Design of a high-power density energy system for solar powered aircraft

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Abstract. Maximum energy utilization and high-power density are critical to solar powered aircraft energy system. SiC devices have the advantages of high frequency and high temperature and it is very promising in the aspect of the development of high temperature and high-power density converter. This paper designed a 1.2 kW SiC based power controller using interleaved two-switch buck-boost converter, analyzed the working process of the converter, put forward small signal model and discussed three mode control strategy, and achieved smooth switching among all modes and maximum utilization of power energy. Experimental results demonstrate that the converter module has the power density of 2.4 kW/kg.

1. Introduction

Smart energy system is one of the key elements to achieve good performance of solar powered aircraft. The energy system adopt maximum power point tracking (MPPT) technology to extract maximum power from solar arrays (SA) and design a high-efficiency lightweight converter to reduce energy loss [1]. A maximum mower mystem topology is shown in figure 1.

In aircraft energy system, due to the wide range of SA voltage and battery bus voltage, the efficiency of the conventional buck or boost DC/DC converter is low, so buck-boost converter should be adopted to realize high efficient power conversion. Cascade buck converter and boost converter can get two-switch buck-boost(TSBB) converter [2], considering that some of the devices may work under large power for long working hours, the TSBB has been optimized. The paper put forward interleaved two TSBB converter [3,4], as shown in figure 2.

The topology has the following characteristics:

● The current stress of switch is reduced by half and this helps to reduce heat.
● The switching frequency is halved and the inductance ripple decreased which is beneficial to increase the power density.
● The output voltage is 100 V ~ 210 V.
● Single-channel power is 600 W; the module output power is 1200 W.
2. Topology description
In order to facilitate analysis, the TSBB converter is divided into two parts: the circuit composed of Q1 and D1 is buck, and the circuit composed of Q2 and D2 is the boost.

The duty ratio of Q1 is $d_1$, and the duty ratio of Q2 is $d_2$, and the average voltages of point A and B in figure 2 is:

$$\bar{V}_A = U_{in}d_1$$  \hspace{1cm} (1) \\
$$\bar{V}_B = U_o(1 - d_2)$$  \hspace{1cm} (2)

Where $U_{in}$ is the input voltage of one TSBB converter, $U_o$ is the output voltage of converter.

When converter operates in steady-state and during a switching period, inductor voltage satisfies volt-second balance, which indicates the average voltage across inductor is equal,

$$\bar{V}_A = \bar{V}_B$$  \hspace{1cm} (3)

According to equations (1)-(3), the TSBB relationship can be introduced as:

$$V_o = \frac{d_1}{1-d_2}V_{in}$$  \hspace{1cm} (4)

2.1. Small signal modeling
When TSBB converter works in buck mode and boost mode, it is equivalent to buck converter and boost converter respectively, and the small signal models are shown in figures 3 and 4.

According to figure 3, transfer function of buck mode from control to output $G_{vd\_buck}(s)$ and
transfer function of buck mode from input to output \( G_{v_{o},v_{i,n},buck}(s) \) can be derived respectively,

\[
G_{v_{o},v_{i,n},buck}(s) = \frac{\hat{b}_o}{\hat{b}_i} = \frac{(sR_cC_f + 1)\hat{V}_{in}}{s^2L_fC_f\left(1 + \frac{R_c}{R_L}\right) + s\left(\frac{L_f}{R_L} + R_cC_f\right) + 1} \tag{5}
\]

\[
G_{v_{o},v_{i,n},buck}(s) = \frac{\hat{b}_o}{\hat{b}_i} = \frac{(sR_cC_f + 1)\hat{V}_{o}}{s^2L_fC_f\left(1 + \frac{R_c}{R_L}\right) + s\left(\frac{L_f}{R_L} + R_cC_f\right) + 1} \tag{6}
\]

Where \( \hat{b}_o \) is disturbance signal of output voltage \( \hat{V}_o \), \( \hat{b}_i \) is disturbance signal of duty cycle of switch Q1 or Q3 in figure 2, \( L_f \) is the inductance value of L1 or L2 in figure 2, \( R_L \) is the equivalent series resistance (ESR) of L1 or L2, \( C_f \) is output capacitance value, \( R_c \) is the equivalent series resistance (ESR) of output capacitance.

Similarly,

\[
G_{v_{o},v_{i,n},boost}(s) = \frac{\hat{b}_o}{\hat{b}_i} = \frac{(sR_cC_f + 1)\left(1 - s\frac{L_f\hat{V}_o^2}{R_LV_{in}}\right)\hat{V}_{o}^2}{s^2L_fC_f\left(1 + \frac{R_c}{R_L}\right)\hat{V}_{o}^2 + s\left(\frac{L_f\hat{V}_o^2}{R_LV_{in}} + R_cC_f\right) + 1} \tag{7}
\]

\[
G_{v_{o},v_{i,n},boost}(s) = \frac{\hat{b}_o}{\hat{b}_i} = \frac{(sR_cC_f + 1)\hat{V}_{o}}{s^2L_fC_f\left(1 + \frac{R_c}{R_L}\right)\hat{V}_{o}^2 + s\left(\frac{L_f\hat{V}_o^2}{R_LV_{in}} + R_cC_f\right) + 1} \tag{8}
\]

Where \( \hat{b}_o \) is disturbance signal of output voltage \( \hat{V}_o \), \( \hat{b}_i \) is disturbance signal of duty cycle of switch Q2 or Q4 in figure 2, \( L_f \) is the inductance value of L1 or L2 in figure 2, \( R_L \) is the equivalent series resistance (ESR) of L1 or L2, \( C_i \) is output capacitance value, \( R_c \) is the equivalent series resistance (ESR) of output capacitance.

From equation (7), there is right half plane (RHP) underboost mode in small signal model and the frequency of RHP (fRHP) is:

\[
f_{RHP} = \frac{1}{2\pi L_f\hat{V}_o^2} = \frac{1}{2\pi L_f\hat{V}_o^2} \tag{9}
\]

2.2. Small signal modeling

Single-mode control and dual-mode control are commonly used in TSBB converters.

- Single-mode control: two switches work at the same time and the power loss is big;
- Dual-mode control: there is RHP in Boost mode, which lead to poor transient response, especially when the input voltage (\( U_{in} \)) and output voltage (\( U_{o} \)) is close, input voltage disturbance will lead to frequent transition between buck and boost models which will increase output voltage ripple.

So introduce a third kind of pattern namely DM (direct mode) where \( U_{in} \) and \( U_{o} \) is very close, to ensure the stability of output voltage [5]. The converter adopts three-mode control method, which contains buck mode, DM, and boost mode. Three-mode control strategy based on single signal dual carrier that of dual-mode control strategy, but needed additional decision conditions, which need real-time comparing of \( U_{in} \) and \( U_{o} \). Figure 5 shows the control strategy and main working waveform of three-mode control method, the specific control strategy is:

- step 1), when detected \( |U_{in} - U_{o}| > \Delta U \), namely the TSBB work in non-DM, the three-mode control strategy is the same as dual-mode control, as shown in figure 5(a);
- step 2), once detected \( |U_{in} - U_{o}| = \Delta U \), namely the converter gone into the DM, the three-mode control strategy is shown in figure 5(b), switch Q1 is on and Q2 is off, at the moment
modulation signal uearemain unchanged, and not overlap with the carrier signal usaw, and record the current input voltage $U_{in} = U_{in}^{'}$;

- step 3), when $|U_{in} - U_{o}| \leq \Delta U$, the converter work in DM, once detected $|U_{in}^{'} - U_{in}| > \Delta U$, the converter will jump out of the DM, uea overlap with the carrier signal usaw to produce PWM signal, the control strategy is shown in figure 5(a).

The main working waveform of the three-mode control strategy is shown in figure 5(c), where the red dashed line refers to the modulation signal under the DM.

To sum up, the three-mode control method has the following advantages:

- Any time only one switch is in the switch working state and switching loss is reduced;
- Effectively reduce the average inductor current, reduce the loss of the power, so as to improve the conversion efficiency of converter;
- By introduce DM, it can effectively solve the problem of smooth transition between buck and boost modes, that will enhance the stability of power conversion.

![Figure 5](image_url)

**Figure 5.** Three-mode control strategy of the TSBB. (a) Control strategy of non-DM, (b) Control strategy of DM and (c) The main working waveform.

2.3. Control logic

System block diagram is shown in figure 6, the power system contains two SA, two interleaved buck-boost converter, corresponding control unit and load. The control units are managed by a digital controller which is implemented by FPGA. Control diagram is shown in figure 7, control system contains signals sample unit, logic unit, CAN communication unit, DC-DC and so on. The control logic mainly contains MPPT control [6], bus voltage control, three-model control and health management.

- MPPT control realizes extracting maximum power from each SA;
- Bus voltage control realizes the stability of the bus;
- Three-model control realizes smooth transition among buck mode, DM, and boost mode;
- The key of health management is to monitor system data and online fault isolation and reconfiguration;
- The controller makes the function of real-time communication with PC through CAN bus.

![System block diagram](image)

**Figure 6.** System block diagram.

![Control diagram](image)

**Figure 7.** Control diagram.

Logic Unit in figure 7 is the core of the control strategy. The specific design of Logic Unit is shown in figure 8, in which SA_ref is provided by MPPT loop, BUS_ref is the reference of bus (sometimes is battery voltage), SA_sample is the real-time voltage of SA, BUS_sample is the real-time voltage of bus. Figure 8 shows the criteria for all modes transition in detail and there are four modes which contain DM, MPPT boost mode, MPPT buck mode and CVM (constant voltage mode). When bus voltage reaches a certain value, system enters into CVM, it means that SA power is more than load needed, so it quit from MPPT.
Figure 8. Multi-mode smooth transition diagram.

Figure 9. Framework of FPGA.

The control units is managed by FPGA controller, the framework of FPGA is show in figure 9, which contains PLL, Trig & Ena, AD_Sample, MPPT_Loop, vol_Loop, Mod_Select, PWM and CAN.

- PLL: to provide time signal;
- Trig & Ena: to trigger and enable;
- AD_Sample: to convert analog signals to digital signals;
- MPPT_Loop: to control SA output maximum power;
- VOL_Loop: to make battery bus voltage stable when the bus reaches a fixed value;
2.4. Driver design

At the same power level, SiC device is more suitable for applications in high voltage, high temperature and high frequency and can improve the power density and conversion efficiency of the converter. So SiC is used in the converter to meet the requirement of high power density. Proper drive circuit design is critical in the application of SiC devices.

The drive of the TSBB shall be isolated. In traditional isolated drive circuit usually use transformer to achieve the purpose of isolation drive. The paper chooses isolation driver chip because the duty ratio of the driving sign high speed, high reliable SiC switch tube drive circuit [7].

According to SiC performance, the isolated drive circuit should meet the following requirements:

- In the process of high frequency switch, input capacitance of the gate need fast charge and discharge, so the driver chip shall provide peak current as large as possible;
- SiC provides higher switching frequency, in order to achieve effective switch in a shorter time, corresponding measures must be taken.
- Due to dv/dt is relatively small in the condition of high frequency switch; the paper takes reverse-turn-off method in order to avoid voltage oscillation to improve the working reliability of the converter.

The drive circuit is shown in figure 10; the peak output current of UCC21521 is 4 A, which can meet the requirements of input capacitance of the gate for fast charging and discharging. In order to speed up turning on of the switch, the rectifiers are connected with the driving resistance separately. At the same time, in order to accelerate the switching speed, the PNP BJT is introduced to complete discharge circuit between the gate and source of Q1. In addition, switch (SCT3080AL) shall be turn off by negative voltage and the minimum driving voltage is -3.3 V.

![Figure 10. Schematic diagram of capacitor isolation drive circuit.](image)

3. Simulation and experimental results

![Figure 11. The designed energy system.](image)

![Figure 12. Power controller module.](image)
Finally, in order to validate the proposal, a 1.2 kW energy system has been designed as it is shown in figure 11. The power controller module is shown in figure 12. The basic specifications of the module are presented in table 1.

Table 1. Basic specifications of the module.

| Specifications     | Values     |
|-------------------|------------|
| Power             | 1200 W     |
| Bus Voltage       | 110-210 V  |
| Switching frequency | 300 KHz   |
| L                 | 100 uH     |
| Cin               | 18 uF      |
| Cout              | 22 uF      |
| Q1,Q2             | SCT3080 L  |
| D1,D2             | SCS230AEW  |
| Full load Efficiency | ≥95%      |
| Max. Efficiency   | ≥98%       |
| Weight            | 500 g      |
| Size              | 220 mm*145 mm |
| Power Density     | 2400 W/kg  |

3.1. Test of transition

Figure 13 shows the behavior in dynamic mode, in this case the simulators are programmed with a transition between the buck and boost in few seconds. As it can be seen, the overshoot of the output voltage and inductance current is small and the adjustment time is short during the transition. Figure 14 shows the experimental waveform of transition performance between MPPT and constant voltage mode. The fully charged battery voltage is 210 V and adjust the electronic load and increase the output voltage from 200 V to 210 V, the converter will exit the MPPT mode to CVM; while the output voltage decrease, the converter returns to MPPT mode.

![Figure 13. Transition performance between buck and boost modes. (a) Boost to buck and (b) Buck to boost.](image1)

![Figure 14. Transition performance between MPPT and constant voltage mode.](image2)
3.2. Test of efficiency
The conversion efficiency curve of the converter is shown in figure 15. The test is implemented under different SA curves and different bus voltages and the efficiency is more than 95%.

![Efficiency curve](image)

**Figure 15.** Efficiency under full load.

3.3. Test of temperature
In order to monitor the temperature of key components (Q1, Q2, D1, and D2) in real time, paste thermistors on the key devices and observe them through data acquisition instrument as it is shown in figure 16.

![Temperature test](image)

**Figure 16.** Temperature test.  
**Figure 17.** Key device temperature before and after temperature test.

In figure 17, the temperature of the key device reach equilibrium after 2 hours when the environmental condition is 35 °C temperature and atmospheric pressure of 4.2 kPa. During the experiment, the converter was fully loaded and its performance is normal and stable, the efficiency was 96.2% (buck).

4. Conclusion
In this paper, a novel interleaved TSBB converter is introduced. By using SiC device, digital control strategy and MPPT technology, the proposed converter can adapt higher voltage, higher temperature, higher efficiency, and higher SA power utilization and achieve higher power-density. The experimental results show that the power density of the converter module is as high as 2.4 kW/kg and smooth transitions among boost, buck, DM, MPPT and non-MPPT is guaranteed by the proposed control scheme.

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