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A Voltage-Lift Switched Inductor DC/DC Multilevel Boost Converter

***Abstract**. In this paper, a single inductor in the conventional multilevel boost converter is replaced by the voltage-lift switched-inductor cell. This proposed technique is a viable solution to step-up a low source voltage into a high voltage gain. The basic mathematical analysis of operation mode analysis with operation waveform is provided to find the circuit characteristic and voltage gain. The simulation results and a prototype have been provided to verify the validity of the proposed converter.*

Streszczenie.** Pojedynczy dławik stosowany w konwencjonalnym wielopoziomowym przekształtniku boost jest zastąpiony przez celkę z przełączanym dławikiem. Taka zaproponowana technika umożliwia wzmacnianie niskiego napięcia Źródła zasilania. **Wielopoziomowy DC/DC boost konwerter z przełączanym dławikiem

Keywords: voltage-lift switched inductor, high voltage gain, multilevel boost converter
Słowa kluczowe: przełączany dławik, boost konwerter, wzmacniacz wysokonapieciowy.

Introduction

DC-DC boost converters are widely used in industrial application and renewable energy system. In many applications high efficiency and high voltage boost DC-DC converter are required to interface between low voltage sources to high voltage load side.

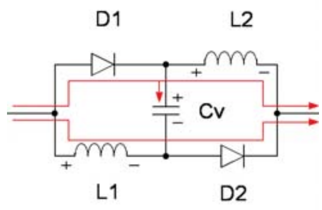
The conversion efficiency and high voltage gain are not easy to achieve with conventional boost converter due to parasitic component [1]. In order to obtain high output voltage, the traditional boost converter should operate at extreme duty cycle this limits the switching frequency and converter size, also increase the electromagnetic interference (EMI) levels [2]. Many research papers are being proposed several compensation topologies for overcoming these challenges and improving quality.

The converter with the coupling inductor can provide high voltage gain in non isolated DC-DC converters in proportion to winding turns-ratio [3-5], but their efficiency is degraded due to the accompanying leakage inductance. Isolated boost converter topology satisfies high efficiency and high voltage gain [6-9], but the system size is large. And because of transformer used, there is the limitation as to the maximum operating temperature above which the magnetic core heating due to core losses. Avoiding the transformers or/and coupling inductors brings obvious benefits of cost, size and absolutely efficiency. Non-isolated DC-DC multilevel boost converter for achieving high voltage gain by using low voltage devices is presented and discussed [10-12]. It combines the function of conventional boost converter and Cockcroft-Walton voltage multiplier, see Fig 1. Some of advantages are self voltage balancing, high voltage gain without using extreme duty cycle, only one drive switch, low voltage stress and without a transformer. Moreover, more output levels can be increased adding capacitors and diode without modifying the main circuit. Recently, there have been a converter developed [13] which meets the formal requirements of high efficiency and high voltage gain. The simple structure of converter is based on bootstrap capacitors and switched inductors [14-17].

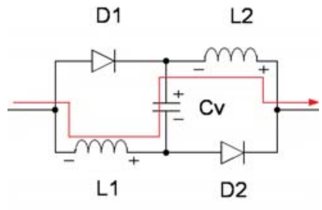
In this paper, a converter topology based on the combination of voltage-lift switched inductor cell and multilevel converter is proposed. The voltage lift switched-inductor cell is used as the first stage to boost a DC source voltage. The second stage is voltage multiplier cell, it is used to generate more high DC voltage from the first stage. The operational principles and steady state analysis have been verified by simulation and small circuit experiments.

Proposed converter topology

In Figure 1, shows a voltage-lift switched-inductor cell, when stage is ON both inductors L_1 and L_2 and the capacitor C_v are charged in parallel by input voltage source. When stage is OFF both inductors and capacitor are discharged in series to obtain high voltage gain.



a) ON state



b) OFF state

Fig.1. Basic voltage-lift switched-inductor cell

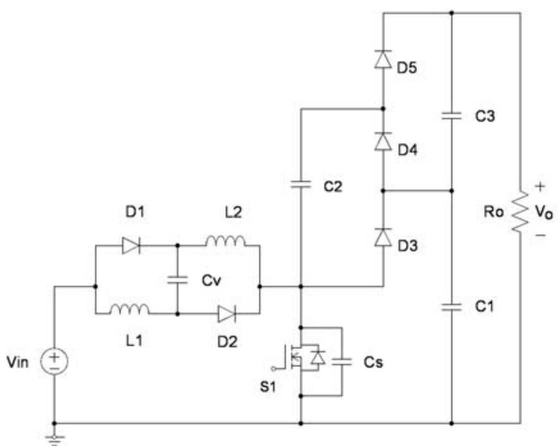


Fig.2. Two level DC/DC boost converter

The proposed DC-DC boost converter is shown in Fig. 2. The circuit topology of the voltage-lift switched-inductor with two level boost converter schematic contains two important parts: the voltage-lift switched-inductor cell is composed of two inductors L_1 and L_2, two diodes D_1 and D_2, and a charge pump capacitor C_v. Another, the two level voltage multiplier cell consist of three diodes D_3, D_4 and D_5, three capacitors C_1, C_2 and C_3. The electrical energy is transferred from low voltage source V_i to the first parts next to the second part and the output load R.

Analysis of operation

Consider a proposed converter in which both inductors L_1 and L_2 have the same value. The following description focuses on discussing the basic operating principles of the proposed converter.

The switching diagrams with main steady-state waveforms during main switch S_1 turned on and turned off period are shown in Fig. 3.

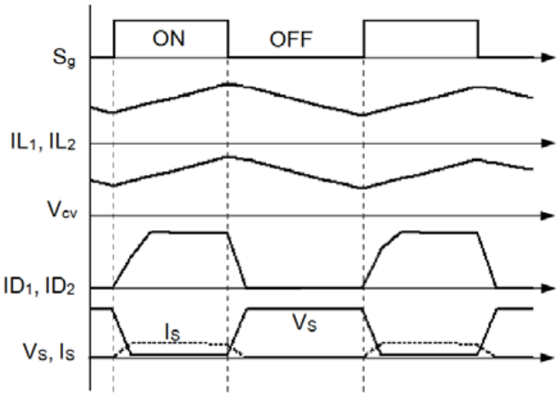


Fig.3. Steady-state waveforms in CCM with L_1 equal to L_2

During the switching on period (Fig. 4a), Inductors L_1 and L_2 are charged in parallel by supply voltage V_{in}. The corresponding voltage across both inductors is equal to V_{in}. Therefore, the equations is

(1) $$V_{L_1} = V_{L_2} = V_{in}$$

At the same time capacitor C_v is charged by V_{in} through diode D_1. The capacitor C_1 is discharged to capacitor C_2 through diode D_4. The expression is

(2) $$V_{Cv} = V_{in}$$

Therefore, voltage across each inductor during the switching-on period is

(3) $$V_{L-on} = DV_{in}$$

where: D – switching duty cycle.

During switch S_1 is turned off (Fig. 4b), both inductors L_1 and L_2 releases energy to capacitor C_1 through diode D_3. The capacitor C_3 is charged by C_2 through D_5. The expressions are

(4) $$-V_{in} - V_{L_1} - V_{Cv} - V_{L_2} + V_{C_1} = 0$$

The corresponding voltage across each inductor with voltage balance on the switching period is

(5) $$V_{L-off} = -\frac{(2V_{in} - V_{C_1})}{2}(1-D)$$

The change of each inductor current over one period is zero, then

(6) $$-\frac{(2V_{in} - V_{C_1})}{2}(1-D) = DV_{in}$$

Therefore, the voltage across capacitor C_1 is derived as

(7) $$V_{C_1} = 2\frac{V_{in}}{1-D}$$

For two-level converter, the output voltage is expression as

(8) $$V_o = 4\frac{V_{in}}{1-D}$$

Assume the average value of capacitor current over the period is zero, the average input current is

(9) $$I_{in} = 16\frac{V_{in}}{(1-D)^2 R} = 4\frac{I_o}{(1-D)}$$

where: I_o - output current.

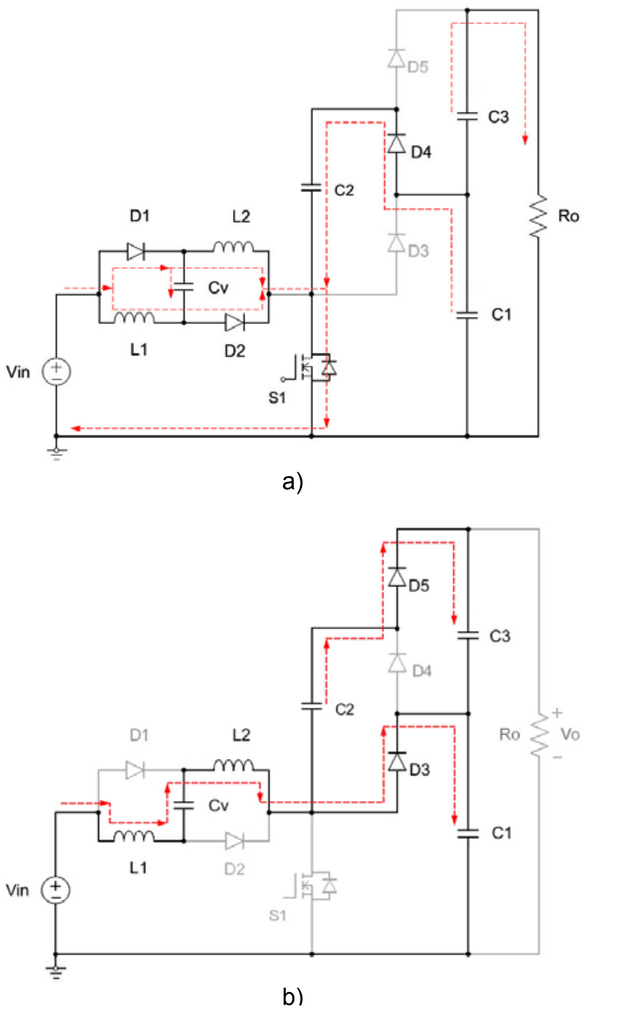


Fig.4. Current flow during: a) switching-on period; b) switching-off period.

Since the peak-to-peak current variation of inductor L_1 current during switching on period i_{L1} is denoted as

(10) $$\Delta i_{L_1} = \frac{DTV_{in}}{L_1}$$

The minimum current of inductor L_1 is

(11) $$I_{min\,L_1} = I_{L_1} - \frac{\Delta i_{L_1}}{2}$$

For CCM, The minimum current through the inductor should not less than zero ($I_{minL1} \geq 0$), so that

(12) $$I_{L_1} = \frac{\Delta i_{L_1}}{2}$$

Given $L_1 = L_2 = L$, The boundary between CCM and DCM is obtained as the minimum value of the inductor.

(13) $$L_{min} = \frac{D(1-D)^2 R}{8f}$$

The voltage-lift switched-inductor DC/DC multilevel boost converter circuit is shown in Fig.5, by adding the multiplier cells. The steady-state characteristics of converter circuit are listed in Table 1.

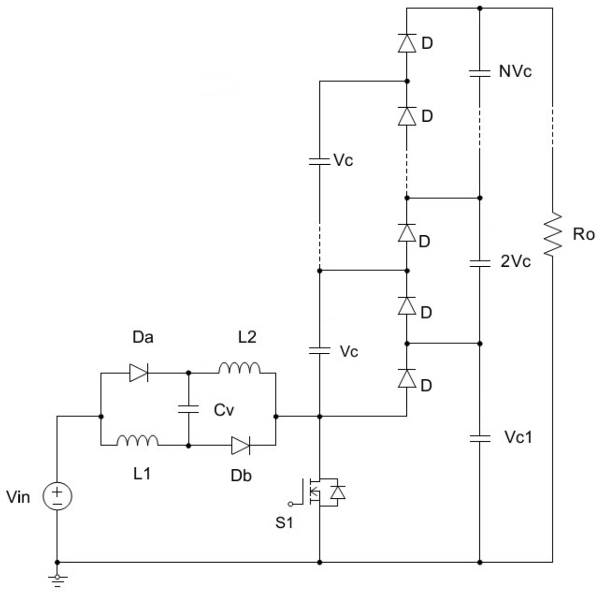


Fig.5. General topology of N-level boost converter.

Table 1. The characteristics of multilevel circuit

N-level converter		
Voltage gain	Average input current	Inductor current
$\frac{2N}{1-D}$	$\frac{4N^2 V_{in}}{R_o(1-D)^2}$	$\frac{2N^2 V_{in}}{R_o(1-D)^2}$

where, N - number of levels of converter.

Switches' and diode's voltage drop

In actual implementations the voltage drop across the switches and all diodes must be taken into account. For simplicity, the voltage drop in switches and diodes is assumed to be equal to V_d. Therefore, the voltage across capacitor C_1 is derived as

(14) $$V_{C_1} = \frac{2Vin - (1+D)Vd}{1-D}$$

The advantage of the multilevel converter topology is that it provides an output of several capacitors in series with the same voltage. According to [11], the efficiency of the multilevel converter is given by

(15) $$\eta = 1 - \frac{(N-1)4V_d}{NV_c}$$

The power losses of the proposed converter circuit can be calculated as follows

(16) $$P_{loss} = P_{in} - P_{out}$$

(17) $$P_{loss} = P_{in} - \eta P_{in}$$

where, $P_{in} = V_{in} I_{in}$.

From (15) and (17), the power losses is defined as

(18) $$P_{loss} = \frac{16(N-1)V_{in}V_d I_o}{N\left[2V_{in} - (1+D)V_d\right]}$$

Simulation and experimental result

Voltage-lift switched-inductor two level boost converter is implemented in the laboratory to demonstrate the practicability of the proposed converter. The proposed converter is operated in CCM under full-load condition. The minimum value of both inductors is calculated from equation (13), all circuit parameters are shown in Table.2.

Table 2. Specifications of proposed converter

2-level converter	
Capacitors Cv, C_1, C_2, C_3	220 μF
Inductors L_1, L_2	600 μH
Load resistor R_o	250 Ω
Input voltage V_{in}	12 V.
Switching frequency f	50 kHz
Duty Cycle	0.5

The simulation software PSIM was applied the proposed converter in the open-loop operation. All diodes and switch are ideal.

In Fig. 6 shows the startup traces of output voltage V_{Load} and output current I_{Load} from the zero condition to the steady state. The measured value of V_{Load} = 95.5 V and I_{Load} = 637.0 mA.

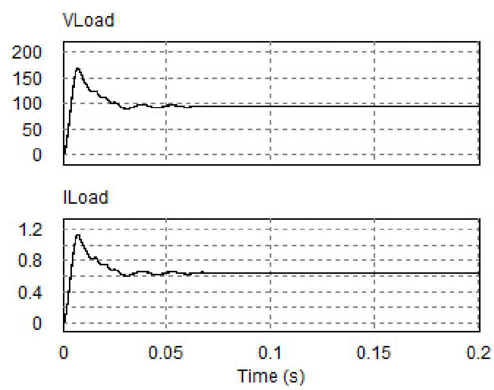


Fig.6. Startup trace of proposed converter circuit.

In the hardware testing circuit, the parameter is the same value as simulation. The N-channel mosfet IRF2807PBF is selected as the power switch S_1. The drain-source resistance is 13.0 mΩ. All diode are realised by using MUR460, the forward voltage drop is 1.05 V. Therefore, the practical output voltage is smaller than the theoretical because of the effects of parasitic parameter.

The output voltage and output current waveform are shown in Fig. 7 when the input voltage V_{in} = 12 V. With an accurate X10 voltage probe, under the steady state condition the output voltage can be kept at 82.2 V.

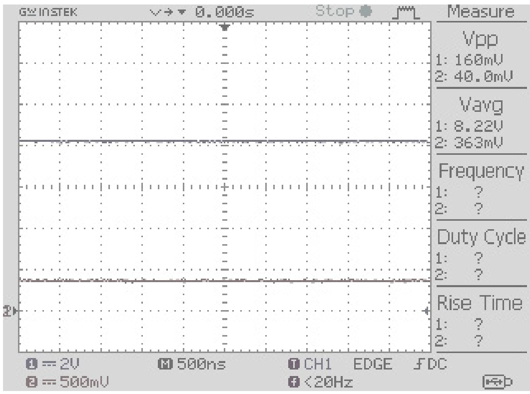


Fig.7. Measured waveform: (above) The Output voltage with an X10 probe; (below) output current.

Conclusion

A voltage-lift switched capacitor DC/DC multilevel boost converter is proposed in this paper. The proposed converter topology combines the function of voltage-lift switched-inductor cell and voltage multiplier cell to get more high voltage gain without transformer. The operation principle and steady state performance are analysed. The PSIM simulation results and an experimental result verify that high step-up voltage gain can be achieved.

Moreover, the advantages of this proposed converter are that it needs only one power dive switch, more level can be obtained by adding the diode-capacitor voltage multiplier cell. Another disadvantage of the proposed converter is that for higher level, more passive component will be used.

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