Design and control algorithm of dual switch forward DC/DC converter with DSP digital control

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Abstract. On the basis of DSP digital signal processing chip TMS320F2812 function as the main control chip of power supply, this paper proposes a dual switch forward topology with RCC converter as auxiliary power supply, the bootstrap drive chip IR2110 as power drive circuit, a dual closed loop control strategy with voltage outer loop and current inner loop, and PID control algorithm using integral separation together with dead zone control. The experimental result show that the power supply structure is easy to operate, and the corresponding control strategy and algorithm effectively improve the stability of the power supply output voltage and the rapidness of the response of the system.

1. Introduction
In space applications, DC/DC converters provide secondary power for spacecraft, due to the special nature of its working environment, the DC/DC converter is required to meet the functional and performance requirements, and the power supply should have high reliability[1]. When the primary DC bus of the space is at a high voltage level, the switching power supply topology switching tubes such as flyback and single-tube forward need to withstand a DC input voltage of 1.5 times or more. The double-tube forward and half-bridge topology switch tube only withstands 1 times the DC input voltage, but the half-bridge structure is complicated and there is a risk of short-circuiting of the bridge arm, while the double-tube forward circuit has a simple structure and the excitation energy is fed back to the input side[2]. High reliability, suitable for high reliability requirements of aerospace products. In this paper, the double-switch forward circuit is used as the main topology of the power supply. The RCC converter is designed as the auxiliary power supply for the 12V power supply of the system, and the system structure is optimized[3]. The control part adopts the TMS320F2812 control dedicated DSP chip produced by TI to realize the system control of the power supply. The double closed-loop control mode of voltage outer loop and current inner loop is adopted to realize the functions of power supply voltage regulation, over voltage and over current protection[4].

2. Hardware circuit design
The control chip of the system uses DSP chip, and TI's TMS320F2812 is selected. One of its outstanding features is the provision of PWM and ADC modules. The control circuit of the system is shown in Figure 1. The control method is closed-loop control of the output voltage and current. The sampled voltage signal and current signal are processed and sent directly to the DSP. The DSP's built-in A/D conversion module performs analog-to-digital conversion on the signal, and the converted digital quantity is sent to the PI regulator separately[5]. After comparing the sampled value with the set value, the PWM generator
built into the DSP generates the PWM of the corresponding pulse width signal. Then, the isolation driving circuit generates a driving signal to control the turning on and off of the Q1 and Q2 switching tubes, so that the output voltage of the system reaches the requirement. In addition, in order to effectively suppress the DC bias of the transformer and protect the primary overcurrent, a primary current detecting circuit of the transformer is designed to limit the detected current to a current cycle by cycle.

![Functional block diagram of the converter system](image)

**Figure 1.** Functional block diagram of the converter system

### 2.1. Power drive circuit

IR2110 can form the driving circuit of power MOSFET based on the principle of bootstrap driving. The driving signal delay is nanosecond, the switching frequency can be from tens of Hertz to hundreds of kilohertz, and IR2110 also has perfect protection function. Therefore, IR2110 is selected as the driving circuit component of the power MOSFET\[6\].

Load the PWM control signal with duty cycle $D$ after the update. When high level, $HIN$ and $LIN$ are both high level, MOS tubes $T1$ and $T2$ are turned on, $Q1$ is turned on, and $Q2$ is turned off. When low level, $HIN$ and $LIN$ are both low level, MOS tubes $T1$, $T2$, and $Q1$ are turned off, and $Q2$ is turned on to provide a charging bootstrap circuit for $C103$.

Due to the limited driving capability of the DSP output PWM control signal, the PWM control signal needs to be amplified by IR2110, and two timing synchronous PWM drive signals are generated to meet the gate drive requirements of the two power MOS transistors of the two-switch forward circuit.
2.2. Sampling circuit

The output samples of the power supply are divided into current sampling and voltage sampling. The voltage sampling signal is used in the feedback loop of the power supply, and the DSP adjusts the PWM pulse width according to the feedback signal to stabilize the output voltage. The current sampling signal is taken from the string sampling resistor in the output loop and can be used for current limiting protection and short circuit protection at the output. The voltage sampling is used for overvoltage protection at the output, and the sampling signal is taken from the voltage dividing resistor connected in parallel to the output circuit. Two sampling signals pass through the conditioning circuit and are isolated from each other by diodes. When the voltage sampling signal of the conditioning circuit is greater than the current sampling signal, D16 is turned off, and the feedback value is a voltage sampling signal. When the current sampling signal passing through the conditioning circuit is greater than the voltage sampling signal, D17 is turned off, and the feedback value is a current sampling signal. The compared feedback value is sent to the AD sampling port of the DSP.
2.3. *RCC auxiliary power supply circuit*

In order to provide 12V power supply (gate drive voltage of the power MOS transistor) to the output terminal of the driver chip IR2110, an RCC circuit is used as an auxiliary power supply circuit. The RCC converter is a self-excited single-ended flyback converter. Its working principle is to make the triode work in a critical state. When the input voltage of 100V passes through the starting resistors R20 and R21 to provide a starting base current to the switching transistor, the triode starts to conduct, the collector current flows through the primary winding N1, and the electromotive force U1 is generated. The positive feedback winding N2 generates an induced electromotive force U2, which is applied to the base of the triode through R22. The base current increases, so that the collector current of the triode is further increased, and the triode is quickly saturated. The collector current rises linearly with time, but due to the existence of C45, the base current decreases with time. At a certain time t, there is Ic(t) = βIb(t). At this time, the triode enters the amplification area again, and Ic is controlled by Ib. As dIc/dt decreases, the potential on the feedback winding decreases, and Ib, Ic further decrease, causing the transistor to turn off. During the flyback period, the feedback winding voltage is negative, and the reverse bias current is supplied to the base of the switch tube through R22 and C45. When the flyback is over, the base reverse bias current is zero, and the switch tube starts to conduct again. Repeatedly, self-oscillation. The self-oscillation method is adopted to realize the peak current control, which not only solves the power supply of the driving chip but also optimizes the system structure of the power supply.
Figure 4. Auxiliary power supply circuit

2.4. Protect the circuit
The protection circuit mainly has output overvoltage protection and output overcurrent protection. The output voltage signal is detected, and is directly sent to the AD port of the DSP after current/voltage conversion and filtering processing. When the input voltage is greater than the set value, the corresponding low level signal is respectively sent to the power protection pin (PAPINTA) of the DSP. The DSP performs corresponding actions to achieve overvoltage and overcurrent protection on the output side of the power supply. The primary current signal of the transformer is processed by the current transformer and sent to the DSP for processing. When the collected current value is greater than the comparator set value, a low-level signal is sent to the power protection pin of the DSP, thereby implementing overcurrent protection of the switch tube.
3. Converter control algorithm
The converter control method adopts double loop control. That is, the feedback voltage loop formed by the output voltage and current sampling conditioning comparison and the current loop formed by the primary current transformer sampling. The DSP first compares the sampling comparison feedback voltage \( V_{\text{o}} \) of the output terminal with the reference voltage \( V_{\text{ref}} \) to generate an error signal \( V_{\text{err}} \), and sends the error signal to the voltage PID regulator, and the output thereof is used as a given signal of the current loop, and the DSP gives the current given signal to the original. The current-to-current transformer sampling signal is compared to obtain a current error signal \( I_{\text{err}} \), and then passed through a current PID regulator to finally generate a PWM output signal of a specific duty cycle.

Figure 5. Overvoltage, overcurrent protection circuit
Figure 6. Dual-loop PID control strategy

PID regulator is widely used due to its simple control algorithm and high stability. In this paper, the voltage and current loop of the converter are all PI regulators. The control law of the PID regulator is:

- **PID adjustment control formula:**

\[ P = k_c \left( e + \frac{1}{T_i} \int \text{edt} + T_d \frac{de}{dt} \right) \]  

(1)

- **Discretization processing:**

\[ \int \text{edt} \rightarrow T_s \sum_{i=0}^{n} e(i) \]

Integral term:

\[ \frac{de}{dt} \rightarrow \frac{e_n - e_{n-1}}{T_s} \]

Differential item:

(2)

- **Nth sampling:**

\[ P(n) = k_c \left[ e + \frac{T_s}{T_i} \sum_{i=0}^{n} e(i) + \frac{T_d}{T_s} (e_n - e_{n-1}) \right] \]

(3)

- **N-1th sampling:**

\[ P(n-1) = k_c \left[ e + \frac{T_s}{T_i} \sum_{i=0}^{n-1} e(i) + \frac{T_d}{T_s} (e_{n-1} - e_{n-2}) \right] \]

(4)

- **Increment of two samples:**

\[ \Delta P(n) = P(n) - P(n-1) \]

\[ = k_c \left[ (e_n - e_{n-1}) + \frac{T_d}{T_s} (e_n - 2e_{n-1} + e_{n-2}) \right] \]

\[ = k_c (e_n - e_{n-1}) + k_i e_n + k_d (e_n - 2e_{n-1} + e_{n-2}) \]

(5)

\[ k_i = k_c \frac{T_s}{T_i} \quad k_d = k_c \frac{T_d}{T_s} \]

- **Set the integral separation logic coefficient, then:**

\[ \Delta P(n) = k_c (e_n - e_{n-1}) + k_i e_n + k_d (e_n - 2e_{n-1} + e_{n-2}) \]

(6)

\[ k_i = \begin{cases} 
1 & |e_n| \leq u \\
0 & |e_n| \geq u 
\end{cases} \]
The integral adjustment is beneficial to eliminate the static difference. However, when the process starts, ends, and greatly increases or decreases the set value, the integral is saturated in a short time, causing the control amount to exceed the execution limit, resulting in a large overshoot and an oscillating phenomenon. The integral separation method is used to judge whether to add the integral adjustment according to the difference value. When the difference is large, the PD adjustment is adopted. When the difference is small, the PID adjustment is adopted, so that the system can obtain better dynamic characteristics and reduce the overshoot amount.

- Set the dead zone parameters $\varepsilon$, then:

$$\Delta P(n) = \begin{cases} 
\Delta P(n) & |e_n| \geq \varepsilon \\
0 & |e_n| < \varepsilon 
\end{cases}$$

(7)

The variable $P(n)$ is the value supplied to the PID controller. If $\varepsilon$ is too small, the conversion of the two modes will be frequent, resulting in an increase in oscillation of the output voltage at steady state. On the other hand, if $\varepsilon$ is too large, the system response will be greatly delayed.

- The incremental PID control algorithm is rewritten as:

$$\Delta P(n) = k_c \left( 1 + k_i \frac{T_c}{T_i} + k_d \frac{T_d}{T_s} \right)e_n - k_c \left( 1 + \frac{2T_d}{T_s} \right)e_{n-1} + k_c \frac{T_d}{T_s} e_{n-2}$$

(8)

among them: $a = k_c \left( 1 + k_i \frac{T_c}{T_i} + k_d \frac{T_d}{T_s} \right)$, $b = -k_c \left( 1 + \frac{2T_d}{T_s} \right)$, $c = k_c \frac{T_d}{T_s}$

When there is no integral term: $a_0 = k_c + \frac{k_i T_c}{T_s}$

When there is an integral term: $a_1 = k_c + \frac{k_i T_c}{T_i} + \frac{k_d T_d}{T_s}$

Then, $\Delta P(n) = ae_n + be_{n-1} + ce_{n-2}$

- Total program flow chart
4. Experimental result

The main technical indicators of the 50W digitally controlled DC/DC converter designed in this paper are: input voltage 100V, steady state value 90~110V, maximum pulsation amplitude 10V; output voltage 24V, steady state value 23~25V, maximum pulsation amplitude 1V; The rated power is 50W; the conversion efficiency is not less than 90%; the protection function is output overvoltage, overcurrent protection and overcurrent protection of the switch. The experimental parameters are selected as follows: input voltage is 100V, switching frequency is 150kHz, transformer ratio n=0.25, output filter inductance L=700uH, filter capacitor C=1000pF. From figure 8 to figure 11, it can be seen that when adopting the double closed-loop integral separation PID control strategy, the PWM start-up waveform regulation process is correspondingly fast, the surge start-up waveform is better than the traditional integral
separation PDF control strategy, and the output voltage stability is better than 0.2%, which can obtain a good control strategy and has a certain practical value.

Figure 8. PWM start waveform

Figure 9. PWM stable drive waveform
Figure 10. Surge waveform of traditional Integral Separated PID control

Figure 11. Surge waveform of double closed-loop integral separation PID control

Acknowledgements
The project was supported by the Vacuum technology and physics Key Laboratory Fund Project (Grants 6142207020901)
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