A study on improving the efficiency of non-isolated buck-boost bidirectional DC–DC converter

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ABSTRACT
In battery-based systems such as hybrid electric propulsion system for ships that use electric propulsion and DC grid, bidirectional converters are often used as interfaces between high-voltage power sources and low-voltage batteries for the purpose of storing excess energy and the fields of application for bidirectional converters are steadily expanding. This study proposes a new bidirectional converter with a high voltage conversion rate and low switch voltage stress. The proposed converter allows current to flow between modules by adding only one capacitor compared to a conventional bidirectional converter. To check the effectiveness of the proposed method, PSIM software by Powersim co. Ltd. was used to perform simulation tests. It was confirmed that the high voltage conversion rate was 4 times that of a conventional bidirectional converter in step-up mode and 1/4 that of a conventional bidirectional converter in step-down mode. Therefore, low-voltage components, such as MOSFETs, GTOs, etc., can be applied in the DC–DC converters thanks to the 1/4 voltage that is required in each switching time.

INTRODUCTION
The use of fossil fuels causes environmental pollution; as a result, the use of clean energy is growing in importance throughout the world. For the past few years, renewable energy systems such as solar energy systems, fuel cell systems, and wind power systems have undergone rapid development. Because new renewable systems cannot provide stable electricity to users, batteries can be used with renewable energy systems in hybrid electrical systems. When renewable energy cannot supply enough electricity to meet the load, the battery compensates for the lack of electricity. The load cannot fully use the total electricity of the renewable energy system, but the excess energy can be used to charge the battery.

Bidirectional converters are widely used in renewable energy systems, UPS (Uninterruptible Power Supplies), PHEV (Plug-in Hybrid Electric Vehicles), and fuel cell vehicles. According to the application, isolated or non-isolated DC–DC bidirectional converters are used as the converters. Isolated converters include flyback converters (Chen et al., 2000; Venkatasan, 1989), forward flyback converters (Huber & Jovanovic, 1999; Zhang & Yan, 2009), half-bridge converters (Li et al., 2003; Peng et al., 2004; B. R. Lin et al., 2008), and full-bridge converters (Mi et al., 2008; Naayagi et al., 2012; Zhao et al., 2010). Isolated full bridge/half-bridge DC–DC bidirectional converters can achieve high step-up /step-down conversion rates by adjusting the turns ratio of the transformer. Adding a transformer to the circuit increases the converter’s capacity but reduces its efficiency and disadvantages of making the circuit complex.

On the other hand, non-isolated converters have high efficiency and a simple structure. Non-isolated bidirectional converters are divided into multi-level, switched capacitor, Cuk/Cuk, SEPIC/Zeta, conventional buck/boost, and buck-boost DC–DC bidirectional converters (C. C. Lin et al., 2013; Lee et al., 2013; Wai & Duan, 2007; Yang & Liang, 2012).

In three-level bidirectional converters, the components’ voltage stress is half of conventional bidirectional converters, but the voltage conversion rate is similar to that of conventional converters. In three-level non-isolated bidirectional DC–DC converters, the components’ voltage stress is half that of the high-voltage side. The voltage conversion rate is twice that of a conventional bidirectional converter in step-up mode and half that of a conventional bidirectional converter in step-down mode (Ching-Tsai et al., 2014). Multi-level and switch capacitor converters require more switches and capacitors to provide a significant voltage gain (Khan et al., 2009; Ko et al., 2011; Lee & Chiu, 2005; Monge et al., 2011; Peng et al., 2003). In this type of converter, the control circuit is complex.

SEPIC/Zeta and Cuk/Cuk DC–DC bidirectional converters are lower than buck-boost converters’ conversion efficiency because they use two inductors and one capacitor in the primary power supply circuit (Jose & Mohan, 2003). Such converters have the disadvantage of a very high or low duty ratio when used for high
step-up or step-down applications, and the voltage applied to the switches is high (Kim et al., 2007). Also, these converters cannot provide a wide voltage conversion range.

Conventional bidirectional DC–DC buck/boost and buck-boost converters are simple to control and have structural advantages. Still, they also have disadvantages in that their duty ratios are unsuitable when used for high step-up/step-down applications and their components must have a high rated voltage (Busquets-Monge et al., 2011). Studies are currently being conducted on bidirectional converters to improve their high step-up/step-down conversion rate and efficiency.

This paper proposes an improved bidirectional DC–DC converter that exhibits low switch voltage stress and a high step-up/step-down conversion rate. This converter consists of three capacitors, four MOSFETs, and a single inductor. The two capacitors on the high-voltage side are charged in step-up mode and discharged in step-down mode. It is possible to obtain a high step-up/step-down conversion rate without using a transformer or incurring an extremely high or low duty ratio.

Conventional bidirectional DC–DC converter

Figure 1 shows the basic equivalent circuit of a conventional bidirectional converter. It consists of the switch $S_1$ that operates the PWM during step-up operation and the switch $S_2$ that uses the PWM during step-down operation.

In step-up mode, energy accumulates in the inductor, while the switch $S_2$ is turned on (DT), and at this time, the inductor voltage is the same as the battery voltage.

$$V_{L1} = V_L$$  \hspace{1cm} (1)

When the switch $S_2$ is turned off ([1-D]T), the energy accumulated in the inductor is transferred to the load together with the input power, and the inductor voltage at this time is as shown in Eq. (2).

$$V_{L1} = V_L - V_H$$  \hspace{1cm} (2)

The inductor voltage’s mean value for one cycle in a steady state is $V_{L1} = 0$; therefore, the following equation can be established.

$$V_{L1} \cdot T = V_L \cdot DT + (V_L - V_H) \cdot (1-D)T = 0$$  \hspace{1cm} (3)

The conventional converter’s step-up DC–DC conversion rate is as shown in Eq. (4).

$$G_{up} = \frac{V_H}{V_L} = \frac{1}{1 - D}$$  \hspace{1cm} (4)

If the same process is used in step-down mode, the conventional converter’s step-down DC–DC conversion rate is as follows

$$G_{down} = \frac{V_L}{V_H} = D$$  \hspace{1cm} (5)

Improved bidirectional DC–DC converter

Principle of operation

Figure 2 shows the converter that is proposed by this paper. It consists of four MOSFETs, three capacitors, and one inductor.

The series capacitors evenly distribute the voltage to reduce the voltage stress on the MOSFETs and increase the converter’s step-up/step-down conversion rate. In continuous current mode, this converter has a high step-up/step-down conversion rate and automatic current adjustment capability when it has a duty ratio of more than 0.5 in step-up mode or a duty ratio of less than 0.5 in step-down mode. On the other hand, in non-continuous current mode, the converter may lose its current distribution adjustment capability, and additional current adjustment methods are needed. The addition of MOSFETs and capacitors increases the cost and switching losses compared to conventional converters.

Step-up mode

Figure 3 shows the typical major waveforms of the proposed converter in step-up mode. In addition, the converter has four operating modes in both step-up mode and step-down mode. Figure 4 shows the equivalent circuits of the converter as it operates in sequence.

\[ \text{Figure 1. Conventional DC–DC bidirectional converter.} \]

\[ \text{Figure 2. Proposed Improved DC–DC bidirectional converter.} \]
during one cycle in step-up mode. The operation of the converter in step-up mode is shown in Figures 3 and 4.

The gate signals of the $S_2$ and $S_3$ switches are similar, and the $S_1$ and $S_4$ switches operate through a diode. The operating status at each time interval is shown below.

**Mode 1**

In this mode, $S_2$ and $S_3$ are turned on, and $S_1$ and $S_4$ are turned off. The current flow path is shown in Figure 4(a).

Figure 3 shows that it increases linearly. The energy of the low-voltage side $V_L$ is transferred to the inductor $L_1$. The capacitors $C_{H1}$ and $C_{H2}$ are stack for discharge of the load $V_H$. Therefore, the voltage across the inductor $L_1$ is as follows.

$$V_{L1}^{(1)} = V_L$$

(6)

The current flowing to the inductor $L_1$ is as follows.

$$i_{L1}^{(1)}(t) = i_{L1}(t_0) + \frac{V_L}{L_1}(t - t_0)$$

(7)

**Mode 2**

Switches $S_1$ and $S_3$ are $S_2$ and $S_3$ are turned on, and switches $S_2$ and $S_4$ are turned off. The current flow path is shown in Figure 4(b). In this mode, the $L_1$ current of is reduced. The low-voltage side and inductor energies release their energies to the capacitor.

Capacitors $C_{H1}$ and $C_{H2}$ are stacked to discharge the load ($V_H$).
Therefore, the voltage across the inductor \( L_1 \) is as follows.

\[ v_{L1}^2 = V_L - \frac{V_H}{2} \tag{8} \]

The current flowing to the inductor \( L_1 \) is as follows.

\[ i_{L1}(t) = i_{L1}(t_1) + \frac{1}{L_1} \left( V_L - \frac{V_H}{2} \right) (t - t_1) \tag{9} \]

**Mode 3 \([t_2(t_3)]\)**

The operating principle is the same as in Mode 1. Therefore, the current at both ends of the inductor is as follows.

\[ v_{L1}^3 = V_L \tag{10} \]

The current flowing to the inductor \( L_1 \) is as follows.

\[ i_{L1}(t) = i_{L1}(t_2) + \frac{V_L}{L_1} (t - t_2) \tag{11} \]

**Mode 4 \([t_3(t_4)]\)**

Switches \( S_2 \) and \( S_4 \) are on, and switches \( S_1 \) and \( S_3 \) are off. The current flow diagram is shown in Figure 4(c).

The energy of the low-voltage side \( V_L \) and the inductor \( L_1 \) are in series to release the energy to the capacitor \( C_H \). The capacitors \( C_{H1}, C_{H2} \) are stacked to discharge the load \( (V_H) \). Therefore, the voltage at both ends of \( L_1 \) is as follows.

\[ v_{L1}^4 = V_L - \frac{V_H}{2} \tag{12} \]

The current flowing to the inductor \( L_1 \) is as follows.

\[ i_{L1}(t) = i_{L1}(t_3) + \frac{1}{L_1} \left( V_L - \frac{V_H}{2} \right) (t - t_3) \tag{13} \]

In addition, if the Volt-Second-Balance (VSB) equation is applied to the inductor \( L_1 \), the following equation is derived.

\[
\int_0^{(DT_1)/2} V_{L1}^1 \cdot \frac{dt}{0} + \int_0^{(1-D)T_2/2} V_{L1}^2 \cdot \frac{dt}{0} + \int_0^{(DT_1)/2} V_{L1}^3 \cdot \frac{dt}{0} + \int_0^{(1-D)T_2/2} V_{L1}^4 \cdot \frac{dt}{0} = 0
\]

(14)

If (6), (8), (10), and (12) are substituted into (14), the proposed converter’s step-up DC–DC conversion rate is as follows.

\[
G_{\text{step-up}} = \frac{V_H}{V_L} = \frac{2}{1 - D}
\]

(15)

**Step-down mode**

The operation of the converter in step-down mode is shown in Figures 5 and 6. The gate signals of the \( S_1 \) and \( S_4 \) switches are similar, \( S_2 \) and \( S_3 \) the and switches operate through a diode. The operating status at each time interval is shown below.

**Mode 1 \([t_5(t_6)]\)**

In this mode, \( S_1 \) and \( S_3 \) are turned on, and \( S_2 \) and \( S_4 \) are turned off. The current flow path is shown in Figure 6(a).

The energy of the high-voltage side \( V_{H1} \) is transferred to the inductor \( L_1 \), capacitor \( C_L \), and load \( V_L \). Therefore, the voltage at both ends of inductor \( L_1 \) is as follows.

\[
v_{L1}^1 = \frac{V_H}{2} - V_L
\]

(16)

The current flowing to the inductor \( L_1 \) is found as shown below.
\[ i_{L1}(t) = i_{L1}(t_0) + \frac{1}{L_1} \left( \frac{V_H}{2} - V_L \right) (t - t_0) \]  \hspace{1cm} (17) 
\[ i_{L1}^2(t) = i_{L1}(t_1) - \frac{V_L}{L_1} (t - t_1) \]  \hspace{1cm} (19)

**Mode 2** \[ t_1(t_2) \]

Switches \( S_2 \) and \( S_3 \) are turned on, and \( S_1 \) switches and \( S_4 \) are turned off. The current's flow path is shown in Figure 6(b). The energy stored in inductor \( L_1 \) is released to the capacitor \( C_L \) and load \( V_L \). Therefore, the voltage at both ends of the inductor \( L_1 \) is as follows.

\[ v_{L1}^2 = -V_L \]  \hspace{1cm} (18)

The current flowing to the inductor \( L_1 \) is as follows.

**Mode 3** \[ t_2(t_3) \]

Switches \( S_2 \) and \( S_4 \) are turned on, and switches \( S_1 \) and \( S_3 \) are turned off. The current's flow path is shown in Figure 6(c). The energy of the high-voltage side \( V_{H2} \) is transferred to the inductor \( L_1 \), capacitor \( C_L \), and load \( V_L \). Therefore, the voltage at both ends of the inductor is as follows.

\[ v_{L1}^3 = \frac{V_H}{2} - V_L \]  \hspace{1cm} (20)

The current flowing to the inductor \( L_1 \) is obtained as
\[ i_L(t) = i_L(t) + \frac{1}{L1} \left( \frac{V_h}{2} - V_L \right) (t - t_2) \]  

**Mode 4**

The operating principle is the same as in Mode 2. The current’s flow path is shown in Figure 6(b). The voltage at both ends of the inductor \( L_1 \) is as follows.

\[ V_L(t) = -V_L \]  

The current flowing to the inductor \( L_1 \) is found as shown below.

\[ i_L(t) = i_L(t_3) - \frac{V}{L_1} (t - t_3) \]  

If the Volt-Second-Balance (VSB) equation is applied to inductor \( L_1 \), the following equation is derived.

\[ \int_0^{(DT_1/2)} V_L^1 \ dt + \int_0^{(1-D)T_1/2} V_L^2 \ dt + \int_0^{(DT_1/2)} V_L^3 \ dt + \int_0^{(1-D)T_1/2} V_L^4 \ dt = 0 \]  

If (16), (18), (20), and (22) are substituted into (24), the proposed converter’s step-down DC–DC conversion rate is as follows.

\[ G_{\text{step-down}} = \frac{V_L}{V_h} = \frac{D}{2} \]  

According to Eq. (15), the proposed converter’s conversion rate in step-up mode is 2 times higher than that of the conventional converter for the same duty ratio. Also, according to Eq. (25), the converter’s conversion rate in step-down mode is 1/2 that of the conventional converter.

**Simulation**

To compare and analyze the conventional method and the improved bidirectional DC/DC converter proposed in this paper, PSIM software was used to perform computer simulations.

**Conventional Buck-Boost Bidirectional DC–DC converter**

Table 1 shows the system parameters for the conventional converter simulations shown in Figure 1.

Figures 7 and 8 show the results of simulations of the conventional converter at a duty ratio of 0.5 in step-up mode and step-down mode, respectively.

Figure 7 shows (a) the power supply voltage and the converted voltage in step-up mode and (b) the voltage waveform applied to the switches. In (a), the output voltage was fixed at two times the input voltage within 0.02 seconds, and in (b), the voltage stress applied to both ends of the switch was 200 V, which is the same as the high load voltage \( V_{\text{equivalent}} \), directly before turning the switch on and directly after turning it off.

Figure 8 shows (a) the power supply voltage and the converted voltage in step-down mode and (b) the voltage waveform applied to the switches. In (a), the output voltage was 1/2 the input voltage within 0.02 seconds, and in (b), the voltage stress applied to

**Table 1. Parameters of the conventional converter.**

| Component            | Specification |
|----------------------|---------------|
| Power Level(W)       | 200           |
| Switches S1, S2      | IRF 640       |
| Inductors L1 (μH)    | 200           |
| Capacitors C (μF)    | 100           |
both ends of the switch was 200 V, which is the same as the high load voltage $V_{\text{eq}}$. Directly before turning the switch on and directly after turning it off. In addition, it can be seen that the shapes of the simulation results were similar in step-down mode and step-up mode.

**Improved bidirectional DC–DC converter**

Table 2 shows the system parameters for the simulations of the improved bidirectional DC–DC converter that is proposed in this paper.

Figures 9 and 10 show the results of simulations at a duty ratio of 0.5 in step-up mode and step-down mode, respectively.

Figure 9 shows (a) the voltage that was converted in step-up mode, (b) the voltage waveform applied to $S_1$ and $S_2$, and (c) the current of the inductor $L_1$. In (a), a voltage that was four times the input voltage was produced within 0.02 seconds. In (b), the voltage stress of switches $S_1$ and $S_2$ was 100 V, which is half of the high voltage. Also, in (c), it can be seen that the current of inductor $L_1$ increased or decreased in a fixed way.

Figure 10 shows (a) the voltage that was converted in step-down mode, (b) the voltage waveform applied to $S_1$ and $S_2$, and (c) the current of the inductor $L_1$. In (a), a voltage that was 1/4 of the input voltage was produced within 0.02 seconds. In (b), the voltage stress applied to switches $S_1$ and $S_2$ was half of the high voltage directly before turning the switch on and directly after turning it off. Also, in (c), it can be seen that the current of inductor $L_1$ was controlled in a stable manner. In addition, it can be seen that the shapes of the simulation results for the proposed converter were also similar in step-down mode and step-up mode.

**Conclusions**

In battery-based systems, such as hybrid ships that use electric propulsion and DC grid ships, bidirectional converters are often used as interfaces between high-voltage power sources and low-voltage batteries to store excess energy, and the fields of application for bidirectional converters are steadily expanding. This study proposes a new bidirectional converter with a high voltage conversion rate and low switch voltage stress. The proposed converter allows current flow between modules by adding only one capacitor compared to a conventional bidirectional converter. To
check the effectiveness of the proposed method, PSIM software by Powersim was used to perform simulation tests, and the following results were found.

The proposed converter achieved a high voltage conversion rate that was twice that of the conventional bidirectional converter in step-up mode and 1/2 that of the conventional converter in step-down mode.

Because a low voltage that was less than 1/4 that of the high voltage side was applied before turning on and after turning off each switch, it was confirmed that low-voltage components such as MOSFETs can be used. The improved DC–DC bidirectional converter proposed in this paper has the advantage of providing high step-up/step-down with a low duty ratio and is
expected to be applicable to the fields of UPS and hybrid systems of ships. The superiority of the proposed converter will be confirmed in future experiments.

**Disclosure statement**

No potential conflict of interest was reported by the author(s).

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