

Bidirectional PWM Converter with High Voltage Conversion Ratio for Single-Cell Battery Power System

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1. Introduction

Vigorous research and development efforts for small scientific satellites are underway to realize frequent and low cost scientific space missions. Traditional power systems in scientific satellites employ an unregulated bus system where a secondary battery and load are directly connected, as illustrated in Fig. 1(a). The unregulated systems are advantageous over regulated bus systems [see Fig. 1(b)] from the viewpoint of the system simplicity as the number of power converters is only one. The number of battery cells connected in series is unambiguously determined by the load voltage requirement—e.g., 8 and 12 cells for 28- and 50-V bus systems, respectively. The energy capacity of the battery in watt-hour should be adjusted by selecting or manufacturing cells with a proper capacity, hence impairing the design flexibility. The poor design flexibility is quite unfavorable for small satellites to provide frequent mission opportunities.

Although the converter count is doubled, the regulated bus system is attractive from the viewpoint of battery design flexibility. The number of battery cells connected in series can be arbitrary changed to meet the energy capacity demand, and even a single-cell battery system is theoretically feasible, as shown in Fig. 1(b) [1]. The cell equalizer is no longer necessary in the single-cell battery system, allowing the simplified system configuration. Although the single-cell battery system offers the flexible battery design and simplified system, challenges concerning to the bidirectional converters arise.

To bridge the huge voltage gap between the bus (50 V) and single-cell battery (3.0–4.2 V for lithium-ion cells), a bidirectional converter with a high conversion-ratio is necessary. Conventional nonisolated PWM converters for high conversion-ratio applications, however, are known to suffer from issues originating from extreme duty cycle operations, such as increased losses and reduced controllability [2]. A current of the low-voltage side is more than 10 times than that of the high-voltage side, and therefore, an interleaving technique using multiple converters operating in parallel to mitigate current stresses is a favorable solution. Conventional interleaved converters, however, require current sensors to match individual currents, increasing the cost and control complexity.

This paper proposes a novel bidirectional interleaved PWM converter with high voltage conversion-ratio and automatic current balancing capability. The fundamental characteristics were experimentally demonstrated using a 100-W prototype.

2. Proposed PWM Converter

2.1. Circuit Description and Voltage Conversion Ratio

The proposed PWM converter with high voltage conversion ratio

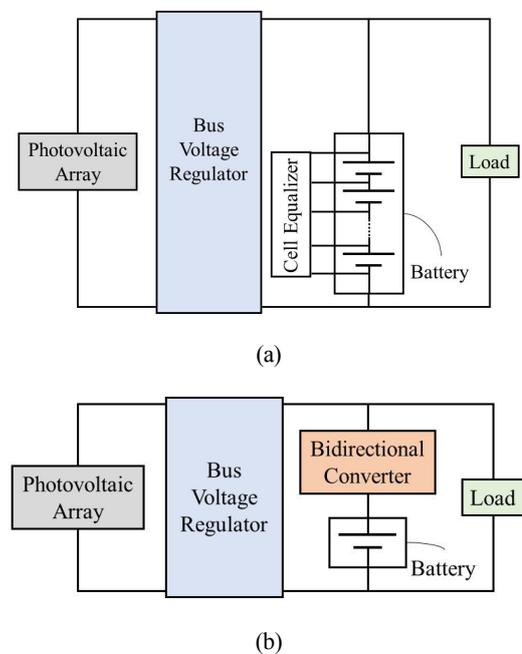


Fig. 1. Satellite power systems based on (a) unregulated bus and (b) regulated bus with a single-cell battery.

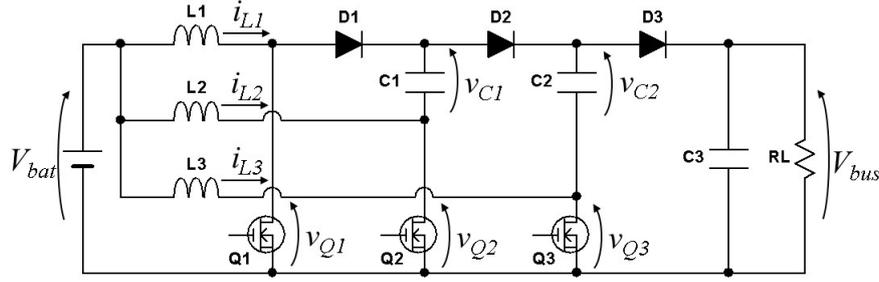


Fig. 2. Proposed PWM converter with high voltage conversion ratio (unidirectional).

is shown in Fig. 2. Although this circuit is the unidirectional version using diodes, it can be a bidirectional one by replacing diodes with switches. Three inductors, L_1 – L_3 , are connected to the battery and share the input current. Currents of these inductors are automatically balanced without feedback control, and therefore, no current sensors nor feedback loop are necessary. Three switches, inductors, and diodes operate in the interleaving manner 120° out of phase, and thus, this converter can be regarded as a three-phase interleaved converter when viewed from the battery side. Capacitors, C_1 and C_2 , play two roles of high conversion ratio and automatic current balancing, as will be discussed later.

L_1 , Q_1 , and D_1 operate as a boost converter that charges C_1 to the voltage level of $v_{C1} = V_{bat}/(1-d)$, where d is the duty cycle of switches. L_2 , Q_2 , and D_2 also behave as a boost converter that together with C_1 charges C_2 to be $v_{C2} = 2V_{bat}/(1-d)$. Similarly, L_3 , Q_3 , and D_3 also form a boost converter, and its output voltage with v_{C2} is outputted to C_3 or the load R_L . The voltage conversion ratio of the proposed PWM converter is yielded as

$$\frac{V_{bus}}{V_{bat}} = \frac{3}{1-d} \quad (1)$$

This conversion ratio is three times greater than that of the traditional PWM boost converter. The voltage conversion ratios of the proposed and conventional converters are compared in Fig. 3. For the 50-V bus system, the required voltage conversion ratio is 12.5–16.7 for a lithium-ion single cell with 3.0–4.2 V. Conventional converters need to operate with extremely high duty cycle of $d > 0.9$. The duty cycle range of the proposed converter, on the other hand, is reduced to around 0.8, avoiding the extreme duty cycle operations.

2.2. Operation Modes

The theoretical key operation waveforms and current flow

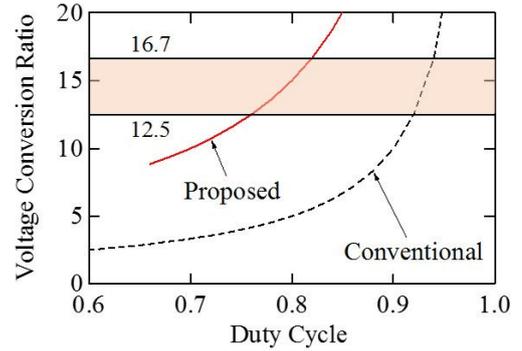


Fig. 3. Theoretical voltage conversion ratios.

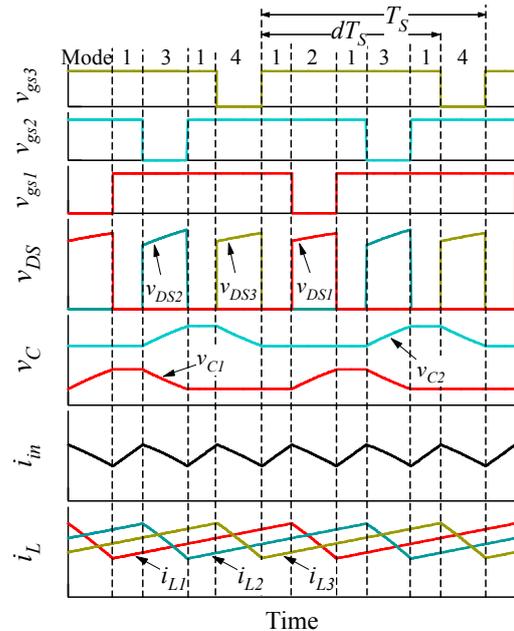


Fig. 4. Key operation waveforms.

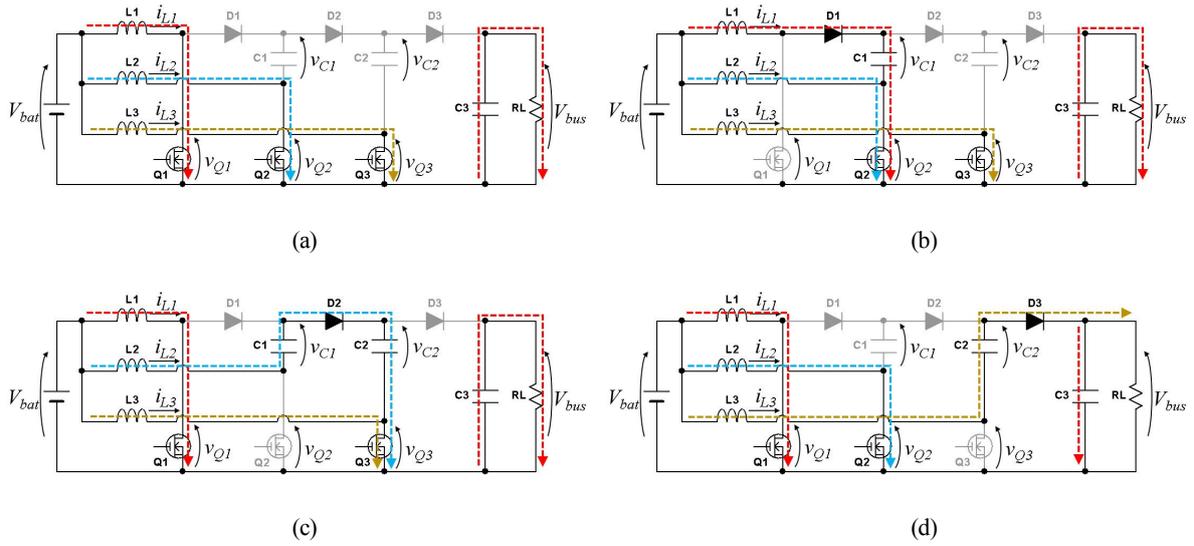


Fig. 5. Current flow directions in (a) Mode 1, (b) Mode 2, (c) Mode 3, and (d) Mode 4.

directions are shown in Figs. 4 and 5, respectively. Gating signals for Q_1 – Q_3 , v_{gs1} – v_{gs3} , are applied so that at least two of three switches are simultaneously on. v_{gs1} – v_{gs3} are 120° out of phase for the interleaving operation. One switching cycle can be divided into 6 modes, but three of them are Mode 1, during which all switches are turned on.

Mode 1 [Fig. 5(a)]: v_{gs1} – v_{gs3} are applied. All switches are on and their drain-source voltages, v_{DS1} – v_{DS3} , are zero. Inductor currents, i_{L1} – i_{L3} , linearly increase as V_{bat} is applied. The input current i_{in} , which is the sum of i_{L1} – i_{L3} , also increases.

Mode 2 [Fig. 5(b)]: v_{gs1} is removed to turn off Q_1 . D_1 starts to conduct, and i_{L1} linearly decreases. C_1 is charged by i_{L1} and its voltage v_{C1} increases. Since one of inductor currents decreases, i_{in} also decreases.

Mode 3 [Fig. 5(c)]: v_{gs2} is at low level to turn off Q_2 . D_2 starts to conduct, and L_2 discharges and its current i_{L2} decreases. i_{L2} together with C_1 charge C_2 , and v_{C2} increases. Similar to Mode 2, i_{in} decreases due to the decrease in i_{L2} .

Mode 4 [Fig. 5(d)]: Q_3 is turned off, and D_3 conducts. L_3 and C_2 charge C_3 .

2.3. Current Balancing Mechanism

All the inductor currents are assumed to be constant without ripple components. C_1 is charged by i_{L1} during Mode 1 [Fig. 5(b)], and is discharged by i_{L2} during Mode 2 [Fig. 5(c)]. Meanwhile, C_2 is charged and discharged by i_{L2} and i_{L3} during Modes 3 and 4, respectively, as shown in Figs. 5(c) and (d). Assuming lengths of Modes 2–4 are identical, the charge conservation law for C_2 and C_3 ensures the automatic current balancing for all inductors. This balancing mechanism does not rely on any active control or current sensing, and therefore, all inductor currents are passively balanced.

3. Experimental Results

A 100-W prototype of the proposed PWM converter was built, as shown in Fig. 6.

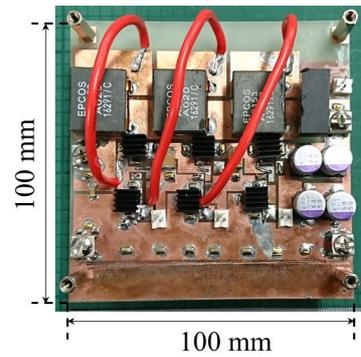


Fig. 6. Photograph of 100-W prototype.

Table 1. Component values.

L_1, L_2, L_3	15 μ H
C_{in}	220 μ F
C_{out}	272 μ F
C_1	22 μ F
C_2	22 μ F

Component values are listed in Table 1. The prototype was operated with $V_{bat} = 4.0$ V and $V_{bus} = 50$ V at the switching frequency of 100 kHz.

Measured current waveforms at the full load are shown in Fig. 7. Measured currents of i_{L1} – i_{L3} were 120° out of phase, and their averages were identical, verifying the passive current balancing capability.

The measured voltage conversion ratio is compared with the theoretical one, as shown in Fig. 8. The experimental results matched satisfactorily with the theory. Slight mismatch was considered due to the power conversion loss in the prototype.

The measured power conversion efficiency is shown in Fig. 9. The efficiency steadily decreased as the output power increased. The efficiency at the full load of 100 W was as high as 90%.

4. Conclusions

The bidirectional PWM converter with high voltage conversion ratio and automatic current balancing capability has been proposed for single-cell battery power systems in small scientific satellites. The proposed converter operates in an interleaving manner, and the added capacitors realize not only high voltage conversion but also automatic current balancing. The 100-W prototype was built, and its fundamental characteristics were experimentally demonstrated.

References

- [1] M. Uno and A. Kukita, "Multi-port converter integrating boost and switched capacitor converters for single-cell battery power system in small satellite," in Proc. *IEEE ECCE-Asia Down Under*, Jun. 2013, pp. 747–752.
- [2] K. Yao, M. Ye, M. Xu, and F. C. Lee, "Tapped-inductor buck converter for high-step-down dc–dc conversion," *IEEE Trans. Power Electron.*, vol. 20, no. 4, pp. 775–780, Jul. 2005.

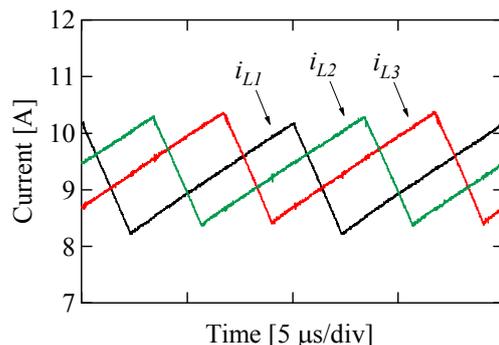


Fig. 7. Measured current waveforms.

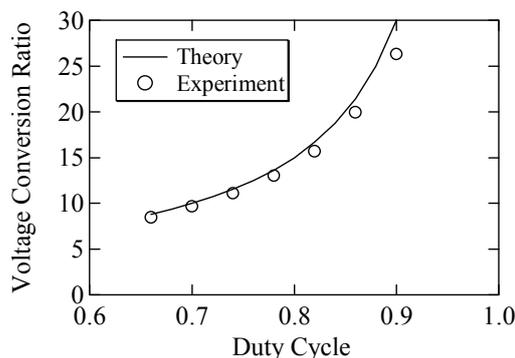


Fig. 8. Measured voltage conversion ratio.

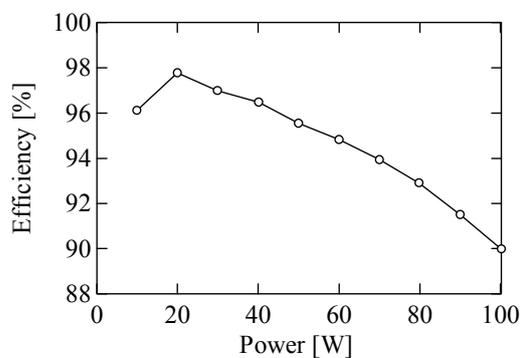


Fig. 9. Measured power conversion efficiency