Switched Capacitor-Based Multiport Converter Integrating Bus Converter, Charge-Discharge Regulator, and Voltage Equalizer for Solar Panel

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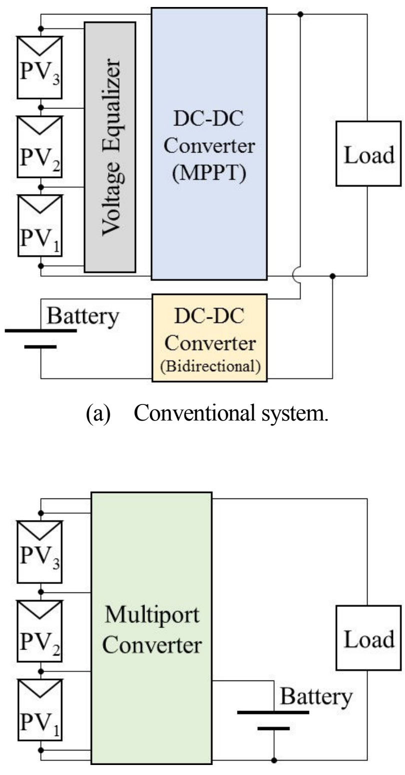
1. Introduction

Multiple dc-dc converters are necessary to maximize the performance of spacecraft power systems. A front-end dc-dc converter that performs maximum power point tracking (MPPT) is indispensable to maximize the power generation of photovoltaic (PV) arrays. A bidirectional dc-dc converter plays a role of battery charge-discharge regulation in regulated bus systems. In addition to these main converters, voltage equalizers that are gaining significant attention as a solution to partial shading issues [1], [2] would be a necessary component for future spacecraft power systems — under partial shading conditions, not only is the power generation of the string as a whole significantly reduced but also multiple power point maxima, which hinder and confuse ordinary MPPT algorithms, appear on the panel's P-V characteristic.

A regulated spacecraft power system employing an MPPT converter, bidirectional converter for batteries, and voltage equalizer to prevent partial shading issues is illustrated in Fig. 1(a). The performance of the system can be mizimized thanks to the three separate converters, but the system is undoubtedly prone to be complex and costly due to the increased number of converters. If these three converters were to be integrated into a single unit, the system would be considerably simplified by reducing the number of converters.

This paper proposes a novel multiport converter (MPC) that realizes three functions: PV panel control, charge-discharge regulation for batteries, and voltage equalization for PV panels to preclude partial shading issues. The notional block diagram of the proposed multiport converter is depicted in Fig. 1(b). The proposed MPC can be derived from the combination of a switched capacitor converter (SCC), PWM converter, and resonant converter.



(a) Conventional system.

(b) Proposed MPC system.

Fig. 1. PV systems.

2. SCC-Based MPC

2.1. Circuit Derivation

By combining conventional PWM converter, series-resonant converter (SRV), and SCC, the proposed MPC is derived. The SRC regulates the output voltage by PFM control while the PWM converter plays the role of battery charge-discharge regulation by PWM control. Meanwhile, the SCC is generally unregulated and is able to operate without feedback control, although its characteristic is dependent on duty cycle *D* and switching frequency f_S to some extent [3].

From the integration of these three converters, the proposed SCC-based MPC is derived, as shown in Fig. 2. The SCC shares switches Q_1-Q_2 and Q_5-Q_6 with the bidirectional PWM converter and SRC, respectively. In the SRC, two resonant tanks (L_{r1}-C_{r1} and L_{r2}-C_{r2}) are equivalently connected in parallel to increase the power capability.

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The SCC equalizes voltages of PV_1-PV_3 and preclude the partial shading issues [2]. Meanwhile, the bidirectional PWM converter and SRC regulator the battery voltage V_{Bat} and output voltage V_{Load}, respectively.

Because the PWM converter and SRC are integrated, the proposed converter employs both PWM and PFM controls. The output voltage V_{Load} is regulated with PFM control while charging/discharging for the battery is regulated by PWM control. In other words, both D and f_S simultaneously are adjusted, and it implies that the PWM converter and SRC mutually interfere and trigger cross-regulation problems. By properly determining f_S and resonant frequency f_r of the resonant tanks with considering duty cycle variation range, the concern about the cross-regulation can be satisfactorily precluded. As for the SCC, PV module voltages can be appropriately equalized even when duty cycle is varied, as reported in [3].

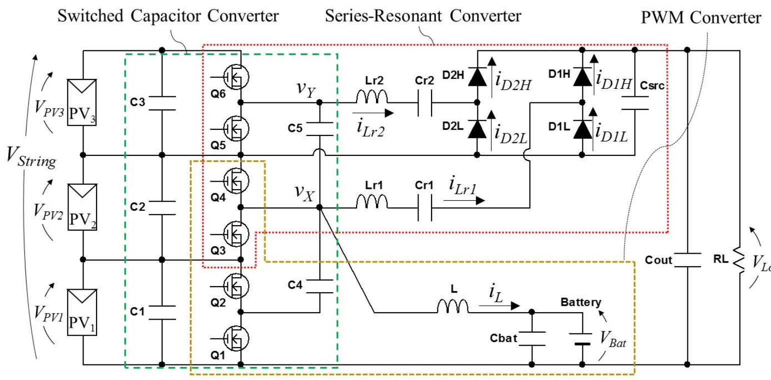


Fig. 2. Proposed SCC-based MPC for three PV modules connected in series.

2.2. Major Benefits

In comparison with the conventional PV system [Fig. 1(a)], the system is dramatically simplified by integrating three converters into a single unit [Fig. 1(b)]. Furthermore, the total switch count can also be reduced, hence achieving the circuit-level simplification; the proposed MPC requires six switches in total, whereas the total switch count is the conventional system is ten (two, two, and six for the SRC, bidirectional PWM converter, and SCC-based voltage equalizer, respectively). In addition to the system- and circuit-level simplifications, miniaturized design is also feasible thanks to the SCC. The proposed MPC is basically a hybrid SCC that can greatly downsize inductors, as reported in [3], [4].

3. Fundamental Operation Analysis

Depending on the power balance between the PV panels and power demand by the load, the proposed integrated converter operates in various power flow scenarios (e.g., a scenario that both PV panel and battery supply power to the load). This paper deals with the case that the PV panels not only supplies power to the load but also charges the battery.

Key operation waveforms and current flow directions are shown in Figs. 3 and 4, respectively. In Mode 1, the high-side switches (Q_2, Q_4, and Q_6) are turned-on, and the current L, i_L, linearly increases, and resonant currents, i_{r1} and i_{r2}, starts flowing through resonant tanks. As i_{r1} and i_{r2} reach zero, the operation shifts to Mode 2. No current flows in the SRC, and therefore, the MPC in this operation mode is equivalently a hybrid SCC [3], [4].

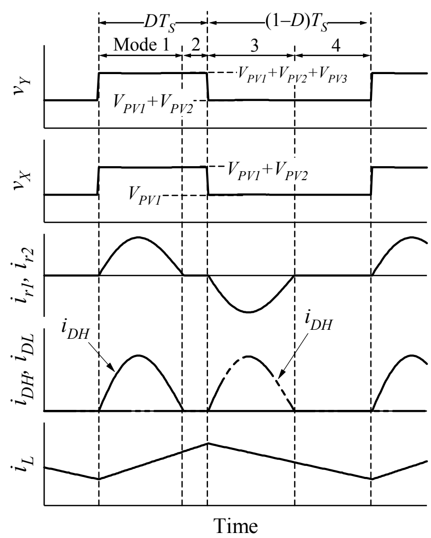
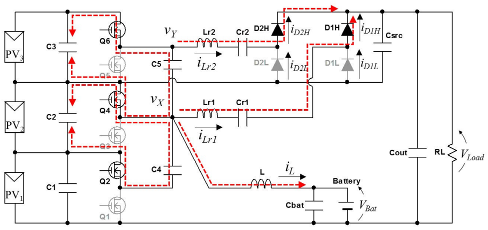
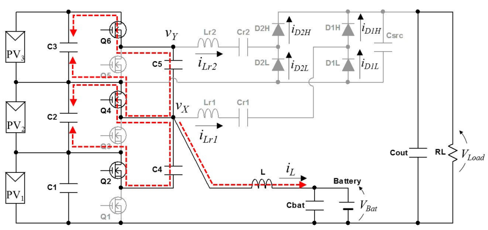


Fig. 3. Key operation waveforms.

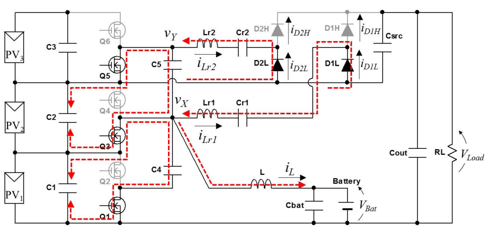
Mode 3 begins as low-side switches (Q_1, Q_3, and Q_5) are turned-on. i_L linearly decreases while i_{r1} and i_{r2} flow in the opposite direction as those in Mode 1. In Mode 4, i_{r1} and i_{r2} become zero again. Therefore, the resonant tanks are inactive,



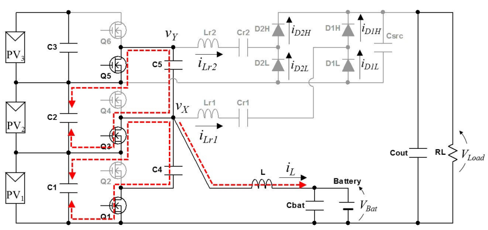
(a) Mode 1.



(b) Mode 2.



(c) Mode 3.



(d) Mode 4.

Fig. 4. Operation modes.

and the MPC in this mode is equivalent to the hybrid SCC.

The proposed MPC consists of the SRC and PWM buck converter, and therefore, a cross-regulation between these two converters is of great concern; duty cycle variation for the PWM buck converter may affect the operation of the SRC that conventionally employs PFM control. As shown in Figs. 3 and 4, the SRC is basically inactive in Modes 2 and 4, as i_{r1} and i_{r2} are zero. This operation suggests that the operation of the SRC is unaffected by duty cycle variation as long as these inactive modes (Modes 2 and 4) exist. In other words, duty cycle variations are buffered in Modes 2 and 4, and the characteristic of the SRC can be independent on the PWM buck converter. To this end, the switching and resonant frequencies, f_S and f_r, need to be designed to fulfill the operation criterion shown below;

$$1-\frac{f_S}{f_r} > D > \frac{f_S}{f_r}. \quad (1)$$

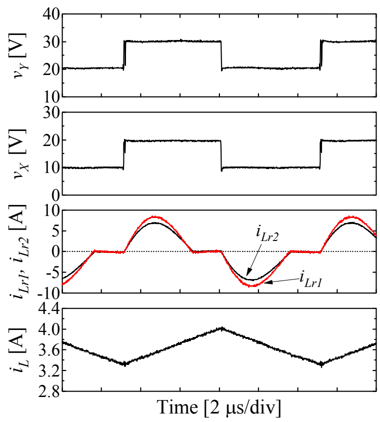


Fig. 5. Measured key waveforms when I_{Load} = 3.46 A and I_{Bat} = 3.65 A.

4. Experimental Results

A 150-W prototype for 60-cell strings comprising three PV modules connected in series was built. The prototype was operated with V_{Load} = 28 V and V_{Bat} = 12–16 V. A resistive load was used instead of connecting a battery to the output port of the PWM converter. Solar array simulators (E4360A, Agilent Technologies) were used to emulate a partial shading condition where PV_2 and PV_3 were unshaded while PV_1 is partially shaded and its short-circuit current is half those of PV_2 and PV_3.

Measured key operation waveforms are shown in Fig. 5. These waveforms agreed very well with the theoretical ones shown in Fig. 3, verifying the operation of the proposed MPC. The measured power conversion efficiency at full load of 150 W was as high as 96%.

To demonstrate the voltage equalization performance, d was manually varies in the range of 0.3–0.7 at f_S of 50 kHz or 100 kHz, while the output port of the SRC was opened so that the total processed power in the prototype was simply determined by the output of the PWM converter. The extractable maximum powers were significantly improved by voltage equalization, as shown in Fig. 6, successfully demonstrating the equalization performance of the integrated converter. The measured characteristics at the higher frequency condition of f_S = 100 kHz exhibited the greater power because SCCs' efficiencies tend to increase at high frequencies as their equivalent resistance is inversely proportional to f_S [2], [3].

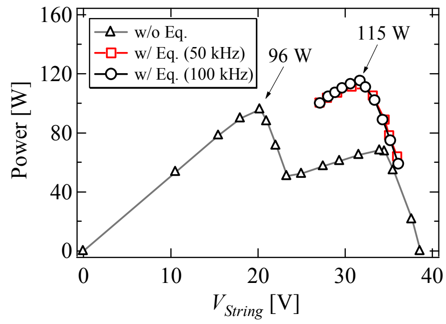
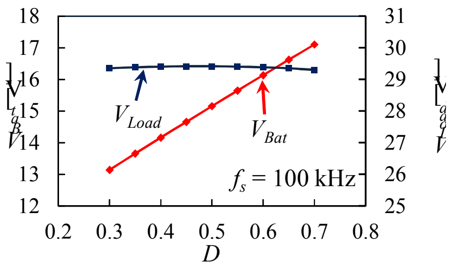
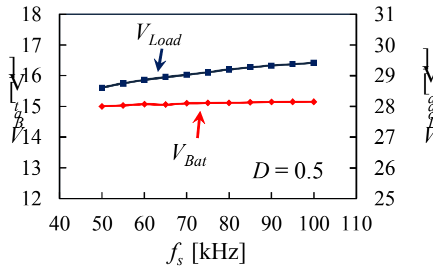


Fig. 6. Measured output power characteristics.

The interdependence of the PWM and PFM controls for the PWM converter and SRC was investigated. At the fixed f_S of 100 kHz, V_{Load} and V_{Bat} were measured with varying D in order to investigate the dependence of D on V_{Load}. Similarly, f_S was changed at the fixed D of 0.5 to observe the dependence of f_S on V_{Bat}. The measured characteristics are shown in Fig. 7. V_{Bat} was chiefly dependent on D and was nearly independent on f_S, and vice versa for V_{Load}. These results suggested that V_{Bat} and V_{Load} can be independently controlled with PWM and PFM controls. To further reduce the interdependence between V_{Bat} and V_{Load}, an advanced control using a decoupling technique [5] should be considered that is a part of our future works.



(a) At fixed f_S = 100 kHz and variable D.



(b) At fixed D = 0.5 and variable f_S.

Fig. 7. Measured characteristics of V_{Bat} and V_{Load}.

4. Conclusions

The PWM- and PFM-controlled SCC-based MPC integrating voltage equalizer has been proposed in this digest. The battery and load voltages are independently controlled with PWM and PFM controls, respectively, while the partial shading issues can be precluded by the SCC-based voltage equalizer. The fundamental operation was briefly explained, and some representative experimental results were shown in this digest.

References

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