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A New Bidirectional DC-DC Converter with a High Step-up/down Conversion Ratio for Renewable Energy Applications

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Abstract–A new bidirectional dc-dc converter based on switched-capacitor-inductor cell was proposed. It features: high step-up/down conversion ratio with a moderate duty cycle; low voltage stress on the switches; non-pulsating input current (step-up mode); easiness of control and driving circuit. The proposed converter contains five switches and four reactive elements (two capacitors and two inductors). It can achieve quadratic-like conversion ratio. Steady-state for both step-up mode and step-down mode were analyzed in this paper and the proposed converter was simulated by PSIM. Results of step-up mode from 66V to 400V, or step-down mode from 400V to 66V, matched the theoretical analysis. Further examinations and experiments can be done to optimize the performance of the circuit. The proposed converter can be widely used as front-end to renewable energy system, e.g. between battery and DC bus, where bidirectional power flow is required.

Key words: switched-capacitor-inductor cell, high conversion ratio, bidirectional power flow, low voltage stress.

I. Introduction

In recent years, bidirectional dc-dc converters are widely used due to the fast development of renewable energy sources [1-5]. For example, in PV distribution generations, when there is less energy required in the dc bus, the excessive output power is stored in the batteries. In peak hours, when more energy is required, the previous stored energy is transferred back to the dc bus (normally 380V) through bidirectional dc converter. In electric vehicle systems, the on-board battery is charged with a relatively low voltage, but a high output voltage has to be provided in order to drive the electric motors. In telecommunication systems working with a 400V dc voltage, usually backup battery with a bidirectional dc converter are needed to ensure the uninterruptible power supply (UPS).

As a result, in the aforementioned applications, bidirectional dc converter with a large conversion ratio becomes more and more popular [6-12]. As addressed by many related publications, there are many solutions for high voltage conversion ratio bidirectional dc converters. Transformer based bidirectional dc converters obtain a large conversion ratio simply by adding more turns at the secondary side of the magnetic core [6-9]. However, due to the bulky size of transformer, the power density decreases. Sometimes, additional circuits for dealing with leakage inductance have to be added.

The pure switched-capacitor (SC) converters also offer a good solution for large dc gain converters, and bidirectional power flow can be achieved by replacing passive switches with active switches [10, 15]. However, the conversion ratio of the SC converter is mostly an integer, i.e. output voltage is N times of input voltage ($\mathrm{N} > 0, \mathrm{N} \in \mathrm{Z}$). To achieve a non-integer conversion ratio that can be regulated by duty cycle, special control strategies should be adopted, which increases the complexity of the circuitry. And the number of components (switches and capacitors) increases as conversion ratio goes up. Interleaved bidirectional dc converter is another possible solutions [11, 16]. One of its advantages is the smaller input current ripple that will increase the line-to-load efficiency. But the disadvantage is that the voltage stress on the switches is still very high, usually is equal to high side voltage V_H.

In this paper, a novel bidirectional dc converter is proposed (Fig. 1). The proposed converter contains 4 reactive elements and five switches. But only two gating signals working in complementary way are required to drive the circuit. Derivation of the proposed converter starts from a switched-capacitor-inductor converter from [12]. Bidirectional power flow is achieved in this converter by using active switches. A quadratic-like conversion ratio is given in both step-up mode and step-down mode. The maximum voltage stress on the switches is lower than V_H, due to which, transistors with low on-resistance (R_{ds_on}) can be selected. The proposed converter will also be compared with other converters [11-17]. Steady-state analysis for the two modes under continuous conduction mode (CCM) were given in detail below.

II. Theoretical Analysis of The Proposed Bidirectional DC Converter

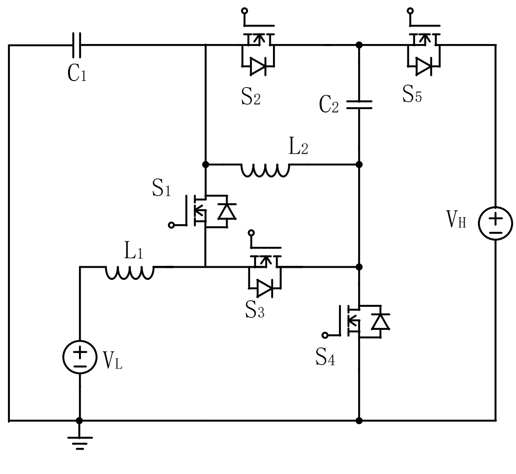


Fig. 1. Proposed bidirectional dc converter

To simplify the analysis, the following assumptions were considered in this section:

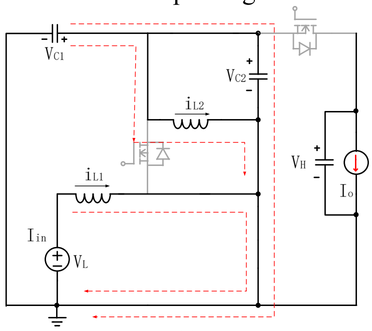
1) All the switches are in ideal state, and $\mathrm{R}_{ds\_on} = 0$.
2) Parasitic resistance of the reactive elements is neglected.
3) Rising time and falling time of the gating signal is neglected.
4) Small ripple approximation, i.e. voltage ripples across the capacitors are neglected.

5) Voltage source V_L (V_H) is constant.

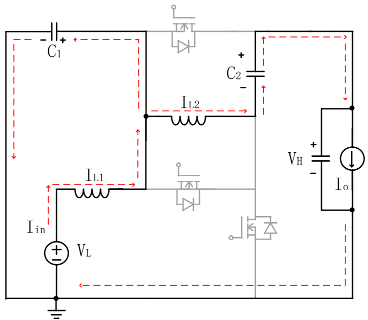
The assumptions have been applied to both step-up and step-down modes which are analyzed in detail below. The converter discussed here is in the field of quadratic converters. Similar quadratic converters with switched capacitor based can also referred to [18].

A. Step-up Mode Analysis

The switching stages of the proposed converter in step-up mode are illustrated in Fig. 2. A filter capacitor can be parallel connected to the output to get a constant voltage.



(a)



(b)

Fig. 2. Switching stages of the proposed converter in step-up mode. (a) First stage (0<t<DT). (b) Second stage (DT<t<T)

In the first stage when switches S_2, S_3 and S_4 are turned on, inductor L_1 is charged by line voltage V_L with its current increasing linearly. Inductor L_2 is charged by capacitor C_1 and its current is also increasing linearly. Capacitor C_2 is charged by capacitor C_1 very quickly and later the energy transfer process between the two capacitors stops. During the first stage, equations can be written:

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

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

$$V_{C2} = V_{C1} \quad (3)$$

In the second stage when switches S_1 and S_5 turned on, input voltage in series with inductor L_1, L_2 and capacitor C_2 transfers energy to the output load. In this stage, two current loops are formed (Fig. 2(b)). Inductor L_1, L_2 and capacitor C_2 are discharged, while capacitor C_1 is charged. From the two current loops, equations can be found.

$$V_L - V_{L1} - V_{L2} + V_{C2} = V_H \quad (4)$$

$$V_L - V_{L1} = V_{C1} \quad (5)$$

Of the two stages, applying volt-sec balance on the two inductors, one can get:

$$\mathrm{DT}V_L + (1-\mathrm{D})\mathrm{T}(V_L + V_{C2} - V_{L2} - V_H) = 0 \quad (6)$$

$$\mathrm{DT}V_{C1} + (1-\mathrm{D})\mathrm{T}(V_L + V_{C2} - V_{L1} - V_H) = 0 \quad (7)$$

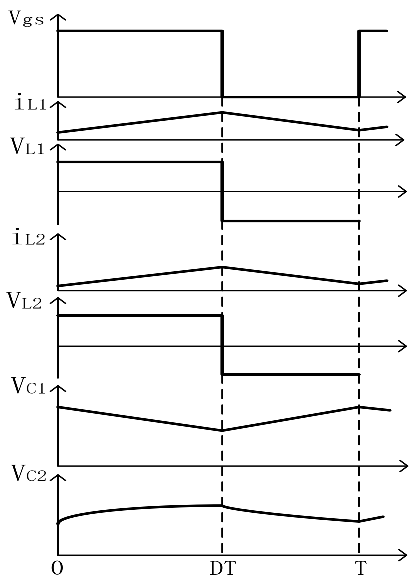
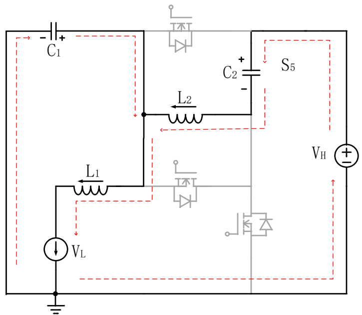
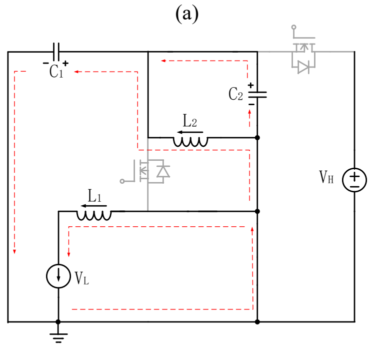


Fig. 3. Key waveforms of the proposed converter in step-up mode



(a)



(b)

Fig. 4. Switching stages of the proposed converter in step-down mode. (a) First stage. (b) Second stage

By solving eqn. (4-7), one can derive the voltage across the capacitors

$$V_{C1} = V_{C2} = \frac{V_L}{1-\mathrm{D}} \quad (8)$$

And the voltage conversion ratio of step-up mode can be found

$$M_{up} = \frac{V_H}{V_L} = \frac{2-\mathrm{D}}{(1-\mathrm{D})^2} \quad (9)$$

The key waveforms for the reactive components of the proposed converter in step-up mode are shown in Fig. 3.

B. Step-down Mode Analysis

The switching stages of the proposed converter in step-down mode are shown in Fig. 4. In the first stage when switches S_1 and S_5 are turned on, capacitor C_1 charges inductor L_1 and supplying the output V_L at the same time. Capacitor C_2 in series with inductor L_2, L_2 is charged by input voltage V_H. V_H is also supplying V_L in this stage. Thus,

$$V_L + V_{L1} = V_{C1} \quad (10)$$

$$V_L + V_{L1} + V_{L2} + V_{C2} = V_H \quad (11)$$

In the second stage, switches S_2, S_3 and S_4 are turned on. There are three current loops in the equivalent circuit:

a) Inductor L_1 discharges, energy transferred from L_1 to the output.

b) Inductor L_2 discharges capacitor C_1.

c) Capacitor C_2 discharges capacitor C_1.

By small ripple approximation, one can get the following equations.

$$V_L = V_{L1} \quad (12)$$

$$V_{L2} = V_{C2} \quad (13)$$

$$V_{C2} = V_{C1} \quad (14)$$

By applying volt-sec balance on the two inductors in step-down mode, one can get

$$DT(V_{C1} - V_L) + (1-D)T(-V_L) = 0 \quad (15)$$

$$DT(V_H - V_L - V_{C2} - V_{L1}) + (1-D)T(-V_{C1}) = 0 \quad (16)$$

By solving eqn. (10-16), the voltage conversion ratio of step-down mode can be found

$$M_{down} = \frac{V_L}{V_H} = \frac{D^2}{1+D} \quad (17)$$

C. Component Voltage and Current stresses

The voltage and current stresses on the components are calculated based on the boost mode (Fig. 2 (a, b)). The same results can be obtained from buck mode.

Equation (8) denotes the capacitor voltage stress. From Fig. 2 (a, b), the voltage stress on the switches can be immediately found. Their values are listed in the Table I.

Let I_{s1}-I_{s5} denote the average current flow through the switches S_1-S_5 when they are turned on; I_{in} the average input current, and I_o the output current.

Hence,

$$I_{s5} = I_o \quad (18)$$

$$I_{s1} = I_{s3} = I_{in} \quad (19)$$

The average inductor current

$$I_{L1} = I_{in} \quad (20)$$

$$I_{L2} = I_o \quad (21)$$

Applying charge balance on capacitor C_2,

$$DI_{s2} = (1-D)I_{s5} \quad (22)$$

one can get

$$I_{s2} = \frac{(1-D)}{D} I_o \quad (23)$$

$$I_{s4} = I_{s3} + I_{s2} + I_{L2} = \frac{1+D-D^2}{D(1-D)^2} I_o \quad (24)$$

The RMS of capacitor current can be calculated by

$$I_{C1\_rms} = \sqrt{(I_{L2} + I_{s2})^2 D + (I_{in} - I_o)^2 (1-D)} \quad (25)$$

$$I_{C2\_rms} = \sqrt{(I_{s2})^2 D + (I_o)^2 (1-D)} \quad (26)$$

RMS value of the components current are also listed in Table I. One can see that the voltage stress on every switch is very low. For the switch S_3, even less than half of V_H is achieved. So the low total voltage stress for the proposed converter is maintained.

Table I. Voltage and Current Stresses for Switches and Capacitors.

Compo-nents	Voltage Stress	Average current	RMS current
S_1	$\frac{1-D}{2-D}V_H$	I_{in}	$I_{in}\sqrt{1-D}$
S_2	$\frac{1}{2-D}V_H$	$\frac{(1-D)}{D}I_o$	$\frac{(1-D)}{\sqrt{D}}I_o$
S_3	$\frac{D}{2-D}V_H$	I_{in}	$\sqrt{D}I_{in}$
S_4	$\frac{1}{2-D}V_H$	$\frac{1+D-D^2}{D(1-D)^2}I_o$	$\frac{1+D-D^2}{\sqrt{D}(1-D)^2}I_o$
S_5	$\frac{1}{2-D}V_H$	I_o	$I_o\sqrt{1-D}$
C_1	$\frac{1-D}{2-D}V_H$	0	$I_o\sqrt{\frac{D^4-3D^3+2D^2-D}{D(1-D)^3}}$
C_2	$\frac{1-D}{2-D}V_H$	0	$I_o\sqrt{\frac{1-D}{D}}$

The above analysis results show that the proposed converter can achieve a large step-up/down conversion ratio with a moderate duty cycle. Moreover, the voltage stress on the switches is lower than that in the conventional bidirectional dc converter, which is V_H. Lower voltage stress facilitates the usage of switches with lower on-resistance (R_{ds_on}) to reduce losses.

III. Comparison with Available Converters

Table II shows the comparison results of the proposed converter with available non-isolated bidirectional dc converters of similar complexity. The proposed converter has the highest conversion ratio compared to those converters having the same number of reactive elements [13-15]. Converters [16-17] also give a relatively high conversion ratio, but they use more active switches and even coupled-inductors are needed in [16], that will decrease the power transferred efficiency, as well as the power density. Different from the other converters [13-17], the proposed converter needs only two gating signals working in a complementary fashion, which makes the control and driving circuit simple.

Table II. Comparison of the proposed Converter with

Available Converters

Conver-ters	Proposed Conv.	Conv. [13]	Conv. [14]	Conv. [15]	Conv. [16]	Conv. [17]
M_{up}	$\frac{2-D}{(1-D)^2}$	$\frac{2}{1-D}$	$2+D$	3	$\frac{4}{1-D}$	$\frac{4}{1-D}$
M_{down}	$\frac{D^2}{1+D}$	$\frac{D}{2}$	$\frac{1}{2+D}$	$\frac{1}{3}$	$\frac{D}{4}$	$\frac{D}{4}$
Switch count	5	4	5	6	8	6
Inductor count	2	1	1	0	0	2
Capacitor count	2	3	3	4	3	4
Couple inductor	0	0	0	0	2	0
Voltage stress	$\frac{V_H}{2-D}$	$\frac{V_H}{2}$	V_L	$\frac{V_H}{3}$	$\frac{V_H}{2}$	$\frac{V_H}{2}$
Common ground	YES	YES	YES	YES	YES	NO

IV. Design Consideration

The proposed bidirectional dc converter was designed according to the following specifications.
Input voltages: $V_H = 400\text{V}, V_L = 66\text{V}$;
Gating signal: f_s=100kHz, 0.5 duty cycle;
Power: 400 W.

A. Inductor Design

Firstly, from Table I, one can find that the average inductor current of L_1 is equal to the average input current. Considering 10% of an inductor current ripple, the inductance of L_1 is determined as

$$L_1 = \frac{V_L DT}{0.1\bar{I}_L} \geq 550\mu H$$

For inductor L_2, the value of inductance can be determined in a similar way:

$$L_2 = \frac{V_{C1} DT}{0.1\bar{I}_L} \geq 1.1mH$$

B. Capacitor Design

The voltage across the capacitors can be found in Table I. The RMS value of the capacitor current should also be taken into consideration (eqn. (25-26)). After that, electrolytic capacitors of 100µF (ESR 0.05Ω) were chosen in the simulation.

C. Transistor Design

The voltage and current stresses of the switches are calculated according to Table I. Maximum voltage stress:

$$V_{s\_max} = \frac{1}{2-D} V_H = \frac{400}{1.5} = 267\text{V}.$$

RMS current:

$$\frac{1 + D - D^2}{\sqrt{D}(1-D)^2} I_o = 7.07\text{A}$$

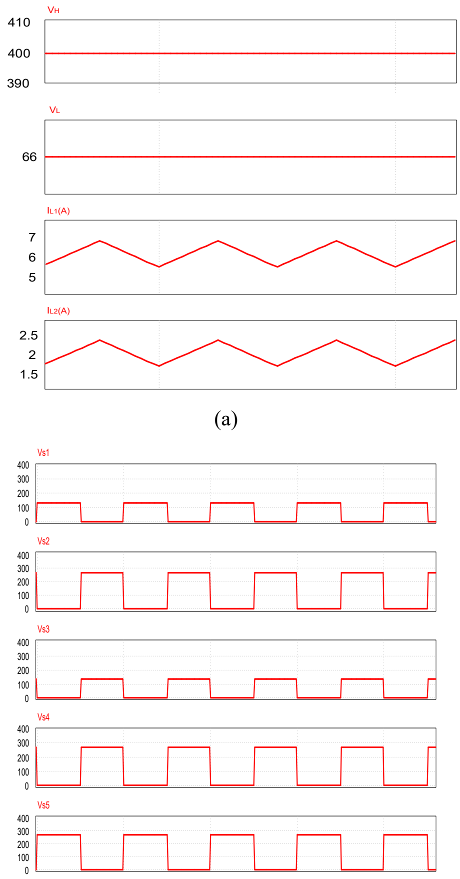
In the simulation, 50mΩ on-resistance was considered.

D. Controller Design

For simplicity, a voltage mode controller with type III compensator was selected in this design. Any changes in the output voltage could be sensed by the voltage sensor immediately and duty cycle regulation was then performed. A pair of complementary gating signals were given by the controller to drive the switches.

V. Simulation Results

A simulation circuit was set up in PSIM. The above design parameters were applied and results are shown as Fig. 5-7. Fig. 5 shows the input and output voltage of boost mode. The inductor current of L_1 and L_2 are also shown in Fig. 5 (a). The switching devices' voltages are shown in Fig. 5 (b). Higher voltage stress can be observed in S_4 and S_5 among the switches. Lower total voltage stress can be tested which confirms the aforementioned advantages of the proposed converter.

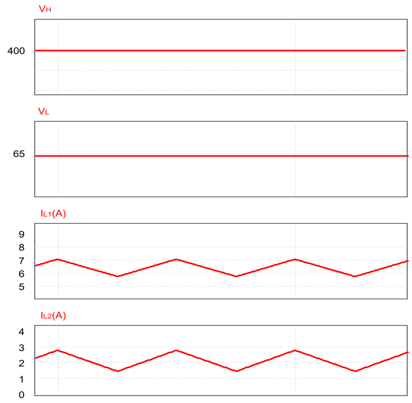


(a)

(b)

Fig. 5. Simulations results of boost mode, (a) output voltage, input voltage and inductors current. (b) Voltage stress on switches $V_{s1} - V_{s5}$.

Fig. 6 presents the waveforms of the proposed converter in buck mode. Current stress of the switches are shown (Fig. 6 (b)). Fig. 7 shows the dynamic response of the proposed converter from half load to full load or full load to half load. Results validate the feasibility of the controller and stability of the proposed converter.



(a)

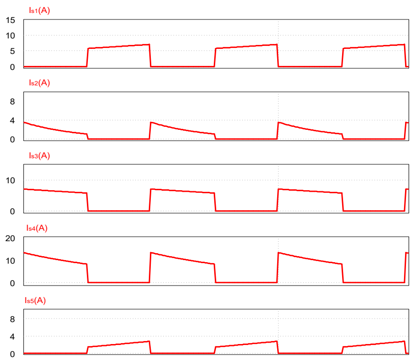


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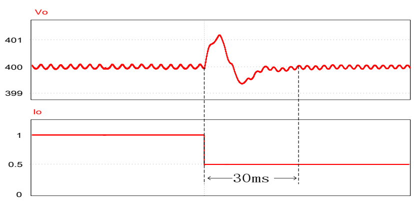
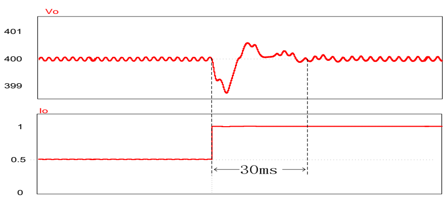
Fig. 6. Simulations results of buck mode, (a) Output voltage input voltage and inductors current. (b) Current of the switches.



(a)



(b)

Fig. 7. Dynamic response of boost mode, (a) step-changes from full load to half load. (b) step-change from half load to full load.

VI. CONCLUSION

A new bidirectional dc converter was proposed, which contains five active switches and 4 reactive elements. It can get a high conversion ratio without using transformers or coupled inductors. Low voltage stress on the switches is achieved. The control of the converter is very simple and relatively high efficiency can be tested. Further experiments will be done to optimize the performance. The proposed converter can be widely used in renewable energy applications where non-isolation is preferred.

ACKNOWLEDGEMENT

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