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A Fast-Dynamic Response Control Strategy for Power Supply Unit of SAR Satellites

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Abstract. For the power supply of spacecraft, the dynamic response is a key requirement for converters. Especially for power supplies of SAR or other pulse power supplies, the transient of load is fast and the output current is high, it is very difficult to guarantee the output voltage in the required range. The ECSS-E_ST-20C has provided a standard for the power quality of power supply for spacecraft. In this paper, a fast-dynamic response control strategy for buck converters is proposed. The proposed strategy does not increase the output capacitance, and increases the dynamic response of the converter. In the proposed strategy, the linear control and non-linear control are combined. The linear control operates in the steady state, while the non-linear control operates in the transit state. Finally, the proposed strategy is verified by simulations and experiments.

1. Introduction

The all-time, all-weather, high-resolution and wide-range earth observation capability of the Synthetic Aperture Radar (SAR) satellite has been widely applied in many fields like military reconnaissance, disaster prevention and mitigation, marine and land observation, topographic mapping and so on, and it has incomparable advantages over optical remote sensing satellites [1]. SAR is a kind of active phased-array antenna. SAR satellite antenna is a pulse load, which is activated in pulse mode under the pulse repetition rate (PRF) between 1~5000 Hz and the duty cycle of 0~10%. The typical power supply unit of SAR satellite is shown in Fig. 1. When the power of high power pulse load changes, its transient DC bus input current could reach several hundred amperes or even heavier, which is very similar to the characteristics of short-circuit current. The current behavior of such pulse load could cause a series of power quality problems. fast output load transient and the heavy load current will bring a great challenge to ensure that the output voltage is within the allowance range [2].

For the power supply of spacecraft, the voltage transient response in the load step transient is a main power supply index. There are strict requirements in ECSS-E-ST-20C standard on the dynamic response of power supply for spacecraft. The existing SAR load powered converters adopt PI controller, which is a kind of linear control strategy based on small-signal model [3]-[4]. It has good control performance near the steady-state point. The DC steady-state operating point range is wide, however, when the load varies in a large range, and the performance of PI controllers would be limited. In order to meet the requirements of the output voltage range at the step transient of load or the change



of pulse load, it is usually realized by increasing the output capacitance. This could result in larger output capacitance and the slow dynamic response of the system. In addition, the space for the power supply in the spacecraft is very limited, and the cost will be greatly increased by increasing the capacitance. In order to improve the dynamic performance of the converter, some researchers have adopted nonlinear control strategies such as hysteresis control [5]-[9]. However, the nonlinear control is in low steady-state accuracy, variable switch frequency, and poor performance of EMI.

In order to raise the dynamic response of the converter without increasing the output capacitance, a control strategy for power supply unit of SAR satellite Buck converter is proposed, which combines the linear control element and nonlinear element. The proposed control strategy is based on the sampling of the output voltage and comparing it with the pre-set threshold. In the process of load steps, if the output voltage exceeds the threshold, the nonlinear control would take over the DC bus voltage control and force maximum or minimum current reference. Once the bus voltage is restored to the set range, the linear PI controller could take over the bus voltage control again. The control strategy can optimize the dynamic performance without increasing the output capacitance. The converter has a fixed frequency and good EMC performance in steady-state operation. In the case of load steps, the converter works in the state of nonlinear variable-frequency mode, which could reduce the variation range of output voltage.

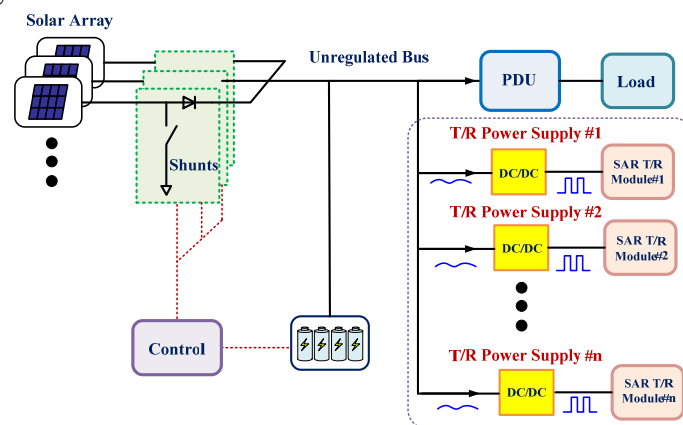


Figure 1. The power supply architecture of SAR satellite

Based on the typical Buck converter in power supply of SAR satellite, the limitations of existing power supply controls are analyzed in this paper. This paper introduces a control strategy to improve the dynamic performance of Buck converter in the power supply of SAR satellite, as well as the detailed design method of parameters. Finally, the proposed strategy is verified by simulations and experiments.

2. Analysis on the Limitations of Traditional Control Methods

Constellation of small Satellites for Mediterranean basin Observation (COSMO-SkyMed) is a typical kind of SAR satellite, whose main function is to detect marine pollution around the Mediterranean. The power supply topology of COSMO-SkyMed is shown in Fig. 2^[10]. Its power supply branches of the transmitter and receiver, adopting Buck converter topology, are in high-power, and the traditional PI control is used in the converter control. Taking the Buck converter of SAR antenna power supply unit as an example, the small-signal model of the existing PI control and its limitations are analyzed. The control diagram of the Buck converter is shown in Fig 3, and its parameters are given in Table 1.

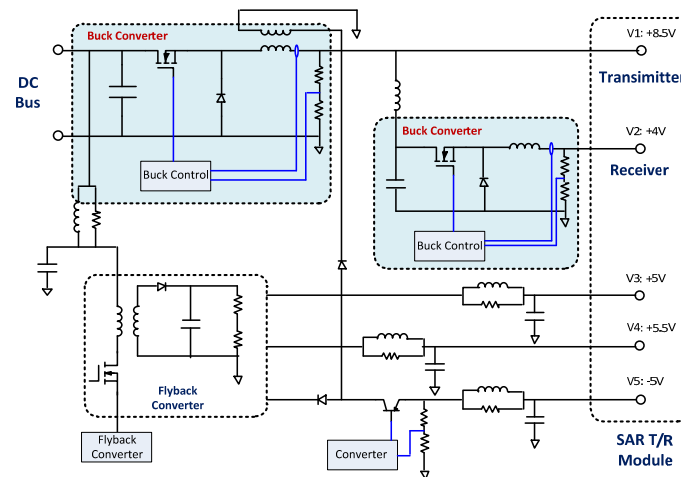


Figure 2. The power supply topology of COSMO-SkyMed

Taking the Buck converter of SAR antenna power supply unit as an example, the small-signal model of the existing PI control and its limitations are analyzed. The control diagram of the Buck converter is shown in Fig 3, and its parameters are given in Table 1.

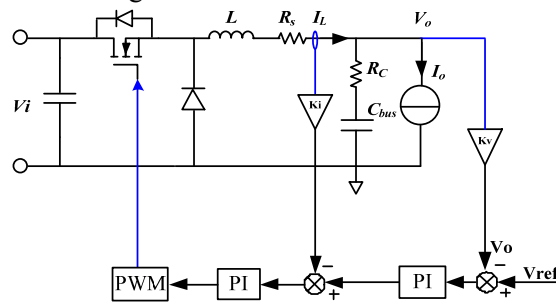


Figure 3. PI control of Buck converter

Table 1. Parameters of Buck converter

Item	Value
Power	300W
Input Voltage	36-50V
Output Voltage	28V
Output Inductance	13uH
Output Capacitance	300uF
Coefficient of	ki = 2.78
Sampling	kv = 0.118

The ECSS-E-ST-20C provides that, for load stepping up to 50 % of the nominal load, voltage transients shall not exceed 1 % of its nominal value; for other load steps, voltage transients shall remain within 5 % of its nominal value. According to the Thevenin equivalent circuit and the output voltage constraint condition of the Buck converter, the impedance equivalent is shown in Fig. 4, and the constraint condition of the output impedance can be obtained:

$$V_o - 50\%I_o Z_o \geq 0.99V_o \quad (1)$$

The maximum allowable impedance of the converter is obtained:

$$Z_o \leq \frac{0.02V_o^2}{P_o} \quad (2)$$

According to the values in Table 1, the maximum output impedance of Buck converter can be calculated as 52m Ω .

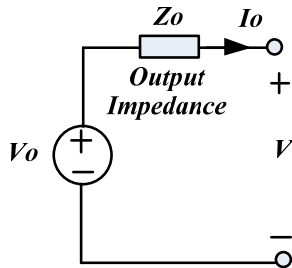


Figure 4. Thevenin equivalent circuit of Buck converter

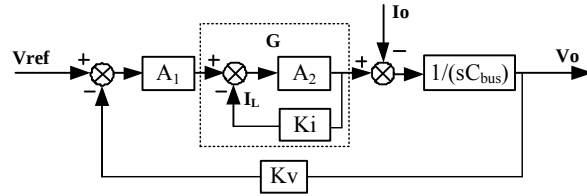


Figure 5. The diagram of output impedance

For the converter using double-loop PI control, the maximum output impedance of the converter is calculated by the following equation:

$$Z_o = -\frac{V_o(s)}{I_o(s)} = \frac{1}{\frac{sC_{bus}}{1 + \frac{k_v A_1 G}{sC_{bus}}}} = \frac{1}{sC_{bus} + k_v A_1 G} \quad (3)$$

The output impedance within the cut-off frequency is;

$$|Z_o| = \frac{1}{k_v A_1 G} \quad (4)$$

Where, k_v represents the sampling factor of the output voltage, and A_1 is the proportional gain of the voltage loop controller. G is transconductance gain. If the current loop bandwidth is high, then G can be expressed as:

$$G = \frac{1}{k_i} \quad (5)$$

Where, k_i is the sampling factor of current sensor.

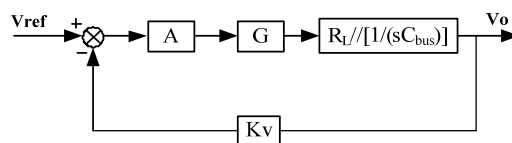


Figure 6. The control diagram

The loop transfer function of the system can be obtained from Fig. 6. If $\omega R_L C_{bus} \gg 1$, the expression of loop gain can be obtained as follows:

$$P(s) = k_v A_1 G \left(R_L // \frac{1}{sC_{bus}} \right) \quad (6)$$

$$|P(s)| = \frac{k_v A_1 G}{2\pi f C_{bus}} \quad (7)$$

If $|P(s)|=1$, the approximate closed-loop cut-off bandwidth could be obtained as follows:

$$f_{BW} = \frac{k_v A_1 G}{2\pi C_{bus}} \quad (8)$$

Where f_{BW} is the control bandwidth of the converter, and the control bandwidth is usually set to about 1/10 of the switching frequency. Assuming a switching frequency of 100~150 kHz, then the bandwidth is between 10 and 15 kHz.

$$C_{bus} = \frac{1}{Z_o 2\pi f_{BW}} \quad (9)$$

The output impedance and the loop transfer function of Buck calculated according to Table 1 are shown in Fig. 7, when low-frequency impedance is 52m Ω and cut-off frequency is 10kHz.

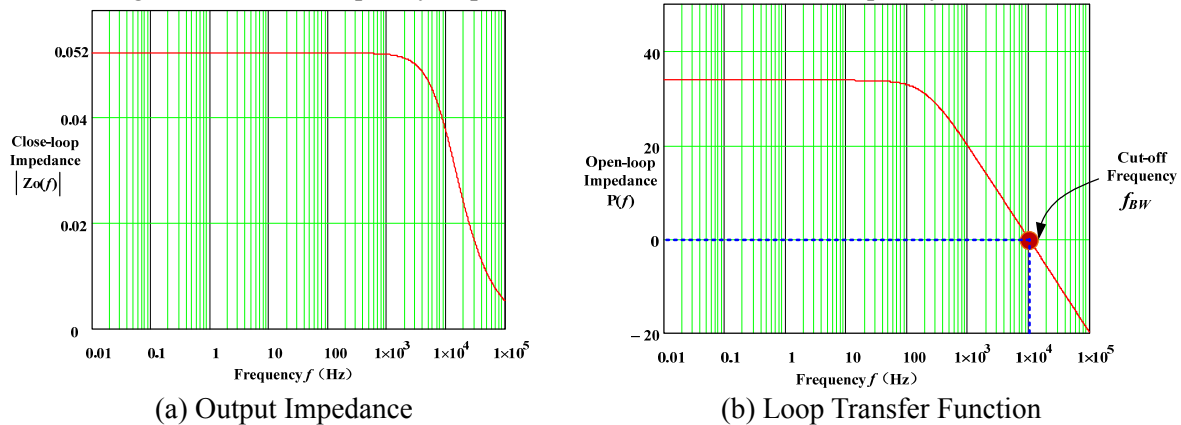


Figure 7. The output impedance of open loop bode plot

The output capacitance corresponding to the required bandwidth is 300uF, which can be obtained from formula (9). When the frequency of load transient exceeds the cutoff frequency, the control system has little influence on the system dynamics, and the transient performance mainly depends on the dynamic characteristics of the output filter. If there is load step transient, the frequency spectrum of the step transient signal will exceed the control bandwidth, and at this time, only by increasing capacitance to meet the threshold of the output voltage transient. However, increasing capacitance may degrade the dynamic performance of the system. For power supply of satellite, the volume is strictly limited, increasing the volume of capacitance would lead to a significant increase in cost. Therefore, it is necessary to improve the voltage transient response of the converter without increasing capacitance.

3. Control Strategy for Improving Dynamic Response

The output capacitance of Buck converter is usually determined by the output voltage ripple and the maximum allowance of output voltage in the dynamic load transient. In order to improve the dynamic performance of the power supply on the premise of minimizing the bus capacitance, an improved control strategy based on linear control and nonlinear control is proposed in this paper.

3.1. The Control Strategy Diagram

The control strategy proposed in this paper consists of a linear PI controller and a nonlinear controller, which is essentially a two-domain control diagram. When load changes, the nonlinear element plays a major role. In the steady state, the steady-state accuracy is improved and the voltage and current ripple are reduced by PI control. So, the control strategy can not only maintain high steady-state accuracy, but also enjoys good dynamic characteristics. Since the two controls need to be coupled, there are two methods. The coupling position of two controls is different, one coupling position in the reference value of the current loop, as shown in Fig. 8. Another coupling position is in the driver signal of the power device, as shown in Fig. 9. In the first coupling mode, the nonlinear element forcibly sets the reference value of the current loop to a minimum (or maximum) by detecting whether the output voltage is higher (or lower) than the predetermined threshold. In the second coupling mode, the nonlinear element sets the driver signal of the power device to low (or high) based on the bus voltage test. When the bus voltage returns to the normal range, the linear PI control is used to adjust the bus voltage. The first coupling method could change the reference value of inductive current with a

relatively smooth switching process but a slower response speed. The second coupling method provides a fast response speed, but a great impact in the switching process.

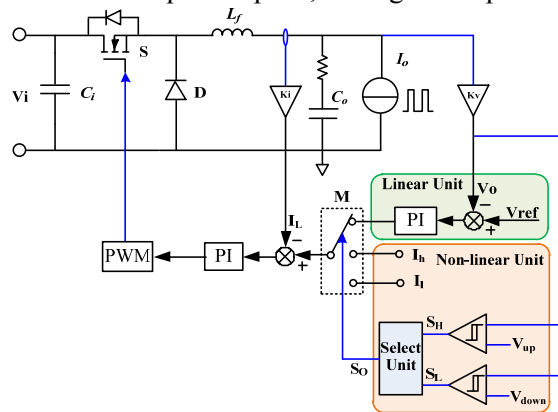


Figure 8. Two domain control diagram of buck converter I

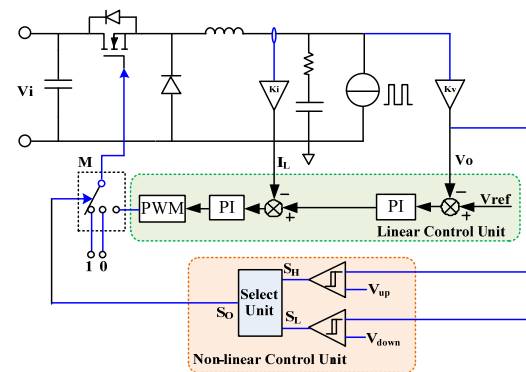


Figure 9. Two domain control diagram of buck converter II

The nonlinear control element is a hysteresis control, which consists of two hysteresis comparators and a selector unit. The output voltage is compared with the voltage threshold V_{up} , V_{down} to obtain the output of the hysteresis comparator. As shown in Fig. 10, the output of hysteresis comparator SH is 1 in the normal state and 0 when the output voltage is higher than the voltage threshold. On the contrary, the output of hysteresis comparator SL is 0 in the normal state and 1 when the output voltage is lower than the voltage threshold. For the coupling method I, when the output of hysteresis comparator SH is 0, the reference value of the inductor current loop is set to the upper limit of the current reference value I_{Lh} ; when the output of hysteresis comparator SL is 1, the reference value of the inductor current loop is set to the lower limit of the current reference value I_{Ll} . The output of hysteresis comparator SH is 1 in the normal state and 0 when the output voltage is higher than the voltage threshold. On the contrary, the output of hysteresis comparator SL is 0 in the normal state and 1 when the output voltage is lower than the voltage threshold. For the coupling method I, when the output of hysteresis comparator SH is 0, the driver signal of the power device is 1; when the output of hysteresis comparator SL is 1, the driver signal of the power device is 0. Adjusting the current reference value or the driver signal of MOSFET according to the output voltage transient improves the dynamic response of the converter.

3.2. Output Capacitance Design

According to the ECSS-E-ST-20C, the main constraints for output capacitance design is that, for load stepping up to 50% of the nominal load, voltage transients of the bus shall not exceed 1% of its nominal value. When load changes, the nonlinear element in the control system plays a major role. The inductive current rises (or decreases) will cause same AC voltage variation of the output filter capacitor.

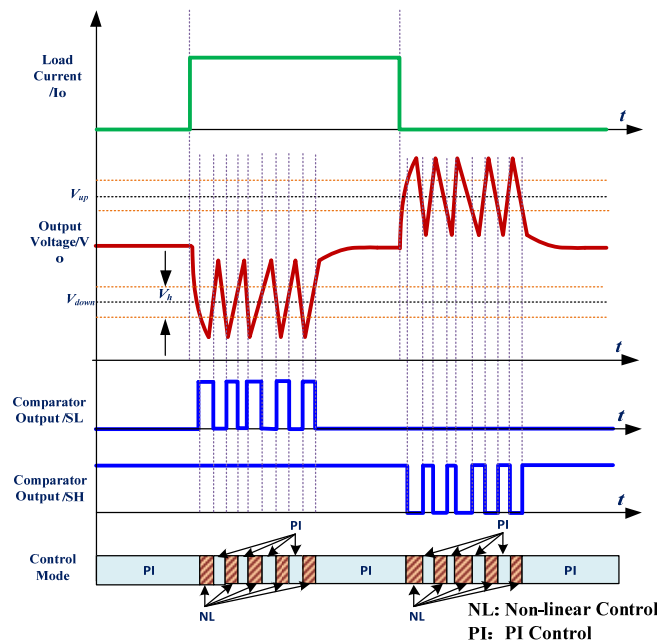


Figure 10. The output of hysteresis comparator

The voltage variation is as follows when there is load step up:

$$\Delta V_o = \frac{\Delta I_o^2 L}{2(V_{in} - V_o)C_o} \quad (10)$$

The voltage variation is as follows when there is load step down:

$$\Delta V_o = \frac{\Delta I_o^2 L}{2V_o C_o} \quad (11)$$

Where, ΔI_o is the load transient, and L_f is the value of the converter inductor. For Buck converter, the worst case in the bus voltage transient is load step up. Based on the formula (10) and according to $\Delta V_o < 0.01V_o$, the value range of output capacitance obtained:

$$C_o \geq \frac{\Delta I_o^2 L}{0.02V_o (V_{in, \min} - V_o)C_o} \quad (12)$$

In addition, the change of ΔI_o depends on the time of the transient: if the sudden load change happens just at the end of the switching period and the power device is off. Inductor current ripple would also affect the transient voltage ripple: the larger the ripple, the greater the sudden variation of the capacitance output voltage, so it is needed to increase the output capacitance.

3.3. Hysteresis Control Ripple

In the proposed control strategy, the output voltage ripple of the converter is affected by many factors, among which capacitance ESR has obvious influence on the capacitor voltage ripple and dynamic transient. In this paper, in order to minimize the variation of output voltage and ripple in the sudden load change, the output capacitance of low ESR is selected. In this case, the output capacitance ripple is approximately equal to half of the band of the hysteresis control, which can be calculated by formula (13). Due to the existence of the control delay, the actual capacitor voltage ripple will be slightly larger than half of the band.

$$\Delta V_{ripple} \approx \frac{V_h}{2} \quad (13)$$

The inductor current ripple can be calculated by input voltage, output voltage, filter inductor and hysteresis control period. The inductor current ripple is obtained from the following equation:

$$\Delta I_{ripple} = \frac{(V_{in} - V_o)V_o T_h}{L_f V_{in}} \quad (14)$$

$$T_h \approx \frac{V_h C_o}{0.5 I_{th} - I_o} \quad (15)$$

$$\Delta I_{ripple} \approx \frac{(V_{in} - V_o)V_o}{L_f V_{in}} \frac{V_h C_o}{0.5 I_{th} - I_o} \quad (16)$$

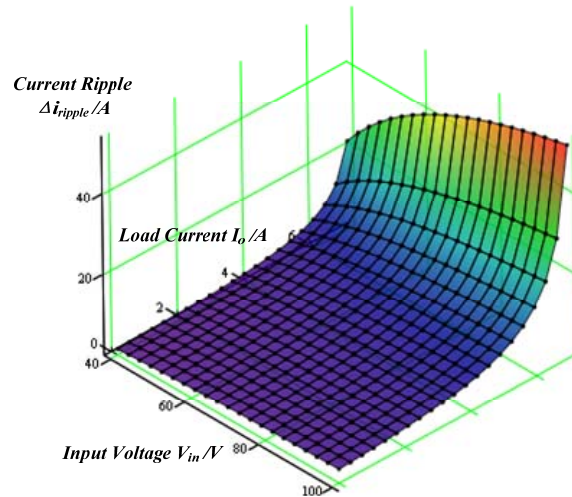


Figure 11. The relationship among current ripple, input voltage and load current

Where, V_{in} is the input voltage; V_o is the output voltage; V_h is the voltage hysteresis band; T_h is the risetime of inductor current in each switching period; L_f is the filter inductor; C_o is the output capacitance; I_{th} is the upper limit of current reference value; I_o is the output current. If $V_{in}=50V$, $V_o=28V$, $V_h=0.2V$, $L_f=13\mu H$, $C_o=85\mu H$, $I_{th}=15A$, $I_o=5A$, then, $T_h=6.8\mu s$, $\Delta I_{ripple}=6.44A$. The relationship among the current ripple, load current and input voltage is shown in Fig. 11. The inductor current ripple increases with the increase of the input voltage and the output current.

4. Simulation Verification

The proposed control strategy is verified by PSIM, and the simulation uses the first coupling method whose coupling position of linear control and nonlinear control is at the reference value of the current loop. The parameters of simulation are given in Table 2.

Fig. 12 shows the waveforms of load step up for existing PI control. Fig. 12 (a) shows the transient response of 50%-100% load switching with an output voltage drop of 2.1%. Fig 12(b) shows the transient response of 0%-50% load switching with an output voltage drop of 1.8%. Fig. 13 shows the waveforms of load step up for proposed control. Fig. 13(a) shows the transient response of 50%-100% load switching with an output voltage drop of 1%. Fig. 13(b) shows the transient response of 0%-50% load switching with an output voltage drop of 1%. By comparing Fig. 12 and Fig. 13, it can be found that the improved control strategy could significantly reduce the output voltage drop in the process of sudden load surge under the same conditions.

Table 2. The parameters of simulation

Item	Value
Power	300W
Input Voltage	36-50V
Output Voltage	28V
Output Inductance	13uH
Output Capacitance	85uF
Coefficient of Sampling	$k_i = 2.78, k_v = 0.118$
Switching Frequency	300kHz

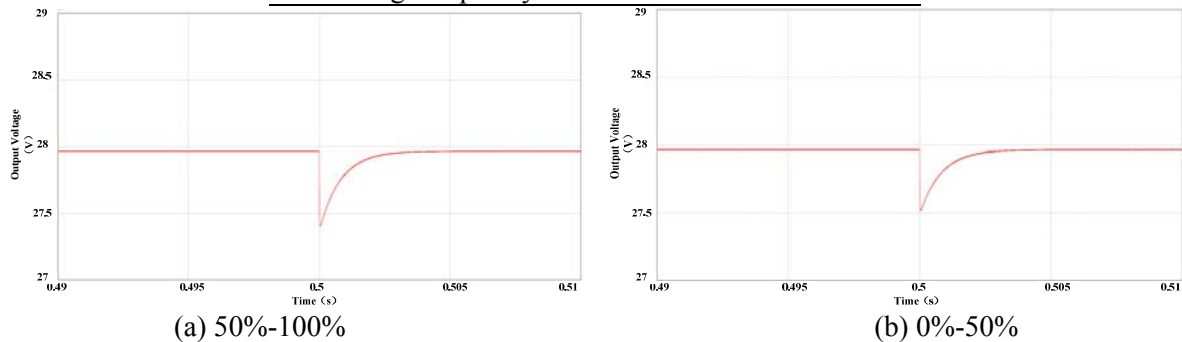
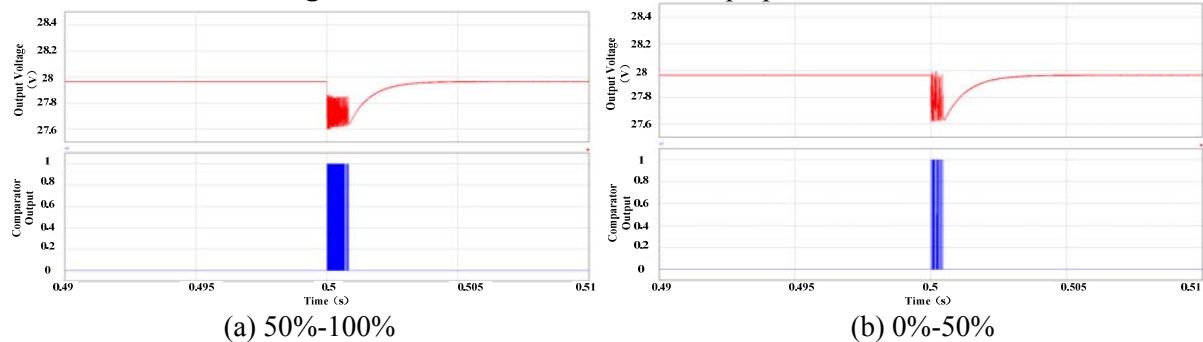
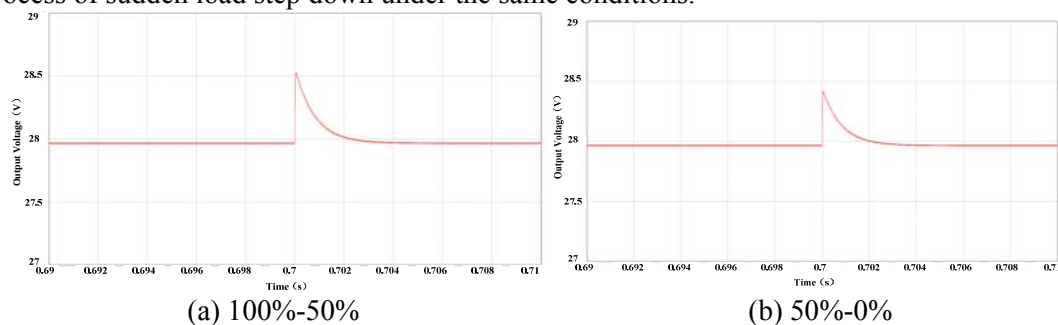
**Figure 12.** The waveforms of load step up for PI control**Figure 13.** The waveforms of load step up for proposed control (red: output voltage, blue: comparator output)

Fig. 14 shows the waveforms of load step down for existing PI control. Fig. 14(a) shows the transient response of 100%-50% load switching with an output voltage surge of 2.1%. Fig. 14(b) shows the transient response of 50%-0% load cut with an output voltage drop of 1.4%. Fig. 15 shows the waveforms of load step down for proposed control. Fig. 15(a) shows the transient response of 100%-50% load switching with an output voltage step up of 1%. Fig. 15(b) shows the transient response of 50%-0% load switching with an output voltage step up of 1%. By comparing Fig. 14 and Fig. 15, it can be found that the improved control strategy could significantly reduce the output voltage drop in the process of sudden load step down under the same conditions.

**Figure 14.** The waveforms of load step down for PI control

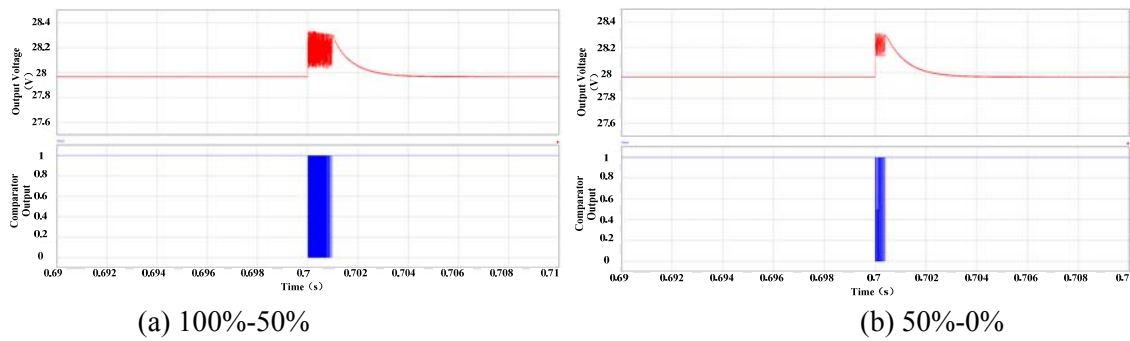


Figure 15. The waveforms of load step down for proposed control (red: output voltage, blue: comparator output)

5. Experiment Verification

An prototype is built to verify the effectiveness of the proposed control strategy. The specifications of prototype are as follows:

Table 3. Specifications of prototype

Item	Value
Rated Power	300W
Input Voltage	50V
Output Voltage	28V
Switching Frequency	300kHz

Fig. 16 shows the experiment waveforms of load step up for PI control. The output voltage on the vertical coordinate is 1V per grid, the output current is 2A per grid, and the horizontal ordinate is 1ms per grid. The waveforms show the transient response of 0%-50% load switching with an output voltage drop of 12.5%. Fig. 17 shows the experiment waveforms of load step up for proposed control. The output voltage on the vertical coordinate is 1V per grid, the output current is 2A per grid, and the horizontal ordinate is 1ms per grid. The waveforms show the transient response of 0%-50% load switching with an output voltage drop of 5.3%. By comparing, it can be found that the improved control strategy could significantly reduce the output voltage drop in the process of sudden load step down under the conditions.

Fig. 18 shows the experiment waveforms of load step down for PI control. The output voltage on the vertical coordinate is 1V per grid, the output current is 2A per grid, and the horizontal ordinate is 1ms per grid. The waveforms show the transient response of 50%-0% load switching with an output voltage step up of 8.9%. Fig. 19 shows the experiment waveforms of load step down for proposed control. The output voltage on the vertical coordinate is 1V per grid, the output current is 2A per grid, and the horizontal ordinate is 1ms per grid. The waveforms show the transient response of 50%-0% load switching with an output voltage step up of 3.5%. By comparing, it can be found that the improved control strategy could significantly reduce the output voltage drop in the process of sudden load step down under the same conditions.

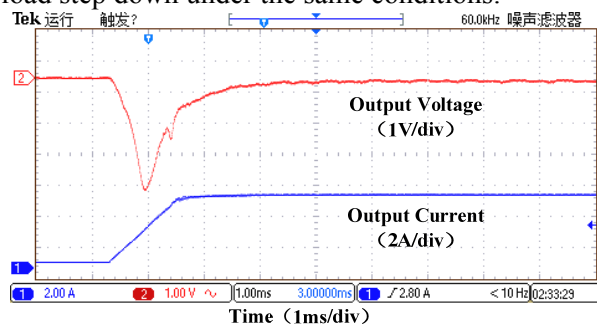


Figure 16. The experiment waveforms of load step up for PI control

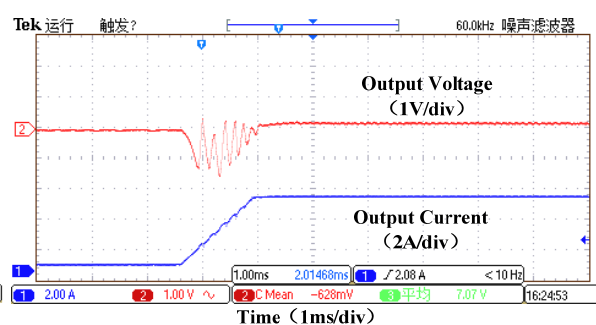


Figure 17. The experiment waveforms of load step up for proposed control

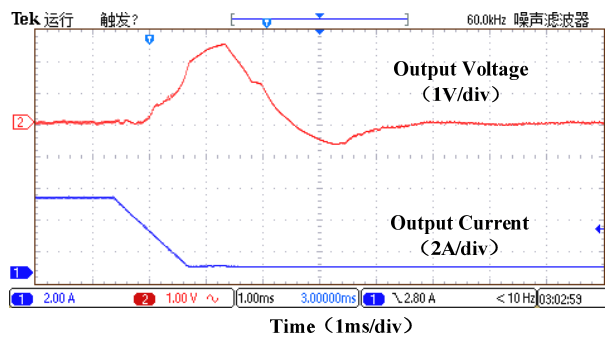


Figure 18. The experiment waveforms of load step down for PI control

The pulse load experimental test is carried out on the test prototype with the proposed control strategy. Fig. 20 shows the experiment waveforms of pulse load (300Hz, duty cycle 15%). The peak current of pulse load is 20A. The output current on the vertical coordinate is 10A per grid, the output voltage is 10V per grid, and the horizontal ordinate is 4ms per grid.

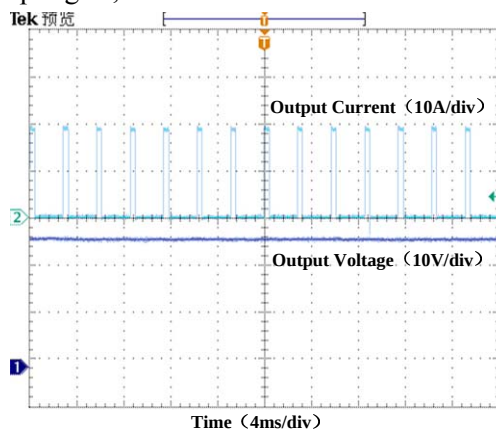


Figure 20. The experiment waveforms of pulse load (300Hz, duty cycle 15%)

Fig. 21 shows the experiment waveforms of pulse load (150Hz, duty cycle 15%). The peak current of pulse load is 20A. The output current on the vertical coordinate is 10A per grid, the output voltage is 10V per grid, and the horizontal ordinate is 4ms per grid. The experimental results show that, under this control strategy, the output dynamic response is fast and the waveforms of output voltage and current are normal when it applied to pulse power load.

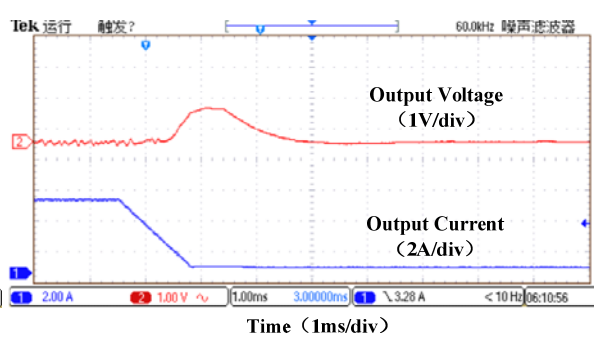


Figure 19. The experiment waveforms of load step down for proposed control

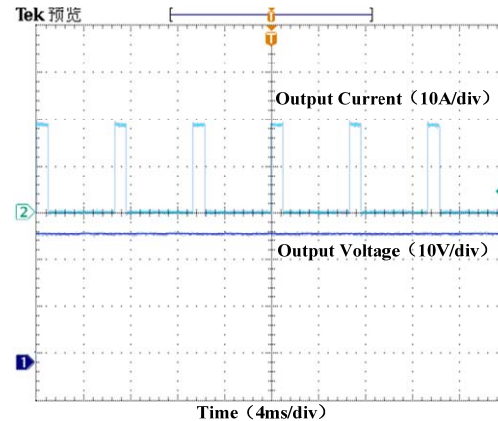


Figure 21. The experiment waveforms of pulse load (150Hz, duty cycle 15%)

6. Conclusion

This paper presents a control strategy for power supply unit of SAR satellites Buck converter. The control strategy integrates the advantages of linear control and nonlinear control to improve the dynamic response of the power supply. The proposed control strategy is based on the detecting of the output voltage and comparing it with the preset threshold. In the process of load changes, if the output voltage exceeds the threshold, the nonlinear control would take over the DC bus voltage control and force maximum or minimum current output. Once the bus voltage is restored to the set range, the linear PI controller could take over the bus voltage control again. The advantage of the proposed strategy is that the dynamic response time and DC bus voltage drop are reduced without increasing DC bus capacitors. The simulation and experiment results show that the proposed control strategy could optimize the dynamic performance of the power supply and improve the dynamic response of the power supply for SAR without increasing the output capacitance.

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