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New bidirectional step-up DC-DC converter derived from buck-boost DC-DC converter

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ABSTRACT

This paper proposes a new bidirectional step-up DC-DC converter, namely modified buck-boost DC-DC converter. The proposed DC-DC converter was derived from the conventional buck-boost DC-DC converter. Output voltage expression of the proposed converter was derived by considering the voltage drops across inductors and switching devices. The results have shown that with the same parameter of input LC filter, proposed DC-DC converter has lower conduction losses. Moreover, the proposed DC-DC converter has lower rated voltage of filter capacitor than the conventional boost DC-DC converter which lead to cost efficiency. Finally, a scaled-down prototype of laboratory experiment was used to verify its theoretical analysis.

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1. INTRODUCTION

Indonesia is an archipelagic country that has an electrification ratio of more than 99%. However, because Indonesia consists of more than 17,000 islands, remote areas in Eastern Indonesia still do not have access to electricity. The government has launched various programs to improve electricity access, especially in remote areas or islands. Because of its isolated location, the microgrid system is suitable for this application. Energy sources can be obtained from local energy potentials such as solar, wind, micro-hydro, and biomass. As most of the output potential local energy is in the form of DC electricity, DC microgrid is desirable in this application. Moreover, DC system has no synchronization problem and easy load sharing.

Figure 1 shows a DC microgrid system with power source from photovoltaic (PV) module. The DC bus voltage of 400 Vdc was selected so that it can be converted easily into 220 Vac by using an inverter. DC-DC converters are used to connect PV modules, batteries, and DC loads to the DC bus. To achieve the DC bus voltage from the PV voltage, the DC-DC converter must have a boost characteristic. The DC-DC converter for battery energy storage must be a bidirectional DC-DC converter to allow charging and discharging. In order to ensure long-term operation of the system, very low input current ripple is desired. Moreover, it is desirable that the converter is low cost and high efficiency [1]-[3].

References [4]-[16] have proposed various DC-DC power converters for this application. In [4], an isolated DC-DC converter is used, however it has low efficiency because of the two-stage conversion. Nonisolated DC-DC converters are preferred due to power loss considerations over isolated DC-DC converters. Converters proposed in [5]-[12] have high boost characteristics, however, those converters do not have common node between input and output (floating converter) which is undesirable in many applications.

Converters in [13] and [16] have a quadratic voltage gain so that a high voltage-ratio can be achieved with moderate duty cycle. However, these converters have complex controls due to the higher order of the plant. A simple converter that easy to control has also been proposed but has a narrow voltage gain and needs more components than the conventional one [14]. A new buck-boost converter with wider voltage conversion ratio has also been proposed but it also has complex control and reversed output polarity [15]. The most commonly used DC-DC converter for PV generation is still the conventional DC-DC boost converter because it is simple, low cost, and efficient [17]-[21]. Though conventional boost converter has a continuous input current, an input LC filter is almost always needed in an application to reduce further the DC input current ripple. A large current ripple is undesirable in many applications. The development of this type of converter is always an ongoing hot topic [22], [23].

In this paper, a new simple, low cost, and efficient step-up DC-DC converter is proposed. The proposed converter is derived from the conventional DC-DC buck-boost converter. As it is derived from buck-boost converter, the input and output currents are discontinuous. Therefore, an LC filter must be added to the input side to minimize the input current ripple [24]. This paper organize as follows: In Section 2, the construction of proposed topology is described in detail. It is shown that the proposed converter has lower output capacitor rating than the conventional DC-DC boost converter. A lower capacitor voltage rating means lower price which is desired in most applications. Section 3 gives a detailed expression of the output voltage by considering the voltage drops across inductors and switching devices. It is shown that the conduction losses are lower than the conventional DC-DC boost power converter. Section 4 gives experimental results to verify the analysis presented in this paper. The conclusion is given in Section 5.

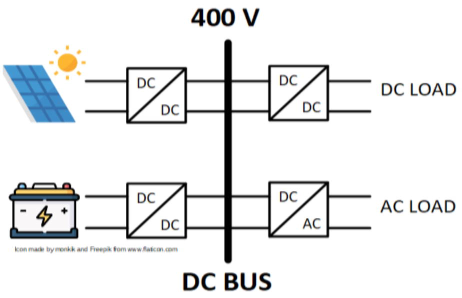


Figure 1. Schematic of DC microgrid system

2. NEW STEP-UP DC-DC CONVERTER

Figure 2 shows a conventional DC-DC buck-boost converter with terminal output voltage taken at the capacitor port which has reversed polarity. Though the active switching device is shown using metal oxide semiconductor field effect transistor (MOSFET), other type of switching devices can also be used. Under continuous conduction mode of inductor current, it can be shown that the average output voltage is

$$V_o = E_d \frac{\alpha}{1-\alpha} \tag{1}$$

where V_o is the output voltage of conventional buck-boost converter, E_d is the input voltage, and α is the duty cycle of transistor Q_1. The value of duty cycle α can be changed from zero to unity and, therefore, the average output voltage can be lower or higher than the input voltage. This is the reason why this converter is also called as up-down DC-DC power converter.

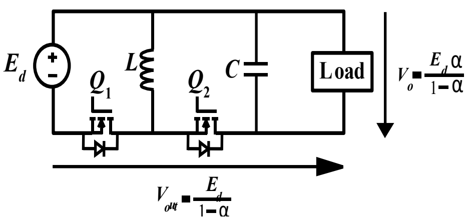


Figure 2. Modification of conventional buck-boost DC-DC converter

In addition to the conventional output terminal as shown in Figure 2, another terminal can also be used for load connection as shown in Figure 2. If the load is connected to this terminal, then the converter can be redrawn as shown in Figure 3. In this case, the average load voltage is:

$$V_{out} = E_d + V_o = E_d \frac{1}{1-\alpha} \quad (2)$$

Different to the converter in Figure 2, the new converter in Figure 3 has a load voltage that is always higher than the input voltage. The new converter has output voltage characteristic that is the same as the conventional DC-DC boost power converter. However, the rated voltage of filter capacitor C of the proposed converter is lower than conventional DC-DC boost converter according to (3).

$$V_c = \alpha\, V_{out} \quad (3)$$

A lower input ripple is desirable in many applications of DC-DC power converters. As the converter in Figure 3 is derived from the DC-DC buck-boost converter, the input current is discontinuous with high ripple content. In practices, therefore, an LC filter is added on the input side of the converter. If an input LC filter is added, the proposed step-up DC-DC power converter will become as the one shown in Figure 4. It should be noted that the proposed DC-DC converter in Figures 3 and 4 are bidirectional DC-DC converters and, therefore, can be operated both as step-up and step-down DC-DC power converters. A similar derivation method for Cuk DC-DC power converter has been done in [25]. Thus, the proposed power converter is another application of converter derivation method that has been proposed in [25].

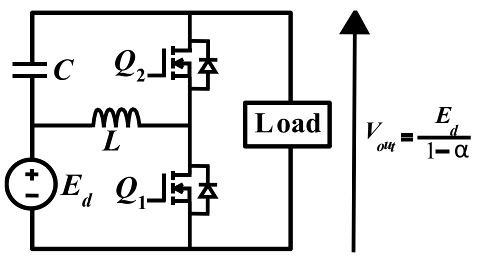


Figure 3. Bidirectional modified buck-boost DC-DC converter

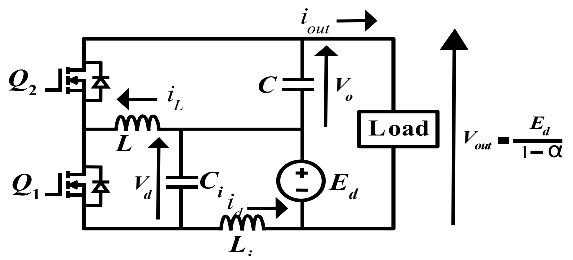


Figure 4. Modified buck-boost DC-DC converter with input LC filter

3. OUTPUT VOLTAGE EXPRESSIONS

Expressions (1) and (2) have been derived by neglecting the voltage drops across the switching devices and inductors. In practices, these voltage drops are finite and will affect the maximum voltage gain that can be achieved by the DC-DC converter. Moreover, these voltage drops will determine the conduction losses and, therefore, the converter efficiency. In this section, the voltage drops across the transistor during the conduction mode is represented as:

$$v_Q = V_Q + R_Q i_Q \quad (4)$$

where V_Q is the constant component and R_Q is the resistive component of the voltage drop across the transistor during conduction mode, respectively, and i_Q is the current through the transistor. On the other hand, the voltage drop across the diode can be represented as:

$$v_D = V_D + R_D i_D \quad (5)$$

where V_D is the constant component and R_D is the resistive component of the voltage drop across the diode during conduction mode, respectively, and i_D is the current through the diode. The capacitors are considered as ideal capacitors without equivalent series resistance. Continuous conduction mode is considered in this analysis. The two transistors in Figure 4 are working complimentary, that is, transistor Q1 receives an ON(OFF) signal when transistor Q2 receives an OFF(ON) signal. When transistor Q1 receives an ON signal, the state-space expression is:

$$p\begin{bmatrix} i_d \\ v_d \\ i_L \\ v_o \end{bmatrix} = \begin{bmatrix} -\frac{R_i}{L_i} & -\frac{1}{L_i} & 0 & 0 \\ \frac{1}{C_i} & 0 & -\frac{1}{C_i} & 0 \\ 0 & \frac{1}{L} & \frac{-(R_L+R_Q)}{L} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} i_d \\ v_d \\ i_L \\ v_o \end{bmatrix} + \begin{bmatrix} \frac{E_d}{L_i} \\ 0 \\ -\frac{V_Q}{L} \\ -\frac{I_{out}}{C_o} \end{bmatrix} \tag{6}$$

where R_i and R_L are the resistances of inductors L_i and L, respectively, and p is the differential operator. i_d and i_L are the currents through input filter inductor and energy-transfer inductor, respectively. v_d is the voltage across input filter capacitor and I_{out} is the load current. The state-space expression when transistor Q1 receives an OFF signal is

$$p\begin{bmatrix} i_d \\ v_d \\ i_L \\ v_o \end{bmatrix} = \begin{bmatrix} -\frac{R_i}{L_i} & -\frac{1}{L_i} & 0 & 0 \\ \frac{1}{C_i} & 0 & 0 & 0 \\ 0 & 0 & \frac{-(R_L+R_Q)}{L} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} i_d \\ v_d \\ i_L \\ v_o \end{bmatrix} + \begin{bmatrix} \frac{E_d}{L_i} \\ 0 \\ -\frac{V_D}{L} \\ -\frac{I_{out}}{C_o} \end{bmatrix} \tag{7}$$

State-space in (6) and (7) are valid during ON and OFF periods of Q1, respectively. Averaging the state-space (6) and (7) over one switching period will result in the average state-space (8):

$$p\begin{bmatrix} \overline{i_d} \\ \overline{v_d} \\ \overline{i_L} \\ \overline{v_o} \end{bmatrix} = \begin{bmatrix} -\frac{R_i}{L_i} & -\frac{1}{L_i} & 0 & 0 \\ \frac{1}{C_i} & 0 & -\frac{\alpha}{C_i} & 0 \\ 0 & -\frac{\alpha}{L} & \frac{-(R_L+R_Q\alpha+R_D(1-\alpha))}{L} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} \overline{i_d} \\ \overline{v_d} \\ \overline{i_L} \\ \overline{v_o} \end{bmatrix} + \begin{bmatrix} \frac{E_d}{L_i} \\ 0 \\ -\frac{V_Q\alpha}{L} - \frac{V_D(1-\alpha)}{L} \\ -\frac{I_{out}}{C_o} \end{bmatrix} \tag{8}$$

where bar over the variables denote the average quantity. During the steady-state condition, the average state-space (8) became:

$$0 = \begin{bmatrix} -\frac{R_i}{L_i} & -\frac{1}{L_i} & 0 & 0 \\ \frac{1}{C_i} & 0 & -\frac{\alpha}{C_i} & 0 \\ 0 & -\frac{\alpha}{L} & \frac{-(R_L+R_Q\alpha+R_D(1-\alpha))}{L} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} \overline{i_d} \\ \overline{v_d} \\ \overline{i_L} \\ \overline{v_o} \end{bmatrix} + \begin{bmatrix} \frac{E_d}{L_i} \\ 0 \\ -\frac{V_Q\alpha}{L} - \frac{V_D(1-\alpha)}{L} \\ -\frac{I_{out}}{C_o} \end{bmatrix} \tag{9}$$

Based on (9), the average load voltage as a function of duty cycle and load current can be obtained as:

$$V_{out} = \frac{E_d}{1-\alpha} - \frac{V_Q\alpha}{1-\alpha} - V_D - \frac{I_{out}}{(1-\alpha)^2}\left(R_i\alpha^2 + R_L + R_Q\alpha + R_D(1-\alpha)\right) \tag{10}$$

By using the same method, the average output voltage of conventional DC-DC boost converter with additional input LC filter as shown in Figure 5 can be obtained as:

$$V_o = \frac{E_d}{1-\alpha} - \frac{V_Q\alpha}{1-\alpha} - V_D - \frac{I_{out}}{(1-\alpha)^2}\left(R_i + R_L + R_Q\alpha + R_D(1-\alpha)\right) \tag{11}$$

Comparison between (10) and (11) shows that the voltage drop in the proposed converter is lower than the one in conventional DC-DC boost converter. The difference is the voltage drop in the input filter inductor. Figure 6 shows a comparison graph of the voltage drop across the input filter inductor resistance of proposed DC-DC converter and the conventional boost converter, as a function of duty cycle, with R_i = 0.1 Ω and I_{out} = 5 A. In Figure 6, other components are assumed as ideal components. Figure 6 represents the conduction losses when the voltage drops across switching devices are neglected.

As the voltage drops also represent the conduction losses, the conduction losses in the input filters will be lower than the ones in conventional DC-DC boost power converter. As the switching losses are the same, the efficiency of the proposed DC-DC power converter will be higher than the one of conventional DC-DC boost power converter. The difference of conduction losses becomes bigger when the duty cycle is high. Figure 7 shows the plot of the voltage gain (V_o/E_d) comparison between proposed converter and conventional DC-DC boost converter, as a function of duty cycle three different load currents. In Figure 7, only the input filter inductor resistance is considered. This figure shows that the maximum voltage gain of the proposed converter is higher than the one of conventional DC-DC boost power converter.

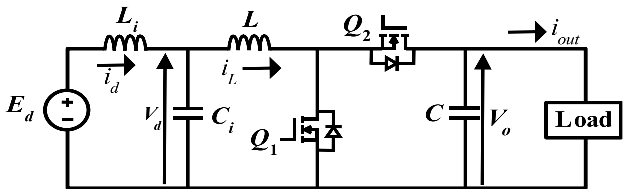


Figure 5. Conventional DC-DC boost converter with additional input LC filter

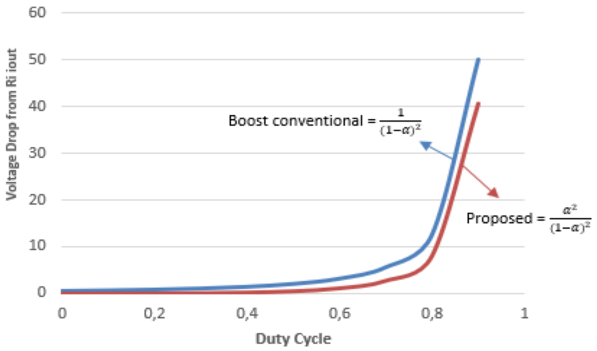


Figure 6. Voltage drop comparison

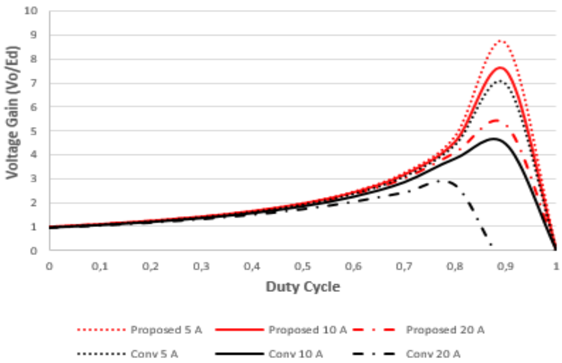


Figure 7. Voltage gain comparison

4. EXPERIMENTAL RESULTS

A small prototype modified buck-boost with input LC filter as the one shown in Figure 4 was constructed. Experimental scheme for unidirectional and its setup are shown in Figures 8 and 9, respectively. The DC voltage source of the power converter is obtained from a rectification of single-phase AC voltage source. The output of rectifier is filtered by using a 5-mF capacitor. The DC voltage source is maintained constant at 36 Vdc. Wattmeters are placed in both input and output of the DC-DC power converter. The digital oscilloscope can measure both input and output waveforms of the proposed DC-DC power converter. In this experiment, power MOSFET IRFP260N and ultrafast diode MUR1560G were used as switching devices, an inductor filter (L_i) of 47.8 μH, a film capacitor filter (C_i) of 10 μF. 1-mH of energy-transfer inductor (L) was chosen to ensure the converter operates in continuous conduction mode (CCM). Capacitor output (C) is chosen at 30 μF film capacitor and the load is variable resistor. The switching frequency is fixed at 20 kHz.

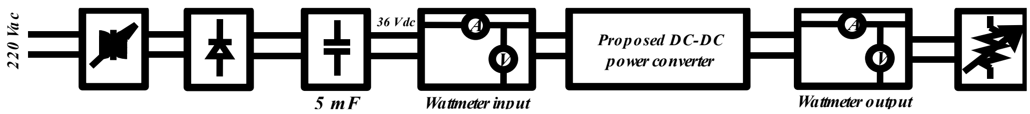


Figure 8. Experimental scheme for unidirectional

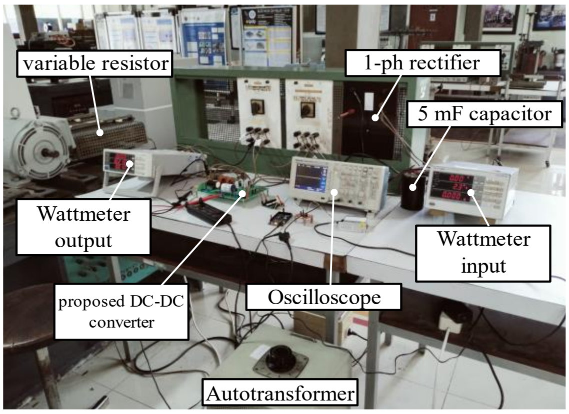
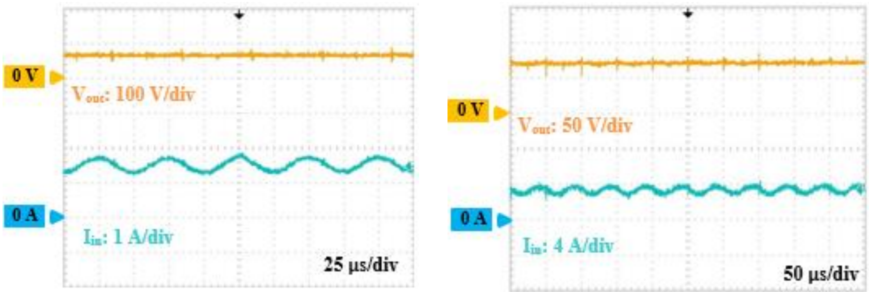


Figure 9. Experimental setup

Figure 10 shows the output voltage and input current waveforms of modified buck-boost with input LC filter. Figure 10 (a) is at 50% duty cycle with 1.5 A of input current while Figure 10 (b) is at 50% duty cycle and 3.3 A of input current. The output voltage is flat, and the input current is continuous with low ripple content because of the input LC filter. Figure 11 shows the calculation and experimental results of voltage gain (V_o/E_d), as a function of duty cycle. Line and dashed line indicate calculation results with different load current, while diamonds and circles indicate experimental results with different load current. Accuracy of the analysis results can be appreciated from Figure 11. Higher load current makes lower output voltage; hence, reduces the voltage gain, especially at higher duty cycles. Figure 12 shows efficiency as a function of load currents with variations in the duty cycle. The efficiency will be higher on lower duty cycle. It can be noted that according to (10) and (11), for the same output voltage, modified buck-boost has lower duty cycle than conventional boost converter. It means the modified buck-boost has higher efficiency than conventional boost converter.



(a) (b)

Figure 10. Output voltage and input current waveforms of input LC filtered modified buck-boost at 50% duty cycle and input current of, (a) 1.5 A, (b) 3.3 A

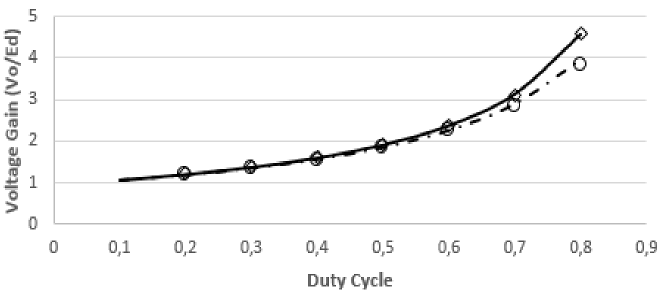


Figure 11. Voltage gain calculation and experimental results

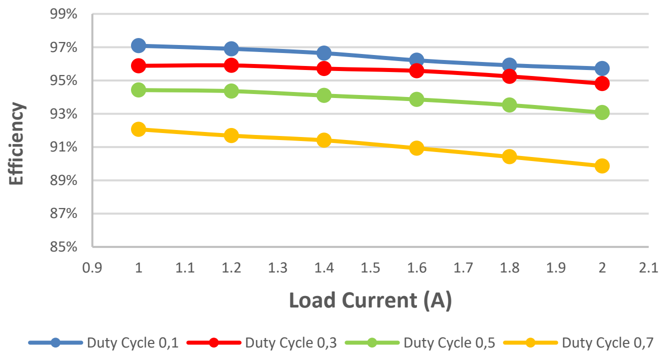


Figure 12. Experimental result of converter efficiency

A bidirectional experiment was done by using the scheme as shown in Figure 13. Although the DC sources are showed as ideal sources which can absorb power, in fact the DC sources used in the experiment are obtained from rectifier AC voltage, thus it cannot absorb power. Therefore, resistors are needed on both sides. The DC power sources, wattmeters, and fixed resistors are placed on both input and output of proposed DC-DC converter. Power MOSFETs IRFP260N were used as switching devices. The bidirectional experiment step is to increase one of the DC sources to a certain value, then increase the other source until the power flow reverses (indicated by the reverse direction of the current). Figure 14 shows the input and output current in bidirectional experiment. It shows that the current can be reversed, thus indicating the proposed DC-DC converter is applicable in bidirectional mode.

Figure 13. Experimental scheme of the bidirectional experiment

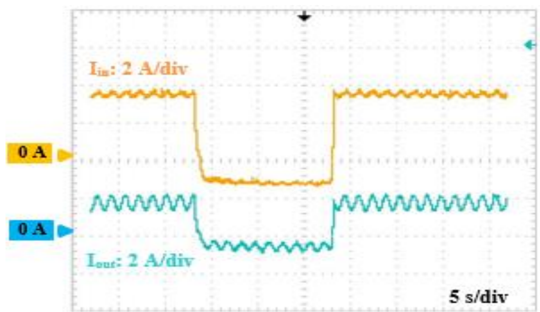


Figure 14. Input and output currents in the bidirectional experiment

5. CONCLUSION

A new step-up bidirectional DC-DC power converter based on the modification of conventional buck-boost DC-DC power converter has been proposed. As it is derived from the conventional buck-boost DC-DC power converter, it has simplicity and bidirectional characteristics. Under the same LC filter parameters, the proposed DC-DC power converter can achieve higher output voltage compared to the conventional DC-DC boost power converter. As the result, the proposed DC-DC power converter has better efficiency compared to the conventional DC-DC boost power converter. Moreover, it has lower capacitor voltage rating than the conventional one which lead to cost efficiency. Experimental results have verified the analysis method given in this paper. Applications of the proposed converter is left for future investigation.

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