3-Port Converter Integrating a Boost Converter and Switched Capacitor Converter for a Single-Cell Battery Power System in a Small Satellite

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1. Introduction

Small satellites were previously regarded as educational tools for university students. However, their applications have been steadily expanding, from Earth observations to engineering demonstrations. The major advantages of small as opposed to large satellites include risk mitigation, cheaper development cost, and accelerated development, etc. However, since they are basically small, all components, including the power system, must also be constructed compactly and simply.

Building and testing batteries for such small satellites are daunting tasks for students and engineers since they usually involve retrofitting commercial batteries for terrestrial use which must withstand harsh space environmental conditions, such as the vacuum in space, radiation, and vibration during the rocket launch [1]. The power requirement for such small satellites is basically less than a few hundred watts. Therefore, batteries for small satellites include several small lithium-ion cells, each having a few ampere-hours, connected in series to meet the voltage requirement of a satellite bus. Although space-qualified lithium-ion batteries, which are rugged and radiation-tolerant, have been developed by manufacturers, these are usually for large satellites and too large for small satellites; with a nameplate capacity larger than several tens of ampere-hours [2]. Although even a single space-qualified lithium-ion cell is enough to cover the energy requirement of small satellites, a significant voltage gap between a single-cell (3.0–4.2 V) and bus voltage (14–28 V) must be bridged.

Bidirectional dc-dc converters with a high voltage-conversion ratio may be applicable for small satellite applications. However, to minimize the size of the power system, such bidirectional converters should be as compact and efficient as possible. In this paper, a 3-port converter integrating a boost converter and a switched capacitor converter is proposed for single-cell battery power systems in small satellites. With the proposed 3-port converter, the cell current and voltage are PWM-controlled by the boost converter, while a high voltage-conversion ratio is achieved by the switched capacitor converter.

2. 3-PORT CONVERTER INTEGRATING BOOST AND SWITCHED CAPACITOR CONVERTERS

2.1. Comparison between Traditional and Proposed Power Systems

Traditional and proposed power systems for small satellites are compared in Fig. 1. In the traditional power system, shown in Fig. 1(a), the charging power from a photovoltaic (PV) array to a battery consisting of series-connected cells is controlled by a so-called array power regulator (APR). Loads are directly connected to the battery, hence the bus voltage is basically unregulated. In this traditional power system, since the battery consists of series-connected cells, a cell equalizer, which equalizes cell voltages to ensure years of safe operation, is necessary. Conversely, in the proposed power system shown in Fig. 1(b), the cell equalizer is no longer necessary because of its single-cell battery configuration, while the bus voltage is still unregulated, as explained in the next subsection. This means the power system can be simplified by eliminating the cell equalizer.

In addition, a space-qualified cell is likely to be used in the proposed power system. For example, four 5-Ah cells connected in series in the traditional power system can be replaced with a single 20-Ah cell in the proposed power system. 5-Ah cells are out

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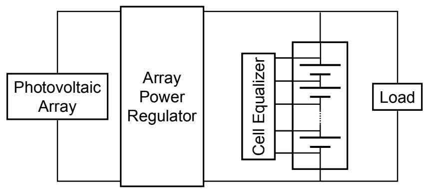
of range of space-qualified cells, while there are 20-Ah-class space-qualified cells in the market.

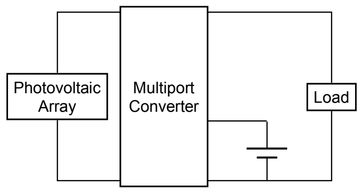
2.2. Circuit Description of a 3-Port Converter Integrating Switched Capacitor and Boost Converters

Various multi-port converter concepts have been proposed for renewable energy systems [3],[4]. The proposed 3-port converter is based on a combination of a synchronous boost converter and a switched capacitor converter, shown in Figs. 2(a) and (b), respectively. In the synchronous boost converter shown in Fig. 2(a), switches Q_a and Q_b are alternately driven, and the voltage at the switching node, V_{SN}, swings between V_{in} and V_{Boost}. Conversely, in the switched capacitor converter, odd- and even-numbered switches are alternately driven, and there are four switching nodes in this configuration — nodes A–D. Ideally, the voltage of V_a is four times that of V_b in this example configuration due to four capacitors, C_1–C_4, stacked in series.

Integrating the synchronous boost converter shown in Fig. 2(a) and the switched capacitor converter shown in Fig. 2(b) yields the proposed 3-port converter, as shown in Fig. 3. The inductor in the boost converter is tied to the switching node A in the switched capacitor converter, and switches Q_7 and Q_8 are shared. Either switching node can be used depending on the voltage relationship between V_{in} and V_{Bus}.



(a) Traditional unregulated power system using series-connected cells.



(b) Proposed unregulated power system using a single-cell.

Fig. 1. Comparison between traditional and proposed unregulated power systems for small satellites.

2.3. Control for Charging and Discharging Modes

In general, switched capacitor converters are basically unregulated; voltage regulation is possible but significant power conversion loss is very likely [5]. However, since the switched capacitor converter is used alongside the boost converter, the cell current and voltage can be regulated with a PWM control.

In this configuration, since the single-cell battery is tied to C_1 while the bus is connected to C_4, the ideal voltage relationship between cell voltage, V_{Cell}, and bus voltage, V_{Bus}, is

$$V_{Bus} = 4V_{Cell} . \qquad (1)$$

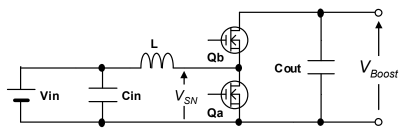
Ideally, the voltage of the switching node, V_{SN}, swings between $3V_{Cell}$ and $4V_{Cell}$, meaning the relationship among V_{in}, V_{Cell}, and V_{Bus} can be yielded as

$$V_{Cell} = \frac{V_{in}}{4-D} = \frac{V_{Bus}}{4} , \qquad (2)$$

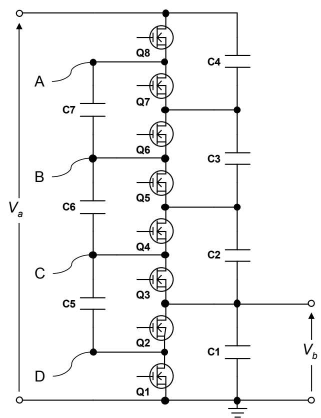
where D is the duty cycle of the odd-numbered switches.

For the charging mode, either the cell voltage V_{Cell} or current I_{Cell} is PWM-controlled based on (2), while the bus voltage V_{Bus} varies arbitrarily according to (2). Accordingly, the boost converter controls the charge current and voltage while the switched capacitor converter achieves a high voltage-conversion ratio. For a discharging mode, conversely, no control is necessary; switches are operated with a fixed duty cycle of 50%.

In this paper, a switched capacitor converter consisting of four capacitors stacked in series, C_1–C_4, is shown as an example. By changing the number of



(a) Synchronous boost converter.



(b) Switched capacitor converter.

Fig. 2. Key elements of the 3-port converter.

series-stacked capacitors, the voltage ratio of V_{Bus} to V_{Cell} can be arbitrarily adjusted. Generally, the voltage of lithium-ion cells varies within the range 3.0–4.1 V. According to (1), the variation range of the bus voltage is expected to be 12.0–16.4 V. The proposed 3-port converter shown in Fig. 3 is considered suitable for 14-V unregulated systems where the bus voltage varies between approximately 11–17 V. For higher/lower bus voltage power systems, the number of series-stacked capacitors in the switched capacitor converter should be increased/decreased to obtain suitable voltage relationships among V_{in}, V_{Cell}, and V_{Bus}.

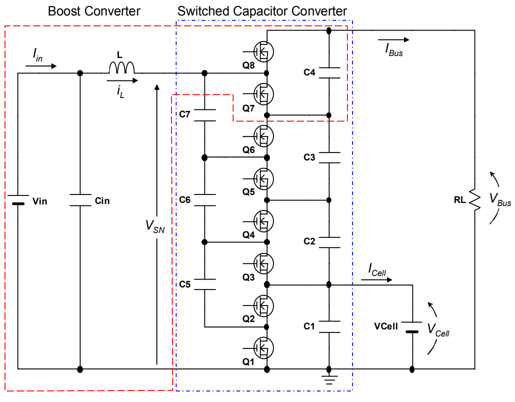


Fig. 3. 3-port converter integrating boost and switched capacitor converters.

3. EXPERIMENTAL RESULTS

3.1. Prototype and Efficiency Measurement

A 20-W prototype of the proposed 3-port converter was built as shown in Fig. 4. Ceramic capacitors with capacitance of 44 µF and N-Ch MOSFETs (RJK0329DPB, R_{on} = 1.8 mΩ) were used for C_1–C_7 and Q_1–Q_8 in the switched capacitor converter. The inductance of L was 10 µH. The prototype was operated at a switching frequency of 100 kHz. For a battery charging mode, the current and voltage of I_{Cell} and V_{Cell} were PWM-controlled with a constant current–constant voltage (CC–CV) charging scheme of 1.0 A–4.1 V. For a battery discharging mode, duty cycles for odd- and even-numbered switches are fixed at 50%.

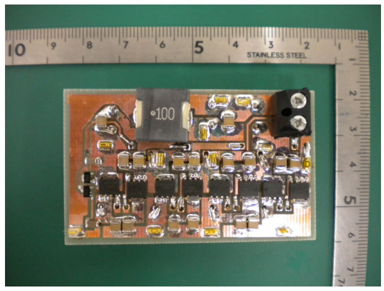
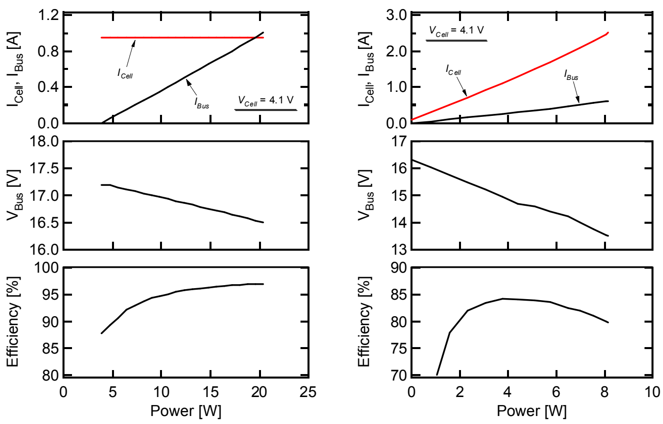


Fig. 4. A photograph of a 20-W prototype.

The measured power conversion efficiencies and bus voltage characteristics for charging and discharging modes are shown in Figs. 5(a) and (b), respectively. The charging mode was measured when V_{Cell} = 4.1 and I_{Cell} = 1.0 A. As the power rose with increasing I_{Bus}, V_{Bus} decreased, which implies that the conversion loss rose with increasing power and I_{Bus}. Power conversion efficiency as high as 97% was achieved at 20 W. For a discharging mode, conversely, the measured power conversion efficiency was lower than that for the charging mode, with peak efficiency of about 84.5%. In discharging mode, since power from the cell had to traverse capacitors and switches in the switched capacitor converter before reaching the bus, the collective loss in each component was considerable.

Thus, high efficiency was relatively easily achieved for the charging mode, whereas further improvement is preferable for the discharging mode. To achieve positive power system performance, the round-trip efficiency, which is defined as a product of efficiencies for charging and discharging, should be improved. These experimental results imply that the proposed multi-port converter should be designed with particular focus on discharging modes to improve round-trip efficiency.



(a) Charging mode. (b) Discharging mode.

Fig. 5. Measured power conversion efficiencies and bus voltage characteristics.

3.2. Experimental Charge-Discharge Cycling

A lithium-polymer cell with capacity of 2200-mAh at a rated charge voltage of 4.2 V was cycled with the prototype. While in charging mode, the cell was charged with a CC–CV charging scheme of 1.0 A–4.1 V. I_{Bus} was set at 0.5 A for both charging and discharging modes.

Experimental cycling profiles are shown in Fig. 6. During the charging mode, V_{Cell} increased from 3.3 to 4.1 V, while V_{Bus} varied between approximately 15.0 and 16.8 V. When V_{Cell} reached the CV charge voltage level of 4.1 V, I_{Cell} started to taper and I_{in} also declined. While in discharging mode, the cell was discharged to 3.3 V, while V_{Bus} declined to approximately 11 V. The voltage ratio of V_{Bus} to V_{Cell} during the discharging mode was smaller than the ideal ratio of (1) as well as that during the charging mode. Like the results shown in Fig. 5(b), the lower power conversion efficiency reflected the smaller voltage ratio, hence improved power conversion efficiency for discharging mode is considered key to achieving both higher round-trip efficiency and an improved V_{Bus} to V_{Cell} voltage ratio.

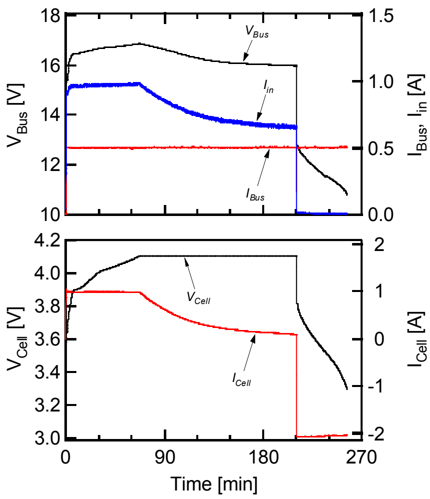


Fig. 6. Experimental cycling profiles.

4. CONCLUSIONS

In this paper, a 3-port converter integrating a boost converter and a switched capacitor converter was proposed for a single-cell battery power system in small satellites. In traditional power systems for small satellites, several small lithium-ion cells must be connected in series to meet the voltage requirement of loads, and a voltage equalizer for the series-connected cells is necessary. In the proposed power system, conversely, since the boost converter controls the charge current and voltage while the switched capacitor converter achieves a high voltage-conversion ratio, a single large-capacity cell can be used and the voltage equalizer is no longer necessary. When in charging mode, the charge current and voltage for the single-cell is PWM-controlled by the boost converter, while an unregulated voltage is provided for the bus by the switched capacitor converter. In discharging mode, conversely, the switched capacitor converter is operated with a fixed duty cycle to supply unregulated voltage to the bus. A 20-W prototype of the proposed 3-port converter was built for a 14-V unregulated bus system. The measured power conversion efficiencies for charging and discharging modes were 97 and 84.5%, respectively. A lithium-polymer cell of capacity 2200-mAh was cycled with the prototype. The cell voltage varied between 3.3–4.1 V, while the bus voltage variation range was approximately 11–16.8 V, thus demonstrating the proposed concept as well as its performance.

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