1109/TIE.2018.2829471)

[7] L. He, Z. Zheng, D. Guo: “High step-up DC-DC converter with active soft-switching and voltage-clamping for renewable energy systems”, IEEE transactions on power electronics, 33(2018) 9496. (DOI: 10.1109/TPEL.2018.2789456)

[8] H. M. Hsu, C. T. Chien: “Multiple turn ratios of on-chip transformer with four intertwining coils,” IEEE Trans. Electron Devices 61(2014) 44 (DOI: 10.1109/TED.2013.2292855).

[9] H. Q. Wen, W. D. Xiao, B. Su: “Nonactive power loss minimization in a bidirectional isolated DC–DC converter for Distributed power systems”, IEEE Trans. on Ind. Electron. 61(2014) 6822 (DOI: 10.1109/TIE.2014.2316229).

[10] G.M.L. Chu, D.D.C. Lu, V.G. Agelidis: “Flyback-based high step-up converter with reduced power processing stages”, IET Power Electronics. 5(2012) 349 (10.1049/iet-pel.2011.0204).

[11] S.-K. Kao, J.-H. Wu, H.-C. Cheng: “All-digital controlled boost DC-DC converter with all-digital DLL-based calibration”, Microelectronics Journal. 46(2015) 970 (https://doi.org/10.1016/j.mejo.2015.07.011).

[12] V. Samavatian, A. Radan: “A novel low-ripple interleaved buck-boost converter with high efficiency and low oscillation for fuel-cell applications,” Int. J. Electr. Power Energy Syst. 63(2014) 446-454 (DOI: 10.1016/j.ijepes.2014.06.020).

[13] S. Ćuk, R. D. Middlebrook, “A new optimum topology switching dc-to-dc converter,” PESC (1977) 160 (DOI: 10.1109/PESC.1977.7070814).

[14] B. Axelrod, Y. Berkovich, A. Ioinovici: “Hybrid switched-capacitor-Ćuk/Zeta/Sepic converters in step-up mode”, ISCAS (2005) 1310 (DOI: 10.1109/ISCAS.2005.1464836).

[15] Axelrod B, Berkovich Y, Ioinovici A: “Switched-capacitor/switched-inductor structures for getting transformerless hybrid DC–DC PWM converters,” IEEE Trans. Circuits Sys. I, Fundam. Theory Appl. 55(2008) 687 (DOI: 10.1109/TCSI.2008.916403).

[16] B. Axelrod, Y. Berkovich: “Switched-capacitor(SC)/switched inductor (SL) structures for getting hybrid step-down Ćuk/Sepic/Zeta converters,” ISCAS (2006) 5063 (DOI: 10.1109/ISCAS.2006.1693770).

[17] Y. Tang, D. J. Fu, T. Wang, Z. W. Xu: “Hybrid Switched-inductor converters for high step-up conversion,” IEEE Trans. on Ind. Electron. 62(2015) 1480 (DOI: 10.1109/TIE.2014.2364797).

[18] F.L. Luo: “Positive output Luo-converters, voltage lift technique”, IEE proceedings-electric power applications, 146(1999) 415 (10.1049/ip-epa:1999
0291).

[19] F.L. Luo: “Negative output Luoconverters, voltage lift technique”, IEE proceedings-electric power applications, 146 (1999) 208 (10.1049/ip-epa:1999 0302).

[20] F.L. Luo: “Double output Luoconverters, advanced voltage lift technique”, IEE proceedings-electric power applications, 147 (2000) 469 (10.1049/ip-epa: 20000622).

[21] Y. Jiao, F.L. Luo, B.K. Bose: “Voltage-lift split-inductor-type boost converters”, IET Power Electron., 4 (2011) 353 (10.1049/iet-pel.2010.0093).

[22] O. Abutbul, A. Gherlitz, Y. Berkovich, A. Ioinovici: “Step-up switching-mode converter with high voltage gain using a switched-capacitor circuit”, IEEE transactions on circuits and systems I: fundamental theory and applications, 50 (2003) 1098 (10.1109/TCSI.2003.815206).

[23] L.-S. Yang, T.-J. Liang, J.-F. Chen: “Transformerless DC–DC converters with high step-up voltage gain”, IEEE transactions on industrial electronics, 56 (2009) 3144 (10.1109/TIE.2009.2022512).

[24] F.L. Luo, H. Ye: “Hybrid split capacitors and split inductors applied in positive output super-lift Luoconverters”, IET Power Electronics, 6 (2013) 1759 (10.1049/iet-pel.2012.0634).

1 Introduction

Recently, with the increasing application of high voltage DC power supplies, the high-gain step-up DC-DC converter has become more and more popular in many industrial fields. In general, DC-DC converters can be divided into two types: the isolated converter and the non-isolated converter [1-7]. The isolated DC-DC converter introduces an AC link where a transformer can be used to realize the isolation between the input and output. In fact, the converter might better be called an DC-AC-DC converter. The circumstances where the isolated converter is preferred are as follows [8]: 1) The output and the input of the converter need to be separated. 2) The required ratio of the output and input voltages is much greater than or much less than 1. The isolated converter with a transformer is then more convenient than the non-isolated converter for stepping up the voltage. However, for the isolated converter, the volume and weight of the transformer, filter inductor and filter capacitor are far larger than that for the non-isolated converter. In reference [9], the author discussed nonactive power loss minimization in a bidirectional isolated DC–DC converter for distributed power systems. However, the volume of their converter was large, because it had a transformer, which reduced the working efficiency. In reference [10], a flyback-based high step-up converter with reduced power processing stages was proposed in which the topological structure of the circuit was relatively simple, compared with other isolated converter. However control of this type of circuit is more complex.

The class of non-isolated converters includes the Buck, Boost [11], Buck-Boost [12-13], Ćuk [13-14], Zeta [14-15], Sepic [14-15], SL [16], SC [16], AH-SLC and SH-SLC [17] converters. Among the above converters, the Buck and Buck-Boost converters can realize step-down of the voltage, and the Boost,
Buck-Boost, Ćuk, Zeta and Sepic converters can step up the voltage. However, for the Boost, Buck-Boost, Ćuk, Zeta and Sepic converters, only when the duty cycle is at the maximum value, can they achieve a slightly higher voltage gain. Although the SL, SC converters can realize increased voltage gain, the voltage gain is still limited, and can not meet many of the needs of industry. At the same time, the voltage stress in the switches is high, which reduces the working efficiency. AH-SLC and SH-SLC converters can realize higher voltage transfer gain, higher working efficiency, lower voltage stress and smaller inductor current ripple. However, because of the increasing demands for higher voltages, higher conversion gain is required.

Luo-converters[18-20] can step up the voltage, but their voltage transfer gains are not very high. In references [21-22], voltage-lift split-inductor, boost converters and step-up switching-mode converters with high voltage gain were proposed. However, they had too many switches, which increased the voltage stress and the difficulty of control, and reduced the working efficiency.

A new kind of transformerless DC-DC converter is proposed in this paper: an asymmetric (HB-LDC) converter. The switching structure, a diode, a capacitor and a switch were added into an elementary additional circuit. The HB-LDC converter discussed here has particular characteristics: 1) It has higher voltage gain, compared to transformerless step-up DC-DC PWM converters[23]. 2) Its main switching voltage stress is lower, compared to the basic boost and SH-SLC converter[17]. 3) It has lower inductance ripple.

2 The switching structure

![Fig. 1.](image1)  
The step-up switching structure, 1 is input and 2 is output.

![Fig. 2.](image2)  
a) $T_{on}$  
b) $T_{off}$  
Switching of the step-up structure.
The switching structure is shown in Fig. 1 (where \( L_1 = L_2 = L_3 \)), and Fig. 2 indicates the switching strategy. In Fig. 2.a), because the three inductors have the same inductance, it can be seen that the branch currents are equal \( (i_{L_1} = i_{L_2} = i_{L_3}) \), and that the inductors are charged by the DC power supply during the \( T_{on} \) period. Fig. 2.b) shows how the inductors are discharged during the \( T_{off} \) period.

3 Operation conditions of the HB-LDC converter

The conditions for CCM operation can be seen in Fig. 3. In Fig. 3, \( D \) is the duty ratio, and \( T_s \) is the working cycle.

![Fig. 3. Switching condition of CCM.](image)

The topological structure of the HB-LDC converter is shown in Fig. 4 (with \( L_1 = L_2 = L_3 = L_4 = L \)), and shows how the switching structure is added into the elementary additional circuit[24]. The working mode of the HB-LDC converter in CCM is shown in Fig. 5. The normal lines represent those parts of the circuit that are in operation, and the broken lines represent those parts of the circuit that are not operation.

![Fig. 4. The topological structure of HB-LDC converter.](image)

The equivalent circuit for CCM operation is shown in Fig. 5.a) and b). The operation mode of the circuit during the \( T_{on} \) period is shown in Fig. 5.a. The DC power supply transfers energy to \( L_1, L_2, L_3, L_4, C_1 \) and \( C_4 \), and \( C_2 \) charges \( C_3 \). The operation mode of the circuit during the \( T_{off} \) period is shown in Fig. 5.b). The DC power supply, \( L_4 \) and \( C_1 \) charge \( C_2 \), and the DC power supply, \( L_1, L_2, L_3, L_4, C_3 \) and \( C_4 \) charge the load.
In Fig. 5.a), the switches S1 and S2 are turned on during \( t_0-t_1 \), and then the voltages at \( L_1, L_2, L_3, L_4, C_1, \) and \( C_4 \) are:

\[
V_{L_1} = V_{L_2} = V_{L_3} = V_{L_4} = V_{C_1} = V_{C_4} = V_i
\]  

(1)

The voltages at \( C_2 \) and \( C_3 \) are:

\[
V_{C_2} = V_{C_3} = V_i
\]  

(2)

In Fig. 5.b), the switches S1 and S2 are turned off during \( t_1-t_2 \), the voltages at \( L_1, L_2, L_3 \) are then:

\[
V_{L_1} = V_{L_2} = V_{L_3} = \frac{V_o - V_i - 2V_i - V_{L_4}}{3}
\]  

(3)

The voltage at \( L_4 \) is:

\[
V_{L_4} = V_i - 2V_i
\]  

(4)

According to voltage-second balances on \( L_4 \), the expression can be expressed as:

\[
\int_{t_1}^{t_2} V_i dt = \int_{t_1}^{t_2} (V_i - 2V_i) dt
\]  

(5)

According to Fig. 3 and equation (5), the voltage at \( C_2 \) and \( C_3 \) are both:

\[
V_i = \frac{2-D}{1-D} V_i
\]  

(6)
Combining the formulas (4) and (6), the voltage at L4 is:

\[ V_{L4} = \frac{D}{1-D} V_i \]  

(7)

According to voltage-second balances on the L1, L2, L3, the formula can be expressed as:

\[ \int_0^t V_i \, dt = \int_0^t \left( V_o - 2V_i - V_i - \frac{V_{L4}}{3} \right) \, dt \]  

(8)

According to Fig. 3 and equation (8), the voltage gain in CCM operation can then be expressed as:

\[ G_{CCM} = \frac{V_o}{V_i} = \frac{4+D}{D_i} \]  

(9)

Where \( D_i = 1-D \) in CCM operation.

4 Analysis of the proposed converter

Section 4 discusses the voltage gain, voltage stress, external characteristic, and inductor current.

4.1 Voltage gain

The voltage gains of the HB-LDC converters are shown in Fig. 7, and for comparison, the gains of the SH-LDC, AH-LDC and Boost converters discussed in reference[17] are also shown. The voltage gain of the SH-SLC converter is given by [17]:

\[ G_{CCM} = \frac{1+3D}{D_i} \]  

(20)

The voltage gain of the AH-SLC converter can be expressed as [17]:

\[ G_{CCM} = \frac{1+2D}{D_i} \]  

(21)

and the voltage gain of the Boost converter can be expressed as [17]:

\[ G_{CCM} = \frac{1}{D_i} \]  

(22)

Fig. 6. Voltage gain of the converters.
From Fig. 6, it is obvious that the voltage gain of the HB-LDC converter is significantly higher than that of the AH-SLC, SH-SLC and Boost converters.

4.2 Voltage stress of the switch
When S1 and S2 are turned off, the voltage stress of S1 on the HB-LDC converter is:

\[ V_{S1} = V_i + V_{L4}, \]  

(23)

and the voltage stress of S2 on HB-LDC converter is:

\[ V_{S2} = V_o - V_i - V_{L4} \]  

(24)

Combining (7), (9) and (23), the voltage stress on S1 in the HB-LDC converter is:

\[ V_{S1} = \frac{G_{CCM} + 1}{5} V_i \]  

(25)

Combining (6), (7), (9) and (24), the voltage stress on S2 in the HB-LDC converter is found to be:

\[ V_{S2} = \frac{3G_{CCM} - 7}{5} V_i \]  

(26)

For comparison, we note that the voltage stress on the Boost converter as given in reference[17] is:

\[ V_S = G_{CCM} V_i \]  

(27)

While the voltage stress on the SH-SLC converter in reference[17] is:

\[ V_S = \frac{G_{CCM} + 1}{2} V_i \]  

(28)

Since the voltage stress of the SH-SLC converter is less than that for other topologies such as the SC-Boost and SL-Boost converters[17], it is most illustrative to compare the HB-LDC converters with the SH-SLC converter. Following formulas (25), (26), (27) and (28), Fig. 7 shows the voltage stress \( V_S \) of these converters as a function of \( V_i \). From Fig. 7, the voltage stress of the HB-LDC converters can be seen to be lower than the voltage stress of the SH-SLC converter, which results in improved working efficiency of the circuit.

![Fig. 7. Voltage gain of the converters.](image)

4.3 Inductor Current of the HB-LDC converter
The formula for the peak current can be expressed as:

\[ I_{peak-L} = (1 + K_i) I_L \circ \omega I_L \]  

(29)
Where $K_I$ is the current ripple factor. Because the ripple current is proportional to the inductor current, the smaller the inductor current, the smaller the current ripple, and the more stable the output voltage.

When the HB-LDC converter operates over the whole cycle, the ratio of the inductor current and the output current $I_L/I_o$ can be obtained:

$$\frac{I_L}{I_o} = \frac{1}{5}(G_{CCM} + 1)$$  \hspace{1cm} (30)

On the other hand, the average inductor current of the SL-Boost converter is[17]:

$$\frac{I_L}{I_o} = \frac{G_{CCM} + 1}{2}$$  \hspace{1cm} (31)

The average inductor current of the SH-SLC converter is[17]:

$$\frac{I_L}{I_o} = \frac{G_{CCM} + 3}{4}$$  \hspace{1cm} (32)

and the average inductor current of the SC-Boost converter is[17]:

$$\frac{I_L}{I_o} = G_{CCM}$$  \hspace{1cm} (33)

The average inductor current of the converters is shown in Fig. 8, which gives the relationship between $G_{CCM}$ and $I_L/I_o$ according to formulas (30), (31), (32) and (33). From Fig. 8, it can be seen that the values of $I_L/I_o$ for the HB-LDC converter are much lower than for the SC-Boost, SL-Boost and SH-SLC converters.

![Fig. 8. Average inductor currents of the converters.](image)

**4 Experimental results**

In order to verify the correctness of the above analysis, an HB-LDC converter circuit was constructed. The physical parameters of the components are shown in Table I.

| Components | Parameters |
|------------|------------|
| fs(switching frequency) | 24kHz |
| L1,L2,L3,L4'(inductors) | 600µH |
| C1,C4(capacitors) | 375µF |
| C2,C3(capacitors) | 125µF |
| S1,S2(Power MOSFET) | G4PC50K |
| D1,D2,D3,D4,D5,D6,D7,D8,D12,D23,Do(Diodes) | MBR20100CT |
| Co | 68µF/450V |

The HB-LDC converter is shown in Fig. 9, including the basic HB-LDC circuit, DC power, MOSFET signal device (using a Microcomputer to generate a pulse signal and lifting the voltage through the EXB841), and the load. The physical parameters had the values shown in TABLE 1.
The experimental waveforms are shown in Fig. 10 for $V_i=5\text{V}$. From Fig. 10, it can be seen that when the input voltage was $5\text{V}$ (the green line, $D=0.5$), the output voltage was about $40.2\text{V}$ (the yellow line). The label 1 (green bar) represents the reference line of the input voltage, and label 2 (yellow bar) represents the reference line for the output voltage.

For the case where $V_i=10\text{V}$ ($D=0.5$), the experimental waveforms are shown in Fig. 11. For this input, the output was about $80.5\text{V}$.

The voltage stresses of $S_1$ and $S_2$ on HB-LDC converter are shown in Fig. 12 and 13, when $V_i=10\text{V}$. Since the currents of the inductors $L_1$, $L_2$, $L_3$, and $L_4$ are equal, the current waveform of $L_1$ is only shown here. The current waveform of the inductors $L_1$ is shown in Fig. 14 (the sampling resistance is $0.5\Omega$, and the inductor current is obtained by measuring the voltage of the sampling resistor). From Fig. 14,
it can be seen that the average currents of the inductors L1 is basically consistent with the formulas (30).

Fig. 12. The experimental waveforms when $V_i=10$V.

Fig. 13. The experimental waveforms when $V_i=10$V.

Fig. 14. The experimental waveforms when $V_i=10$V.

5 Conclusion

A new, transformerless step-up DC-DC converter, referred to as the HB-LDC converter, has been proposed. The operation of the HB-LDC converter in continuous-conduction mode has been described, demonstrating that the HB-LDC
converter can achieve high voltage gain. The voltage gain, voltage stress, and inductor current of the converter have been analyzed, emphasizing the advantages of the HB-LDC converter. Experimental studies of an HB-LDC converter constructed in the laboratory were used to verify the theoretical analysis. The HB-LDC converter discussed in this paper has many advantages compared to existing converters. 1) It has higher voltage gain. 2) Its switching stress is lower, which improves the working efficiency. 3) Its inductor current ripple is lower than that in existing converters.

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