Processor-in-the-Loop Simulation of Three Port DC/DC Converter for DC Power Generation and Distribution System

Yang Yang∗1,2, Yiting Jia2, Anshou Li2, Hua Zhang2, Zicai Wang 1
1 Harbin Institute of Technology, Harbin, China
2 Shenzhen Academy of Aerospace Technology, Shenzhen, China
E-mail: *yangyang.yy@139.com

Abstract. Offline microgrid systems often use DC power generation and distribution systems. The spacecraft power system is a typical application of this system. The demand for massive, intensive launch and diversified functions in new aerospace applications puts forward requirements for off-the-shelf sales, fault tolerance, and rapid integration for the spacecraft power system. This article uses a three-port converter SRB3C to design a scalable DC power generation and distribution system with MPPT and flexible parallel ability. The power converter uses TMS320F28335 as a microcontroller to realize MPPT, droop control, current and voltage closed-loop control, and other functions. To fully verify the system and ensure the reliability of the spacecraft, the processor-in-the-Loop simulation model of the system is built to verify the binary program running in the processor under various operating conditions. The results show that the DC power generation and distribution system composed of SRB3C can meet the needs of spacecraft applications.

1. Introduction
The spacecraft power system is a typical DC power generation and distribution system. In the mainstream spacecraft configuration, a photovoltaic-battery power system is used[1]. The photovoltaic cell generates electrical power, which is distributed to the platform and the payloads through the DC bus after conversion. When the generated power is greater than the load power, the battery is charged. When the generated power is less than the load power, the battery is discharged. During the eclipse period, the spacecraft power system is maintained by the battery alone.

In the traditional spacecraft power system, the Direct Energy Transfer power system is used usually[2, 3]. As shown in Figure 1, the SR (Shunt Regulator) connected in parallel with the solar cell array. The fraction of the generated current higher than the load and charging demand is shunted to maintain the stability of the bus voltage. The battery is connected to the bus through the BCR (Battery Charge Regulator) and BDR (Battery Discharge Regulator) which are DC/DC converters. The three converters are controlled by an MEA domain[4]. This system has a simple structure, requires few components, and consumes extra energy outside the spacecraft cabin, reducing the pressure on the thermal control system. Because the working point voltage of the solar cell array is lower than the maximum power point voltage at the beginning of life, part of the generated power is wasted. The separation of the system structure
also complicates system integration, fails to achieve off-the-shelf sales, and affects the spacecraft delivery period.

The new integrated spacecraft power controller uses a single three-port topology to replace the SR, BCR, and BDR modules in the traditional DET power system, as shown in Figure 2. This system uses a single power module to replace the original three power modules and reduces the size and weight of the power controller. At the same time, it implements MPPT (Maximum Power Point Tracking) on the solar cell array, which reduces the area of the solar array, and further improves the power density of the power system. The highly integrated design of the DC bus ports that can be connected in parallel makes the system configuration simple. Different types of spacecraft only need to select the appropriate number of power controllers according to the power requirements, which realizes off-the-shelf sales of the spacecraft power supply system and fulfills the demands of commercial aerospace of batch manufacture, high-density, reasonable cost, and diverse functions.

The integrated power controller uses a microcontroller so that energy can be more intelligently dispatched between PV, battery, and load. Meanwhile, the MPPT for PV can be implemented in the processor. Further, the processor can collect and process data for TMTC (Tele-Metry and Tele-Command). High reliability is required in spacecraft applications, which requires full verification and working condition testing of processor programs during R&D. In this paper, the three-port converter topology B3C (Boost Bidirectional-Buck Converter) [7] is improved to a synchronous rectification B3C (SRB3C) topology. Texas Instruments TMS320F28335 is used as a processor to implement functions such as closed-loop control, droop control, and MPPT. PSIM software is used to simulate the system to fully verify the reliability of the system.

The rest of this paper is organized as follows. In Section II, the SRB3C converter is introduced and analyzed. Section III presents processor-in-the-loop (PIL) simulation of the spacecraft power system equipped with the SRB3C converter. Simulation results are presented and analyzed in Section IV. A final summary and conclusion complete this paper in Section V.

2. DC Power Generation and Distribution System of synchronous rectification B3C

2.1. Structure and Principle of the Topology

Figure 3 shows the power stage of the synchronous rectification B3C. The SRB3C topology is developed from the dual-inductance boost topology. By sharing inductance and energy storage capacitors and introducing snubber inductance, it is possible to reduce the number of power devices and increase power density. The topology includes 3 inductors, 2 capacitors, and 4 switch devices. Q1 and Q2, Q3 and Q4 work in complementary mode. There are four phases in the operation of SRB3C.
When $Q_1$ and $Q_3$ are turned on, solar array current flows through $Q_1$ and $L_2$, and another branch through $C_1$ and $L_1$. The inductors are storing energy. The equivalent topology of the circuit is shown in Figure 4 (a).

When $Q_2$ and $Q_3$ are turned on, solar array current flows through $Q_2$, $C_1$ and $L_2$, and another branch through $L_1$ to the bus. The inductors are releasing energy. The equivalent topology of the circuit is shown in Figure 4 (b).

When $Q_2$ and $Q_4$ are turned on, solar array current flows through $Q_2$ and $L_1$ to the bus. Depends on the power status of the solar and bus load, another branch current flows through $C_1$ and $L_2$ when the solar array power greater than the load power. And this branch current flows reversely when the solar array power cannot fulfill the load power. The equivalent topology of the circuit is shown in Figure 4 (c).

In the fourth phase, the $Q_2$ and $Q_3$ are turned on, the current flows are consistent with the second phase. In these four phases, the direction of the current flowing through $L_3$ depends on the power difference between the solar array power and the bus load power. When the solar array power greater than the load power, the current flows to the battery. When the solar array power is less than the load power, the current flows to the bus.

When the converter works in a steady state and the current is continuous, the voltage relationship between the three ports can be deduced according to the circuit principle as

$$V_{BUS} = \frac{V_{SA}}{d_2}$$

$$V_{BAT} = d_3 \times V_{BUS}$$

where $d_2$ is the duty of $Q_2$, and $d_3$ is the duty of $Q_3$.

2.2. Parallel Method of Multi SRB3C

The core of the integrated power controller is a three-port DC/DC power converter. The scalability of the power module is conducive to the production of the power controller. To achieve off-the-shelf sales and flexibility in system integration, power controllers should have the ability to be connected in parallel. The droop control method is a method to achieve the purpose of approximate current sharing of the parallel modules by adjusting the output impedance of the power converter which is adjusting the external characteristic slope. This method is the simplest method to achieve current sharing. The modules are independent of each other, and there is no additional control signal or communication bus. It has poor current distribution characteristics at low currents and better distribution characteristics at heavy loads. However, due to low pressure on heat dissipation and electrical during light load, uneven power-sharing will not cause serious problems.
Figure 4. The equivalent topology of the SRB3C. (a) $Q_1$ and $Q_3$ are ON. (b) $Q_2$ and $Q_3$ are ON. (c) $Q_2$ and $Q_4$ are ON. The green line indicates the current flow from the solar array. The blue line indicates the battery current when the generated power is greater than the load power. The red line indicates the battery current when the generated power is less than the load power.

As shown in Figure 5, the output current $I_o$ is sampled and amplified by $K_{cs}$ times, and it is added to the input terminal of the operational amplifier in combination with the voltage sample $K_d V_o$ output by the module. After comparing with the reference voltage $V_{ref}$, the error is amplified to obtain $V_c$. As the output current of the power supply changes, $V_c$ will change accordingly. By adjusting the duty cycle of the power topology, the output voltage $V_o$ of the module is automatically adjusted, that is, the external characteristic slope changes (output impedance change), so that the output impedance of each parallel module is as consistent as possible to achieve the desired current sharing accuracy.

Figure 5. The block diagram of droop control.
3. PIL Simulation of the SRB3C Power System

3.1. Control Strategy of the SRB3C

The control of SRB3C is realized by TMS320F28335 microcontroller. The internal control logic block diagram of the processor is shown in Figure 6. In order to realize the MPPT, voltage and current closed-loop control and droop control of the system, the processor needs to collect solar array voltage \( V_{sa} \), current \( I_{sa} \), bus voltage \( V_{bus} \), current \( I_{bus} \), battery current \( I_{bat} \). At the same time set the given values of bus voltage and battery current \( V_{busref} \) and \( I_{batref} \).

![Figure 6. The control block diagram of processor program.](image_url)

The solar array voltage and current signals are input to the MPPT module. After finding the MPP, the solar array voltage command signal is output, which forms a closed loop with the solar array voltage \( V_{sa} \). The battery current is sampled to build the battery constant current charging control. The bus voltage and current signals are set up through the reasonable setting of the magnification to form the droop control. The output of the droop control is calculated with the maximum value of the solar array control signal and the battery control signal, and finally form the PWM signals of the switching devices \( Q_1 \) and \( Q_3 \).

3.2. Simulation Setup

Figure 7 shows one section of the DC power generation and distribution system composed of SRB3C. Besides the SRB3C power stage and controlled, the simulation includes a solar array, storage battery, and load resistor. A MOSFET is used to switch the bus load to verify the operating conditions when the bus load suddenly changes. Additional parallel capacitors on the solar array are used to simulate the parasitic capacitance characteristics of triple-junction GaAs solar cells. The PIL block runs in the TMS320F28335 processor as binary code and interacts with PSIM through a JTAG emulator. The emulator sets appropriate breakpoints in the program, injects data into the specific variables and extracts data as configured. The working cycle of the entire system is synchronized with the running speed of the simulation model. Unlike HIL (Hardware-In-the-Loop) simulation, PIL is not a real-time simulation, so the more accurate but time-consuming models can be used.
4. Simulation Results

The SRB3C DC power generation and distribution system model in the previous section is verified in PSIM simulation software. Figure 8 shows the simulation result of the step bus load working condition.

Figure 8. The bus voltage and battery current in the PIL simulation.

In this condition, the bus load resistor steps down through a MOSFET, which means the bus load increase abruptly. A slight drop can be observed from the bus voltage curve, and then it enters a stable state. Due to the droop control, after the load increases, the steady-state bus voltage decreases slightly. As shown in Figure 9, the solar array works at the maximum
power point after increasing the load. It is because the power demand on the bus, including the battery charging power, is less than the MPP power of the solar array. Since the illumination state does not change and the solar array’s power generation capacity does not change, the charging current to the battery decreases. The simulation results indicate that the DC power generation and distribution system works as expected.

![Figure 9. The working pointing of solar array in the PIL simulation.](image)

5. Conclusion
DC power generation and distribution systems are often used in offline microgrid systems, whether in aerospace or ground missions. This paper uses synchronous rectification B3C to build a DC power generation and distribution system with MPPT function that can be used directly in parallel without additional current sharing signals or communication buses. The system control function is integrated into a single-chip processor. The system processor-in-the-loop simulation model is built. The binary program of the control part is run on the processor and interacts with the power stage, solar array, battery, load in the simulation model through the JTAG interface, to fully verify the reliability of the system under different operating conditions. The simulate verification results show that the DC power generation and distribution system constructed by SRB3C can correctly track the maximum power point of the solar array, realize the droop control of the bus, stabilize the bus voltage, and manage the battery charge and discharge.

Acknowledgments
This study is supported by the China Postdoctoral Science Foundation (Grant No. 2019M653064).

References
[1] Patel M R 2004 *Spacecraft Power Systems* (New York : CRC press) p 37 - 38
[2] Garrigs A, Carrasco J A, Blanes J M and Sanchis E 2005 *IEEE Power Electronics Letters* 3 p 7 - 13
[3] Soubrier L, Trehet E 2011 *High Power PCU for Alphabus: PSR100V* (Saint Raphael, France : ESA) p 135 - 143
[4] A Capel, P Perol 2001 *Comparative performance evaluation between the S4R and the S3R regulated bus topologies* (Vancouver, BC, Canada : IEEE) pp 1963 - 1969.
[5] Y M Chen, A Q Huang and X Yu 2013 *IEEE Trans. Power Electron.* 28 pp 5049 - 62
[6] Z Wang and H Li 2013 *IEEE Trans. Power Electron.* 28 pp 4612 - 24
[7] H Y Zhu, D L Zhang, B W Zhang and Z C Zhou 2015 *IEEE Trans. Power Electron.* 62 pp 4937 - 47