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Dual Charge Pump DC-DC Multilevel Boost Converter

***Abstract**. An extra-high voltage gain, non-isolated dual charge-pump DC-DC multilevel boost converter is described in this paper. The proposed converter circuit is divided into two parts: dual charge-pump switched-inductor cell and a multilevel converter. A detailed analysis of operating modes and characteristics of the converter were presented and verified by the experimental results of the prototype circuit when operated at 20 kHz switching frequency with 12V input voltage, and 100W power.*

Streszczenie.** Opisano wielopoziomowy przekształtnik DC-DC z dużym wzmocnieniem napieciowym I opodwójnym pompowaniem ładunku. Układ przekształtnika jest podzielony na dwie części: przełśczny dławik z podwójnym pompowaniem oraz wielopoziomowy przekształtnik. Zbadano prototyp układu pracujący przy częstotliwości przełączania 20 kHz o mocy 100 W. **Przekształtnik DC-DC typu boost z podwójnym pompowaniem ładunku.

Keywords: Dual charge pump, Multilevel boost converter, DC-DC converter, Non-isolated.
Słowa kluczowe: przekształtnik DC-DC, przekształtnik typu boost, podwójne pompowanie ładunku.

Introduction

The important requirements of DC-DC boost converters for industrial applications such as computer periphery power supplies, car auxiliary power supplies, servo motor drives, telecommunication systems, medical equipment and distributed generation systems are high voltage gain and high efficiency [1],[2]. The traditional step-up DC-DC boost converter cannot meet these requirements. A number of researches studied new topologies which could meet these requirements with less cost [3],[4]. The step-up DC-DC boost converter topologies can be classified into two categories: isolated and non-isolated topologies [5]. Isolated topologies using transformer(s) provide higher voltage ratio than non-isolated topologies. However, high leakage of inductance in the transformer cause high voltage stresses on the switches, which then reduces the efficiency of the topologies [6]-[7]. As a result, the non-isolated topologies may typically provide better efficiency and faster dynamic responses due to the absent of transformer(s) [8]. Therefore, this research focused on the non-isolated topologies.

Capacitive charge pump circuits are often used in many applications; where capacitors are used as the energy storage elements that create higher voltage level than the power supply. A high step-up voltage converter circuits with charge pump capacitor have been presented in [9]-[12]. The main advantages of charge pump technique is high static gain without the use of transformer. In [13], a very high multiple-lift circuit using a charge pump capacitor, two charge pump diodes and a coupled inductor for each cell was proposed. However, the use of coupled inductor lead to some problems in leakage inductance. The techniques of voltage lift, voltage multiplier and clamp mode are also used in the topology [14]. However, it has some drawback of high switching stress.

In order to overcome that problem, multilevel boost converter with dual charge-pump is proposed in this paper. A combination of two parts by connected them in series can provide a very high voltage gain as well as higher efficiency. The theoretical analysis of the proposed converter under different modes are provided in Section 2. The designed parameters are presented in Section 3. The experimental results of the circuit prototype with 100 W, 12 V input is shown in Section 4; following by the conclusion - Section 5.

Analysis of the proposed converter

Fig. 1 shows the proposed non-isolated, dual charge-pump DC-DC multilevel converter. There are two switches in the circuit. The topology follows the voltage-lift cells integrated with multilevel converter [15]-[19]. The switch S1 and S2 are operated symmetrically with the same duty ratio D.

In this section, some specifications and assumptions are given as follows: (i) the input voltage is denoted to be V_i; (ii) the input current is denoted to be I_i; (iii) the values of L_1, L_2 and L_3 are the same; (iv) the voltage across L_1, L_2 and L_3 are denoted by V_{L1}, V_{L2} and V_{L3} respectively; (v) the values of C_{b1}, C_{b2}, C_1, C_2 and C_3 are large enough to maintain a constant voltage across its terminals, equal to V_{Cb1}, V_{Cb2}, V_{C1}, V_{C2} and V_{C3} respectively; (vi) the output voltage is signified by V_o.

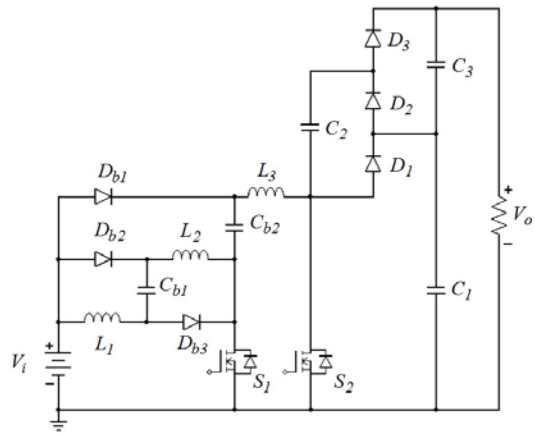


Fig. 1. Proposed dual charge-pump multilevel converter

A. Continuous Conduction mode (CCM)

If the converter operates in CCM, there are two states in one switching period with the key waveforms as shown in Fig. 2. The equivalent circuits during the ON and OFF stages are shown in Fig. 3 (a) and (b), respectively.

Mode 1 [t_0, t_1]: At t_0, both S_1 and S_2 are turned on. Hence, charge pump diodes D_{b1}, D_{b2} and D_{b3} are also turned on. The inductor currents through all inductors increase linearly and the energy is stored in these inductors. The constant voltages appear across the inductors equally to the input voltage V_i. At the same time, charge pump capacitors C_{b1} and C_{b2} are charged. The voltage drop across each charge pump capacitor is equal to V_i. Therefore

$$(1)\qquad \begin{cases} V_{L1} = V_{L2} = V_{L3} = V_i \\ V_{Cb1} = V_{Cb2} = V_i \end{cases}$$

The corresponding voltage across each inductor during this converter operating period is

(2) $$V_{L-on} = DV_i$$

Mode 2 [t_1, t_2]: At t_1, both S_1 and S_2 are turn off. Hence, all charge pump diodes are turned off. The inductors and charge pump capacitors are connected in series. The currents in series all inductor decrease linearly. The energy stored in each inductor and each charge pump capacitor releases to C_1 through D_1. The corresponding equations are

(3) $$-V_i - V_{L_1} - V_{Cb_1} - V_{L_2} - V_{Cb_2} - V_{L_3} = 0$$

The corresponding voltage drop across each inductor during the switching-off period is

(4) $$V_{L-off} = \frac{-3V_i + V_{C1}}{3}(1-D)$$

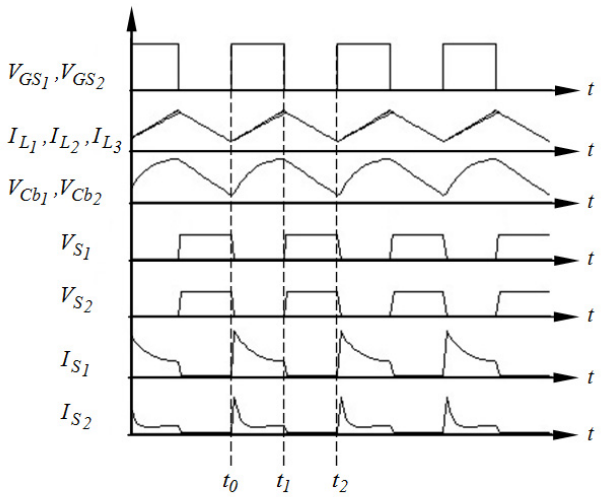


Fig. 2. Key waveforms of the proposed converter.

Applying the voltage-second balance to the inductors obtain the following equation

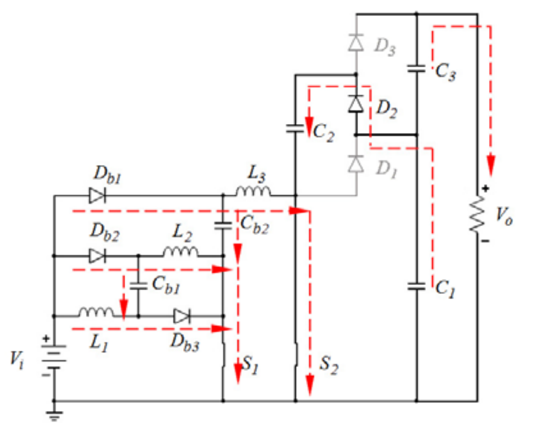
(5) $$\frac{-3V_i + V_{C1}}{3}(1-D) = DV_i$$

Therefore, the voltage drop across C_1 is derived as

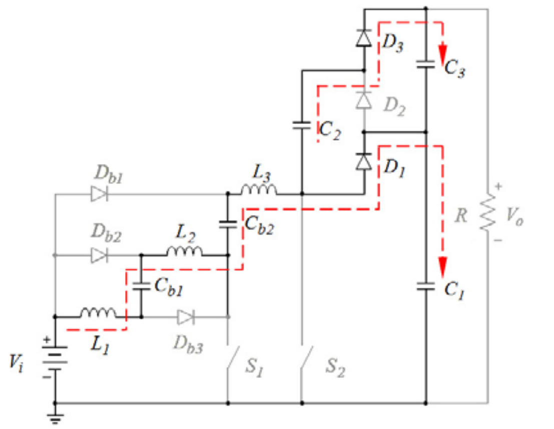
(6) $$V_{C_1} = \frac{3}{1-D}V_i$$

According to the self-balanced voltage level of multilevel converter, the converter voltage gain can be expressed by

(7) $$\frac{V_o}{V_i} = \frac{3 \times 2}{1-D}$$



(a) Switching ON state topology



(b) Switching OFF state topology

Fig. 3. Topological states in CCM for the proposed converter.

B. Discontinuous Conduction mode (DCM)

The dual charge-pump DC-DC multilevel converter will operate in DCM mode if the current I_{L3} reduce to zero during switching-off period and remain to this value until the switch S_2 is turned on. For easier analysis, define average output current equals average input current. Thus,

(8) $$\frac{V_o}{R} = \frac{I_{D_3} D_M T}{2T}$$

Since all inductors are the same values and set to L, the related equations can be expressed as

(9) $$\frac{V_o}{R} = \frac{\left(\frac{V_i}{L}DT\right)D_M T}{2T}$$

where D_M is the PWM turn-off demagnetizing ratio, it is equal to $\frac{DV_i}{\frac{V_o}{6} - V_i}$, substituting this equation in to (9) yields the voltage gain of the converter in DCM as

(10) $$\frac{V_o}{V_i} = 3 + \sqrt{9 + \frac{3D^2}{k}}$$

where, $k = fL/R$

C. Boundaries between CCM and DCM

According to (7) and (10), the critical value of k, for the converter to be operated in boundary conduction mode, k_{crit} results in

(11) $$k_{crit} = \frac{D(1-D)^2}{12}$$

From (11), the curve of k_{crit} versus D is obtained, as draw in Fig. 4. For $k < k_{crit}$, converter operates in DCM, otherwise in CCM.

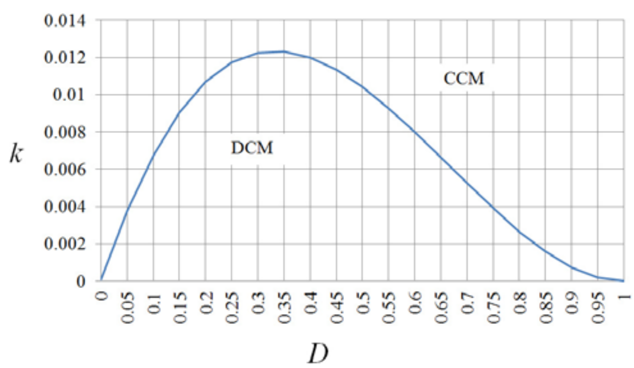


Fig. 4. Boundary condition between CCM and DCM

Designed Parameter

Fig. 5 depicts the N-level dual charge-pump DC-DC boost converter. For CCM operation, it is assumed that components are lossless and the output power equal to the input power. The average input current can be expressed as

(12) $$I_i = \frac{9N^2 V_i}{R(1-D)^2}$$

In case of all inductors are the same values, the current through each inductor is

(13) $$I_{Lavg} = \frac{3N^2 V_i}{R(1-D)^2}$$

Then, the minimum current of each inductor is obtained as

(14) $$I_{L\,min} = \frac{3N^2 V_i}{R(1-D)^2} - \frac{V_i DT}{2L}$$

To achieve the input current requirement in CCM operation, the inductors value must be

(15) $$L_{min} = \frac{RD(1-D)^2}{6\,fN^2}$$

According to the voltage ripple of the charge pump capacitors, the value of C_{b1} and C_{b2} can be expressed as

(16) $$C_{b1,2} \geq \frac{DI_o}{\Delta V_{o,max}\, f}$$

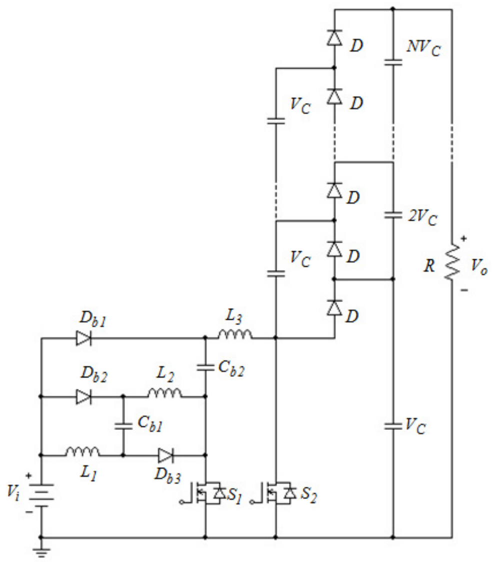


Fig. 5. N-level dual charge-pump DC-DC converter

Experimental Results

In this section, the practical aspect of the proposed converter and the design system developed in CCM were verified with the implementation of a low-power prototype.

The experimental result of a small prototype converter for V_i = 12V was presented. Fig. 6 displays the test bench. The values of all inductors are L_1=L_2=L_3=250µH. All the charge pump capacitors are C_{b1}=C_{b2}=220µF. All charge pump diodes are RHRP8120. The switches are the IRF2807PBF. In the section of multilevel converter, all the capacitors are 220µF-250V aluminum electrolytic and all fast diode are MUR460. Load resistor is R=200Ω . The proposed converter operates at 20 kHz and the duty cycle is 50%. The key wave forms of the experimental converter are shown in Fig.7 and 8.

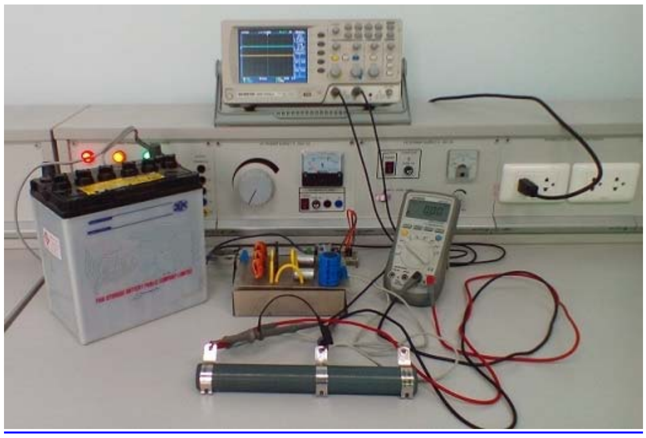
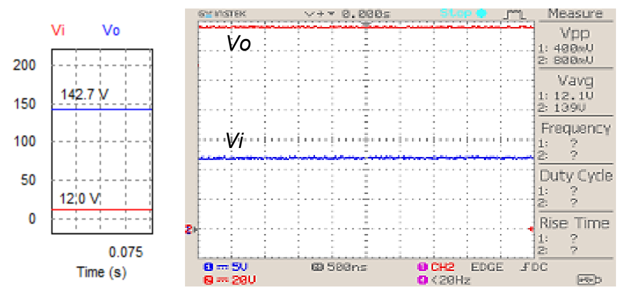
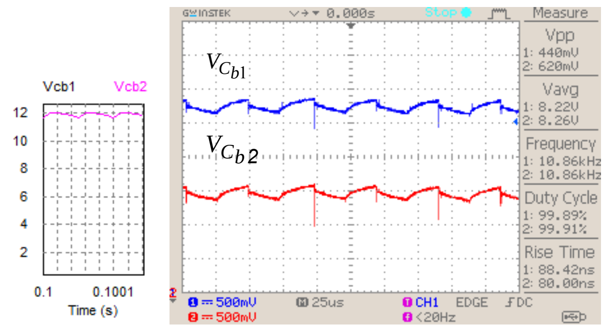


Fig. 6. A 100W prototype of a two level dual charge-pump DC-DC converter setup



(a) (b)

Fig. 7. (a) Simulated and (b) Experimental input and output voltage



(a) (b)

Fig. 8. (a) Simulated and (b) Experimental voltage drop across charge pump capacitors

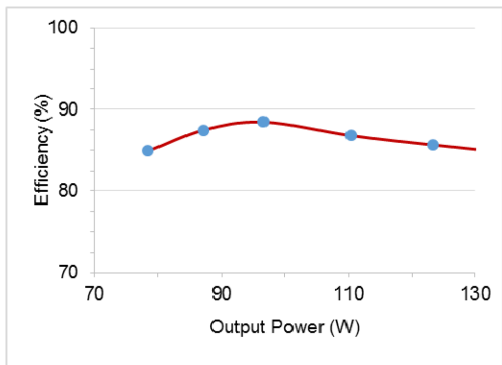


Fig. 9. Efficiency against output power of the proposed converter

Fig. 7 and 8 reveal the similarity between the simultaion and the experimental waveform. Fig. 7 depicts the input voltage (*Vi*) and output voltage (*Vo*) waveforms at rated power. Fig. 7(a) show the simulated waveform, the ideal output volage without the parasitic component consideration is 142.7 V. Fig. 7(b), an output voltage of 139 V is achieved with an input voltage of 12.1 V at the duty ratio of 0.5. The voltage waveforms across charge pump capacitor C_{b1} and C_{b2} are depicted in Fig. 8. The measured power conversion efficiency under full load condition is about 88% as shown in Fig. 9.

Conclusion

This paper proposes a dual charge-pump DC-DC multilevel boost converter. The high voltage ration can be obtained without an isolating transformer or utilizing extreme values of duty cycles. The structure of proposed converter consists of two components: the voltage-lift cell and multilevel converter. The voltage-lift cell is formed by charge pump capacitors and switched-inductors. The voltage-lift cell is used as the first stage to step up the voltage level of the DC source. A multilevel converter based on the diode-capacitor multiplier. The multilevel converter is used to generate more high DC voltage from the first stage. These structures make the output voltage of the proposed converter achieve very high voltage gain and envey higher by adding more circuits at the second step.

The theoretical analysis and designed procedure for the proposed boost converter have been presented. The experimental results agreed with theoretical calculation and simulation, which could comfirm the feasibility of the proposed converter.

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