A New High Efficient Bi-directional DC/DC Converter in the Dual Voltage System

Su-Won Lee†, Seong-Ryong Lee* and Chil-Hwan Jeon*

Abstract - This paper introduces a new high efficient bi-directional, non-isolated DC/DC converter. Through variations of the topology of the conventional Cuk converter, an optimum bi-directional DC/DC converter is proposed. Voltage and current in the proposed DC/DC converter are continuous. Furthermore, the efficiency in both step-up and step-down mode is improved over that of the conventional bi-directional converter. To prove the validation for the proposed converter, simulations and experiments are executed with a 300W bi-directional converter.

Keywords: Bi-directional DC/DC Converter, High efficient, Topology variation, Non-isolation DC/DC converter

1. Introduction

In recent years, a system that makes use of various types of energy has been sought after and the distributed generation system that uses alternative energy such as vehicle power sources like the uninterrupted power system and hybrid electrical vehicles, fuel cells, solar cells and etc. are being studied actively. In these systems, for the greatest efficiency, the control of the charging and discharging systems to give and take energy between the DC bus and storage equipments and the dual voltage system require voltage step-up since the load increase in independent power source systems are essential. Therefore, bi-directional DC/DC converters are required to enable the give and take of energy between the different dc sources and to allow for control. Due to the limitations of energy sources of these systems, the conversion efficiency is very important [1-4].

Generally, as a bi-directional DC/DC converter, in the isolated mode, the topology coupled Buck and Boost converter as shown in Fig. 1 is first considered. This topology does not reverse the polarity and the current although the switch and diode is smaller then that of other converters. As such the conduction loss is small and the efficiency is high. But the converter has the problems of current and voltage pulsation at input and output, which is like the shortage of the Buck and boost converter [5]. This causes ill effects on systems with batteries and solar cells. To solve the problems, an input filter should be added, but this results in poor efficiency due to the conduction loss. Particularly, the increase of use in the alternative energy system as a solar cell generation system makes the efficiency improvement most important.

In this paper, a proposed bi-directional DC/DC converter is introduced on the basis of the conventional Cuk converter but improves the efficiency through the topology variation. Furthermore, the output's polarity is reversed to input's, which is the shortage of the Cuk converter; however, this topology does not reverse the polarity in bi-directions. So, the proposed topology has the advantages of the continuous current at input and output and on the common grounds. As well, this topology improves the properties of the input's and output's voltage and current and increases the efficiency more than the conventional bi-directional DC/DC converters. To prove the validations of the proposed converter, simulations and experiments are executed with a 300W bi-directional DC/DC converter.

2. Bi-directional DC/DC converter

2.1 Conventional bi-directional DC/DC converter

Figure 1 shows the structure coupled with the Buck and Boost converter as the conventional bi-directional converter. In the case of dual voltage systems, because the two voltages are different, in order to have control in both directions, if the positive direction is in step-up mode; the reverse mode requires a DC/DC converter that controls in step-down mode. So the Buck and Boost converter in the reverse mode controls the bi-directional energy. Because a bi-directional converter shown in Fig. 1 has the property of a Buck converter in step-down mode and the property of a Boost converter in step-up mode, the conversion efficiency is relatively high and output's polarity is the same as the

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input's. Therefore, as yet, this converter is most used as a bi-directional DC/DC converter.

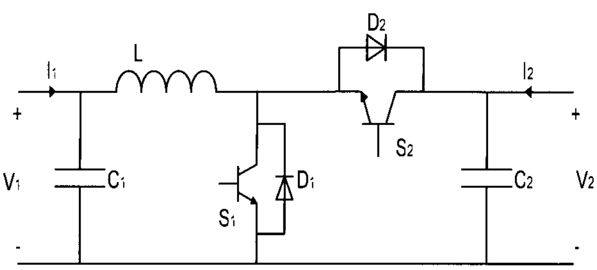


Fig. 1 Conventional bi-directional DC/DC converter

Equations (1) and (2) are the equations to design the inductor and the filter capacitor in step-down mode. Equ. (3) is the equation to calculate the efficiency.

$$L = \frac{V_2 - V_1}{\Delta i_{L(p-p)}} DT_S \quad (1)$$

$$C_1 = \frac{\Delta i_{L(p-p)}}{8\Delta V_{C1(p-p)}} T_S \quad (2)$$

$$\eta_{SD} = \frac{P_O}{P_S} = \frac{V_2 \times (-I_2)}{V_1 \times I_1} \quad (3)$$

Equations (4) and (5) are the equations to design the inductor and filter capacitor in step-up mode. Equ. (6) is the equation to calculate the efficiency.

$$L = \frac{V_1}{\Delta i_{L(p-p)}} DT_S \quad (4)$$

$$C_2 = \frac{-I_2}{\Delta V_{C2(p-p)}} DT_S \quad (5)$$

$$\eta_{SU} = \frac{P_O}{P_S} = \frac{V_1 \times (-I_1)}{V_2 \times I_2} \quad (6)$$

Where $D = T_{ON}/T_S$ (T_{ON} is the turn-on time and T_S is the switching period), $\Delta V_{C(p-p)}$ are the peak-to-peak ripple current of the inductor and the peak-to-peak ripple voltage of the capacitor.

But in the case of step-down mode, because input currents flow discontinuously depending on the on and off switching of the main switch, to control its ripples to be below the prescribed level, an input filter composed of inductor and capacitor is required.

In the case of step-up mode, continuous but high peak current flows through the main switch (S1). Due to the (1-D) coefficient, the average output current is smaller than the average inductor current and the higher rms current flows through the filter capacitor. Therefore, larger capacitors and inductors are needed. And output currents flow discontinuously depending on the on and off switching of the main switch. To control its ripples to be below the prescribed level, a larger capacitor or inductor filter than other converters is required [6, 7].

Because the conventional type bi-directional DC/DC converter has the problem of voltage and current ripples at input and output, which is the shortage of the Buck and Boost converter, to use it in a dual voltage system or in a distributed generation system as batteries or solar cells, suitable filters at input and output should be added. Due to these filters, the number of parts increases and the efficiency due to conduction loss decreases.

2.2 Cuk type bi-directional DC/DC converters

The Cuk converter is the converter that provides the continuous current without the filters at input and output. Fig. 2 shows the structure on the basis of the Cuk converter that is used to improve the properties of current and voltage at input and output. This converter can control the bi-directional power by adding one reverse switch (S2) and one diode (D2) to the conventional Cuk converter.

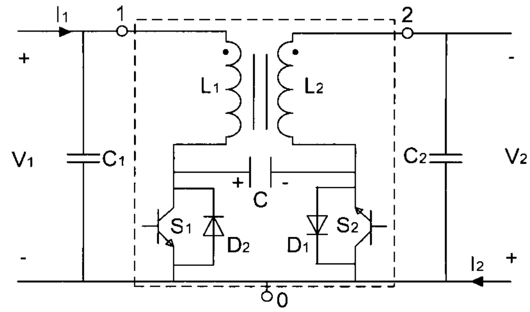


Fig. 2 Bi-directional Cuk converter

Equations (7)~(11) are the equations used to design an inductor and a capacitor for a bi-directional Cuk converter. The efficiency is the same as that in the step-up and step-down modes of Fig. 1.

$$L_2 = \frac{V_S}{\Delta i_{L2(p-p)}} DT_S \quad (7)$$

$$C_2 = \frac{V_S}{8\Delta V_{C2(p-p)} L_2} DT_S^{\ 2} \quad (8)$$

$$L_1 = \frac{V_S}{\Delta i_{L1(p-p)}} DT_S \quad (9)$$

$$C_1 = \frac{V_S}{8\Delta V_{C1(p-p)} L_1} DT_S^{\ 2} \quad (10)$$

$$C = \frac{I_S(1-D)}{\Delta V_{C(p-p)}} T_S \quad (11)$$

Where V_S is the input voltage, I_S is the input current $\Delta i_{L1(p-p)}$, $\Delta i_{L2(p-p)}$, $\Delta V_{C1(p-p)}$, $\Delta V_{C2(p-p)}$, and $\Delta V_{C(p-p)}$ are the peak to peak ripple currents through inductor L_1 and L_2, the peak-to-peak ripple voltage across capacitor C_1 and C_2 and the ripple voltage across the input capacitor filter.

Considering the symmetry, the Cuk converter can replace two inductors with a coupled inductor. As this is two inductors wound in a single core, characteristically either one of the currents at the input and output is able to have zero ripple. Size of inductors at input and output of the Cuk converter can be significantly reduced by the reaction of two inductors with the same effects [8].

But the bi-directional Cuk converter shown in Fig. 2 has the same properties of the conventional Cuk converter. Though this improves the input and output characteristics, this converter has the shortage that the voltage polarity is reversed at input and output and the efficiency in step-up and step-down mode is lower than that of conventional bi-directional converters.

2.3 Topology variation

The dotted box in Fig. 2 represents the switching cell that has 3 ports to get various topologies by external connections to the bi-directional Cuk converter. Fig. 3 shows the equivalent diagram. Fig. 3 (a) represents that the switch S2 of the converter in Fig. 2 turns off but S1 turns on, and Fig. 3 (b) represents that the switch S1 of the converter in Fig. 2 turns off but S2 turns on.

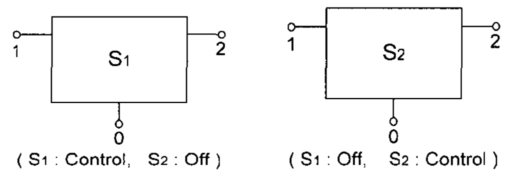


Fig. 3 Switching cell

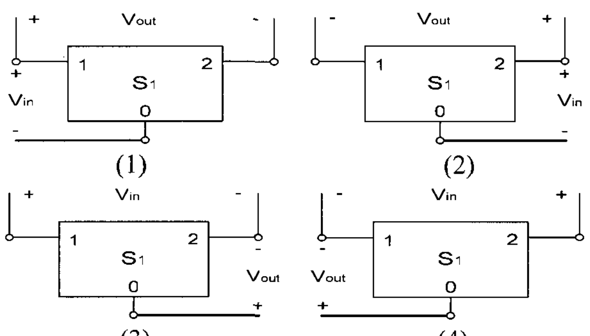


Fig. 4 Topology by switch S1.

On the basis of the Cuk switching cell controlled by the main switch (S1), Fig. 4 is the 2 step-up ((1) and (2)) and step-down ((3) and (4)) topology derived by executing the topology variation considering the property of capacitor (C) for energy transfer.

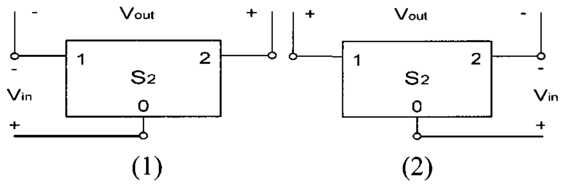


Fig. 5 Topology by switch S2.

Figure 5 is the two topology on the basis of Cuk switching cell controlled by the reverse switch (S2).

The topology having the common ground at both input and output terminals among six topologies and reducing the energy loss during power conversion by executing the load power control with partially required energy and increasing the efficiency without adding the parts to the conventional DC/DC converter is the topology shown in Fig. 5 (2) during the step-up mode and the topology shown in Fig. 4 (3) during the step-down mode.

3. Proposed bi-directional DC/DC converter

For the bi-directional power control, the effective bi-directional DC/DC converter shown in Fig. 6 is derived by combining the step-up mode and the step-down mode.

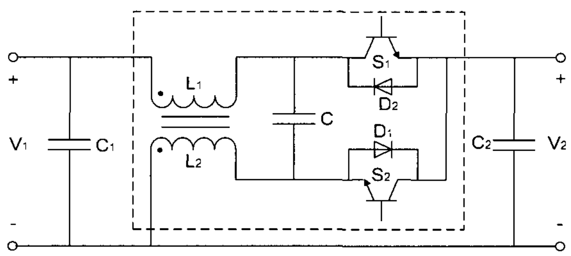


Fig. 6 High effective bi-directional DC/DC converter

Fig. 7 is the equivalent circuit when, in the step-up mode, the high effective bi-directional DC/DC converter shown in Fig. 6 is operating.

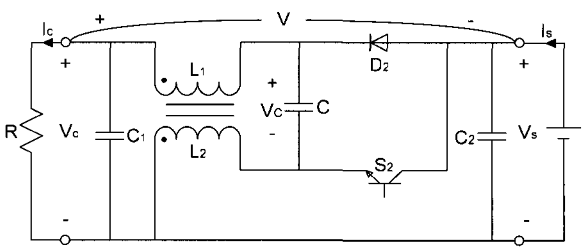


Fig. 7 The equivalent circuit of the step-up mode

This is the structure having the same polarity at input and output terminals with the improved efficient effects as well as the superior characteristics of the input and output voltage and currents than the conventional step-up converter.

Relation of the input and output voltages due to the capacitor (C) for energy transfer and the coupled inductor is always $V_O = V_S + V$. Because the output voltage (V_O) is always greater than V and the output current is I_O, the step-up converter reduces the energy loss due to the power conversion by controlling the load power. Therefore, the converter is able to convert at higher power more efficiently than the conventional bi-directional converter. The efficiency on the step-up mode is as follows:

$$\eta_{C-SU} = \frac{P_O}{P_S} = \frac{V_O \times I_O}{V_S \times I_S} = \eta_C + (\frac{I_O}{I_S}) \quad (12)$$

where η_C is the efficient of Cuk converter.

As the same as the conventional step-up converter, the smaller the ratio of input voltage to output voltage, that is the step-up ratio, is, the better the conversion efficient is and the greater the ratio of the step-up ratio is, the worse the conversion efficient is. But as shown in Equ. (12), the efficiency is better than the efficiency η_C for the conventional Cuk converter by the ratio I_O/I_S. Whatever the step-up ratio is, the proposed converter is able to get higher efficiency than the conventional converter.

Figure 8 shows the equivalent circuit when the high efficiency bi-directional DC/DC converter in Fig. 6 operates in step-down mode. This is the structure having the same polarity at input and output terminals and has the improved efficiency effects as well as the superior characteristics of the input and output voltage and currents than the conventional step-down converter.

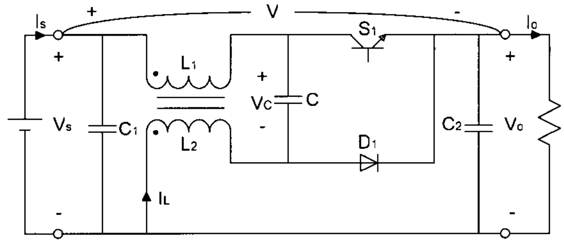


Fig. 8 The equivalent circuit of the step-down mode

Relation of the input and output voltages due to the capacitor (C) for energy transfer and the coupled inductor is always $V_O = V_S + V$. Because the input voltage (V_S) is always greater than V and the output current is I_O, the step-up converter reduces the energy loss due to the power conversion by controlling the load power. Therefore, the converter is able to convert power with higher efficiency than the conventional bi-directional converter. The efficient on the step-down mode is as follows:

$$\eta_{C-SD} = \frac{P_O}{P_S} = \frac{V_O \times I_O}{V_S \times I_S} = \frac{1 + \eta_C \times (V_S/V_O - 1)}{V_S/V_O} \quad (13)$$

Just the same as the conventional step-down converter, the smaller the ratio of input voltage to output voltage, that is the step-down ratio, is, the better the conversion efficient is and the greater the ratio of the step-down ratio is, the worse the conversion efficient is. But as shown in Equ. (13), the efficient is better than the efficient η_C for the conventional Cuk converter by the ratio V_S/V_O. Whatever the step-up ratio is, the proposed converter is able to get higher efficient than the conventional converter.

4. Simulation and experiments

To confirm the validation for the proposed bi-directional DC/DC, the conventional bi-directional DC/DC converter and the proposed high efficient bi-directional DC/DC converter are simulated by PSIM. The simulation parameters are listed in Table 1.

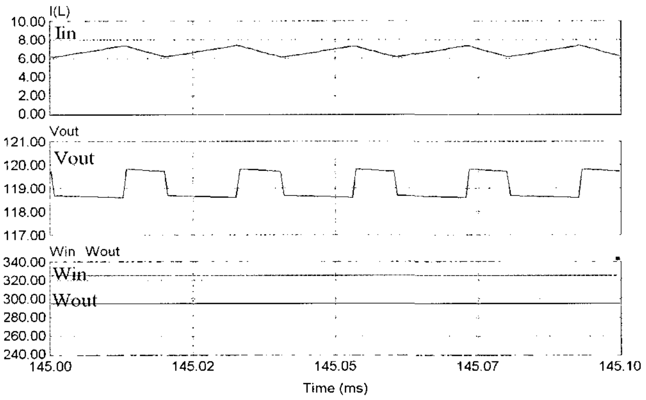
Table 1. Simulation parameters

Parameter	Value	
Input Voltage	Step Down: 120V	Step Up: 48V
Output Voltage	Step Down: 48V	Step Up: 120V
Inductor Current Ripple	< 20%	
Output Ripple	< 1%	
Power Rating	300W	
Switching Frequency	50kHz	
Switch ON Resistance	75mΩ	
Diode Voltage Drop	0.7V	
Inductor's Resistance	1Ω/mH	
Capacitances' ESR	50μ/C	

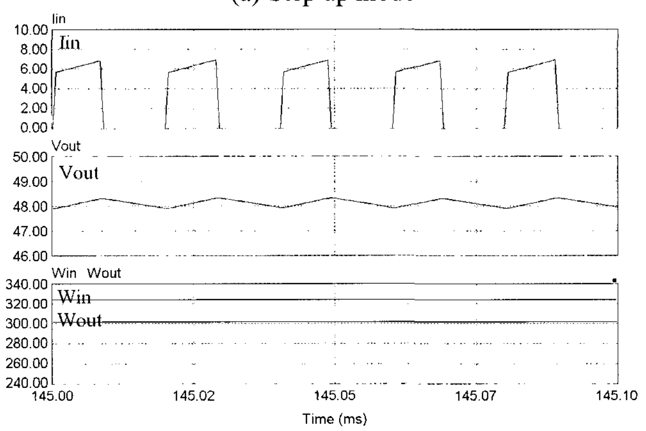
In the case of the conventional bi-directional DC/DC converter, to satisfy the parameters listed in Table 1, we determine the inductor to be 460 μH and the filter capacitor to be $C_2 = 400\mu F$ and $C_1 = 150\mu F$.

For the step-up mode shown in Fig. 9(a), the ripple of the inductor current and the output voltage are 18.44% and 0.77%, respectively. And the efficiency is 91.1%. As shown in the figure, the conventional bi-directional DC/DC converter has the disadvantage that the output is discontinuous depending upon on-off switching of the main switch. That is why the converter requires a large capacitor or inductor filter compared to the other converters. The size of C2, 400 μF, is quite larger than that of the other converters.

For the step-down mode shown in Fig. 9(b), the input current is discontinuous and the output ripple and the efficiency are 0.85% and 93.17%, respectively.



(a) Step up mode



(b) Step down mode

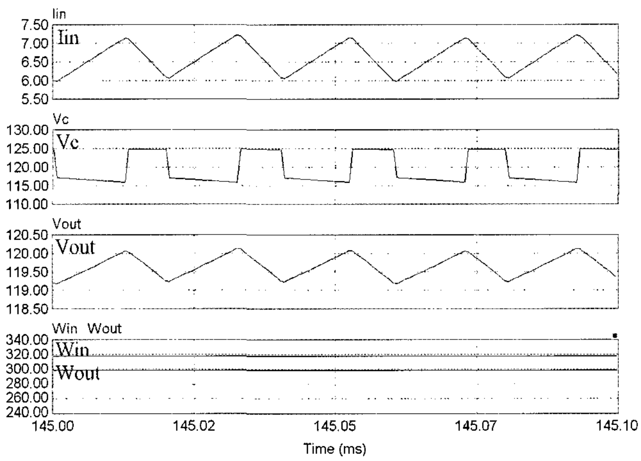
Fig. 9 Simulation results for conventional bi-directional DC/DC converter

Because the input current flows discontinuously by on and off switching of the main switch, to control the ripple under the prescribed value, the input filter composed by inductor and capacitor is required. Adding the filter causes degradation in the efficiency due to the conduction loss.

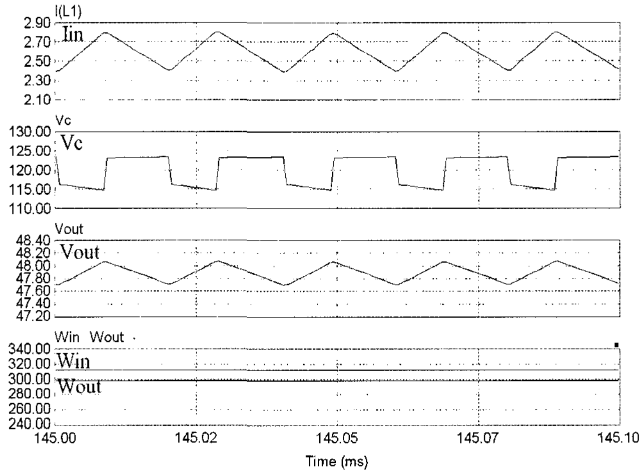
To simulate the high efficient bi-directional DC/DC converter proposed in this paper, a coupled inductor is determined $L_1 = L_2 = 5\mu H$ to meet the parameters listed in Table 1 and a capacitor for energy transfer is determined $C = 40\mu F$ to be the ripple of the capacitor voltage less than 10%. A capacitor for the filter is $C_2 = 20\mu F$ and $C_1 = 150\mu F$.

For the step-up mode shown in Fig. 10(a), the ripple of the input current, the output voltage and the efficiency are 18.67%, 0.75% and 91.1%, respectively. The output voltage is not discontinuous even though the capacitor is 1/20 and the efficiency is improved by 3.6%. This shows the effect of efficiency improvement to be unexpected although the step-up rate is 2.5. If the step-up rate is small, the conversion effect will be improved much more.

For the step-down mode shown in Fig. 10(b), the ripple of the input current, the output voltage, and the ripple of the capacitor for energy transfer and efficiency are 15.9%, 0.776%, 7.35% and 95.84% respectively. This shows that the efficiency is improved by 2.67% compared with the conventional converter under the same conditions. This shows that the effect of efficiency improvement is unexpected although the step-down rate is 2.5. If the step-down rate is small, the conversion effect will be improved much more.



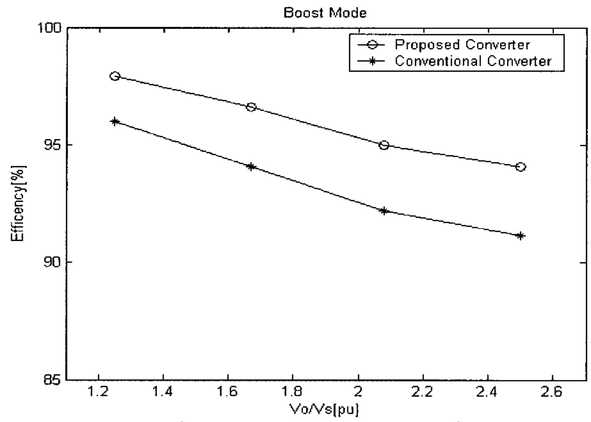
(a) Step up mode



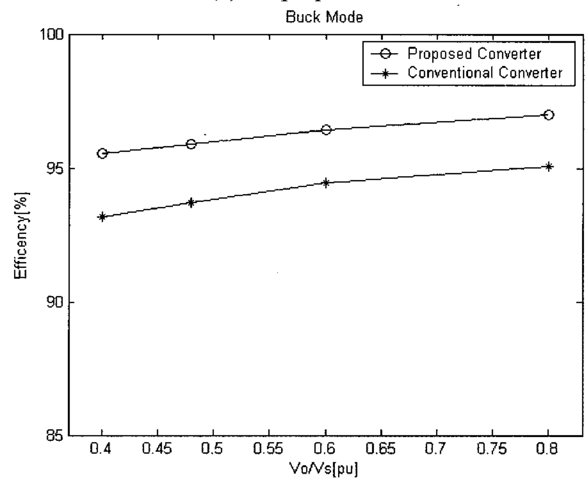
(b) Step down mode

Fig. 10 Simulation results for the proposed bi-directional high-efficiency DC/DC converter

If an input filter is added to the conventional converter due to the discontinuous input current, the proposed converter in the paper requires the same number of elements as the conventional converter but the inductor is very small, and the characteristics of input and output voltage, as well as current and efficiency are much improved with the size of the converter being more compact and the cost being very low.



(a) Step up mode



(b) Step down mode

Fig. 11 The efficiency for the conventional converter and the proposed converter

Figure 11 shows the efficiency of the simulation results in the conditions listed in Table 1 according to the input and output voltage rate in the step-up mode and step-down mode for the conventional Buck-Boost converter and the proposed converter. It shows that the efficiency of the proposed converter is better than that of the conventional converter in both step-up and step-down mode.

To verify the validation of the proposed converter, the converter with the load of 300W in step-up mode and the load of 265W in step-down mode is manufactured and experimented. Fig. 12 shows the proposed bi-directional dc/dc converter system.

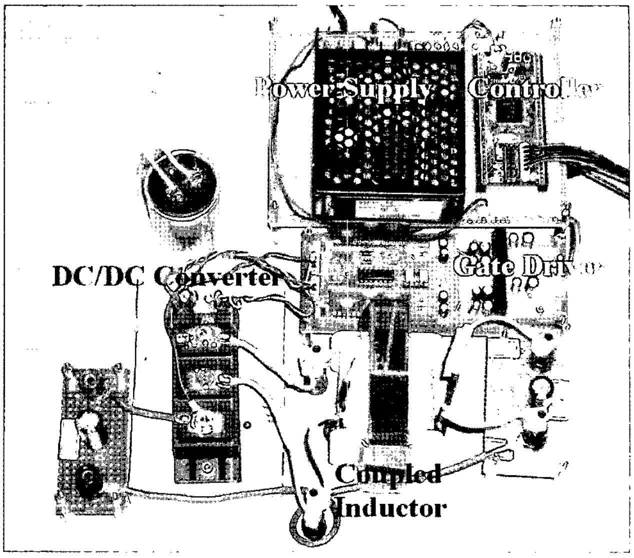
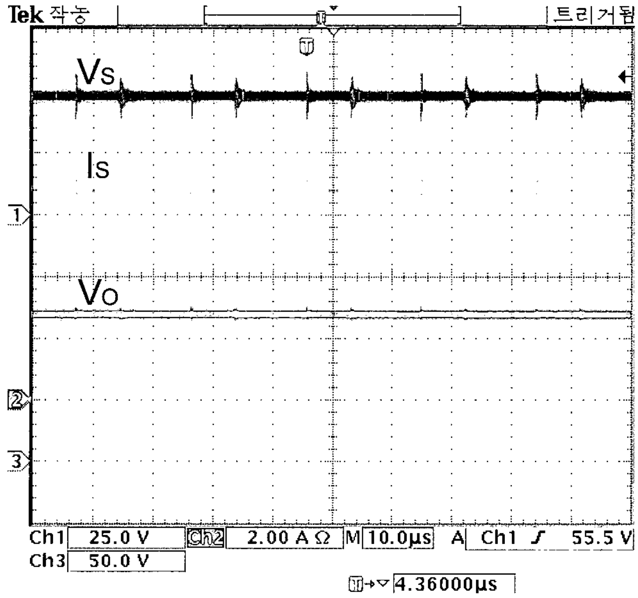


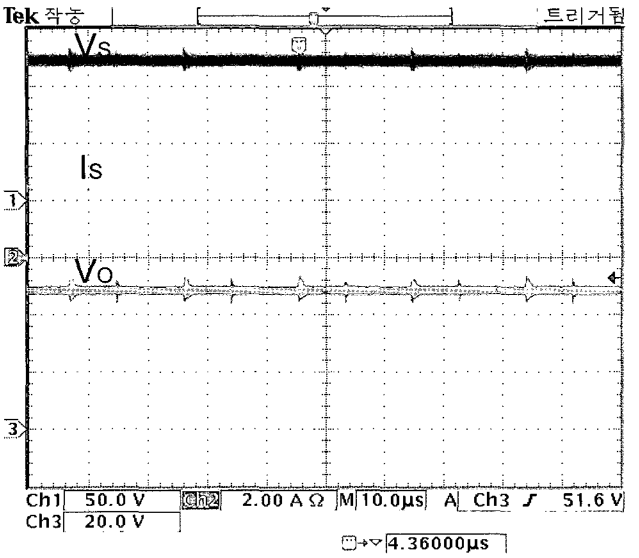
Fig. 12 Photograph of the proposed converter

Figure 13(a) shows the experiment result in step-up mode for the proposed converter. From above, input voltage is $V_S = 48V$, input current is $I_S = 6.67A$, and output voltage $V_O = 120V$. Output power is 299.3W and efficiency is 93.48%. The ripple of input current ΔI_S is 20.62%.

Figure 13(b) presents the experiment result in step-down mode for the proposed converter. From above, input voltage is $V_S = 120V$, input current is $I_S = 2.23A$, and output voltage $V_O = 48V$. Output power is 265.3W and the efficiency is 94.88%. The ripple of input current ΔI_S is 17.83%. PM3000A Power Analysis of Voltech is used for the measurement of the efficiency.



(a) step up mode



(b) step down mode

Fig. 13 Experiment results of the proposed converter

As the results reveal, the voltage and the current at input and output in both the step-up mode and the step-down mode are continuous and the ripples are very small. Even though the voltage rate is 2.5, even under somewhat poor conditions, the characteristics of voltage and current are good and the efficiency is high.

5. Conclusions

In the paper, the high-efficiency bi-directional DC/DC converter continuously controls voltages and currents of the input and the output and the ripples so that they are under a certain level. Though the conventional converter has attempted to improve the efficiency by reducing the switching loss, the proposed converter improves the efficiency by minimizing the energy loss generated at the time of power conversion.

Compared with the bi-directional Buck-Boost converter coupled with the conventional Buck and Boost converter, the proposed converter has the same number of elements (when the input and output filter is added to achieve the characteristics of input and output to be a certain level) although they are smaller and it improves the characteristics of voltage and current of the input and output. In the step-up and step-down mode, the proposed converter enhances the conversion efficiency in both directions. In case of the same power, the proposed converter is more compact and the cost of the proposed converter is lower than the conventional converter.

The proposed converter in the paper can be applied to all areas in which the conventional converter is used. The proposed converter can be also applied to the interrupted power systems and the vehicle power sources used in hybrid electrical cars, fuel cells, solar cells, etc. to effectively make the practical application of various type of energies. The proposed converter is expected to be applied to the system to control the power conversion giving and taking the energy between other DC sources such as the charging and discharging of control systems that give and take the energy between DC bus and storage equipments to use effectively the energy supplied by various distributed power sources, and the dual voltage system requiring the step-up voltage due to increases in the independent power source loads such as motor vehicles.

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