Research on switching loss reduction technology for missile-borne DC-DC power supply

Jun Li*, Wei Qi, Shulin Wang
42 detachment, unit 92941 of the People's Liberation Army

*Corresponding author e-mail: mitsui86425@163.com

Abstract. With the development of power electronics technology, DC-DC power supply is widely used in secondary power supply system on missile. How to restrain the loss caused by the periodical on-off of the switch tube plays an important role in ensuring the normal operation of the missile-borne power supply system. In this paper, the switching-tube Absorption Circuit and ZCT PWM soft-switching circuit are taken as the research objects, and the effects of the two circuits on the switching-tube loss suppression in the dual-pulse-width modulation mode are analysed, and a more effective method to reduce the switching loss of high frequency DC-DC power supply is obtained, it provides a reference for the further research of switching loss reduction technology in high frequency DC-DC power supply.

Keywords: High Frequency DC-DC power supply, Switching transistor loss, Absorption Circuit, ZCT PWM, Dual pulse width modulation, Work efficiency.

1. Introduction
With the rapid development of DC-DC power supply technology, in the input resistance requiring higher peak and the power supply ripple noise has been widely used, as an important part of missile two power supply system, how to suppress the ammunition in DC-DC power switch tube open shut off the high frequency of loss, not only can improve the work efficiency of the power supply, can also reduce the electromagnetic interference of power play on other devices. In this paper, the BUCK circuit, which is common in DC-DC power supply, is taken as an example to analyze and study the traditional switching tube loss and the improved switching tube loss suppression technology of this circuit under the mode of double-pulse width modulation, so as to explore a method that can not only suppress the switching tube loss, but also greatly improve the working efficiency of power supply.

2. Traditional switching tube loss control method
Adding the main switch absorption circuit is a common method of loss suppression. In the actual simulation and experimental research, it is found that the current flowing through MOSFET is very large, exceeding the rated current of MOSFET, so current limiting measures must be adopted in the actual use. The simplest way is to add a series inductor at the back end of MOSFET for current limiting. The circuit after adding current limiting inductor is shown in Figure 1.
The energy absorbed by the capacitor in the circuit shown in Figure 1 is:

$$W_C = \frac{1}{2} C_L U_K^2$$  \tag{1}$$

Where $U_K$ is the capacitance voltage amplitude. Since the energy of charge and discharge of the capacitance in the absorption circuit in each cycle is all absorbed by the absorption resistor $R$, and the receiving capacitor is charged and discharged once in each cycle, the energy dissipation power of the absorption resistor $R$ can be obtained as follows:

$$P_R = \frac{2}{T_s} \times \frac{1}{2} C_L U_K^2$$  \tag{2}$$

Through Equation (2), we can draw a conclusion that when RC absorption circuit is adopted, under the condition that the circuit switching frequency is constant and the maximum value of capacitor charging remains basically unchanged, the loss power of absorption resistance in the circuit increases with the increase of the capacitance value of absorption capacitance and decreases with the decrease of the capacitance value.

3. Improved switching tube loss control method

To solve the problem of the absorption circuit in the upper section, the soft switching circuit can be used to suppress the impulse current generated during the switching on and off of the switching tube under high frequency working conditions. In order to realize the zero current conduction and zero current turn-off of the main power switch in the circuit in the double-pulse width modulation mode, there are many circuits worthy of discussion and selection. In this paper, the ZCT PWM circuit as shown in Figure 2 is selected as the research object.
Figure 2. Buck ZCT PWM circuit

Under the action of a pulse, the circuit has 10 switching states [6]. Under the control of double-pulse width modulation, the circuit has 20 working intervals. The specific working waveform is shown in Figure 4. According to the analysis of relevant literature, when the above Buck ZCT PWM circuit is adopted, the derivation of working process can be referred to the literature [6]. It will not be repeated here, but this paper mainly deduces the circuit constraint conditions under the double-pulse width modulation mode as follows.

Figure 3. The main waveform of Buck ZCT PWM circuit in double-pulse width modulation mode

The conduction time of the auxiliary switch tube $Q_a$ ahead of the main switch tube $Q$ is:

$$t_{d1} = t_{d3} = \frac{3}{4} T_a$$  \hspace{1cm} (3)
The closing time of the auxiliary switch tube ahead of the main switch tube is:

$$t_{d2} = t_{d4} = \frac{3}{4} T_a$$  \quad (4)

The opening time of the auxiliary switch tube is:

$$t_{on} = \frac{3}{4} T_a + \frac{1}{\sigma_a} \arctg \frac{I_a Z_a}{V_{in}}$$  \quad (5)

$$Z_a = \sqrt{L_a / C_a}$$  \quad (6)

To realize zero current switching of the main power switching tube, as long as the maximum resonant current is greater than the current value of the filter inductor, namely:

$$i_{t_{\text{max}}} > I_o$$  \quad (7)

In the sixth working state of the circuit $V_{C_a}(t_o) = 2V_o + V_{C_a}(t_3)$, we can get:

$$i_{t_{\text{max}}} = \frac{V_{in} - V_{C_a}(t_3)}{Z_a} = \frac{V_{in} - V_{C_a}(t_{13})}{Z_a} = \frac{2V_{in} - \sqrt{V_{in}^2 + (I_o Z_a)^2}}{Z_a} = K I_o$$  \quad (8)

Under the premise that the main power switching tube of the circuit can be turned off with zero current, the circulation energy should be reduced as far as possible. Therefore, we generally choose the parameters in equation (8) that $K \in [1.5, 2]$. Make $J = \frac{V_{in}}{I_o Z_a}$, it can be obtained from the above equation: $K = 2J - \sqrt{J^2 + 1}$, so $J \in [1.764, 2.215]

In order to ensure the realization of zero current on and off of the main power switch tube, the parameters of the circuit must meet equation (7). At the same time, in order not to affect the working state of the circuit in the double-pulse width modulation mode, the working time of the auxiliary circuit should be shortened as far as possible, which is generally required $T_a \leq T_s / 10$.

Again by $J = \frac{V_a}{I_o Z_a}$, $Z_a = \sqrt{L_a / C_a}$, we can get

$$\begin{align*}
L_a &= \frac{5V_{in}}{\pi J T_a I_o} \\
C_a &= \frac{5J I_o}{\pi J T_a V_{in}}
\end{align*}$$

Since the opening and closing time of both pulses within a switching cycle must be greater than that of the auxiliary switching tube $T_a$ if the circuit is to realize soft switch in the double-pulse width modulation mode, the following formula can be obtained, which is also the constraint condition for realizing soft switch in the double-pulse width modulation mode.
4. Experimental analysis

In order to compare and analyze the inhibition effect of the two methods on the switching loss of the main power switch under the double-pulse width modulation mode, this section combined with the typical input voltage characteristics of the secondary power supply, the circuit efficiency and the current and voltage waveform of the switching tube using the two methods were experimentally analyzed.

4.1. Experimental analysis of traditional switching tube loss suppression methods

The input voltage is set to fluctuate within the range of 18V~32V, and the switching frequency is 50 kHz. The current and voltage waveform of the power switching tube when the absorption circuit is adopted is shown in Figure 4. As can be seen from Figure 4, after the parameter optimization of the absorption circuit, the opening impulse current of the switch tube is obviously inhibited. Table 1 shows the working efficiency of the switching tube absorption circuit when the circuit operates in the double-pulse width modulation mode with different input voltages.

4. Experimental analysis

In order to compare and analyze the inhibition effect of the two methods on the switching loss of the main power switch under the double-pulse width modulation mode, this section combined with the typical input voltage characteristics of the secondary power supply, the circuit efficiency and the current and voltage waveform of the switching tube using the two methods were experimentally analyzed.

4.1. Experimental analysis of traditional switching tube loss suppression methods

The input voltage is set to fluctuate within the range of 18V~32V, and the switching frequency is 50 kHz. The current and voltage waveform of the power switching tube when the absorption circuit is adopted is shown in Figure 4. As can be seen from Figure 4, after the parameter optimization of the absorption circuit, the opening impulse current of the switch tube is obviously inhibited. Table 1 shows the working efficiency of the switching tube absorption circuit when the circuit operates in the double-pulse width modulation mode with different input voltages.

\[
\begin{align*}
    t_{on1} &> \frac{3}{4} T_a + \frac{1}{\sigma_a} \arctg \frac{I_a Z_a}{V_{in}} \\
    t_{off1} &> \frac{3}{4} T_a + \frac{1}{\sigma_a} \arctg \frac{I_a Z_a}{V_{in}} \\
    t_{on2} &> \frac{3}{4} T_a + \frac{1}{\sigma_a} \arctg \frac{I_a Z_a}{V_{in}} \\
    t_{off2} &> \frac{3}{4} T_a + \frac{1}{\sigma_a} \arctg \frac{I_a Z_a}{V_{in}}
\end{align*}
\]

(9)

Figure 4. The current and voltage waveform of the absorption circuit switching tube

The experimental data of the circuit in the set voltage input range, including input current, voltage, output current, voltage and working efficiency, are counted as shown in Table 1. From the experimental statistical results, we can see that although the absorption circuit has the advantages of simple structure and easy to implement in engineering, the working efficiency of the circuit has not been improved, which also restricts the application scope of the absorption circuit.
Table 1. The efficiency of DP-PWM circuit with different input voltage

| Parameter        | Case 1     | Case 2     | Case 3     | Case 4     | Case 5     | Case 6     | Case 7     | Case 8     |
|------------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Input voltage (V) | 18.52      | 20.1       | 22.67      | 25.06      | 26.21      | 27.54      | 30.84      | 32.09      |
| Input current (A) | 1.91       | 1.69       | 1.58       | 1.33       | 1.32       | 1.25       | 1.17       | 1.09       |
| Output voltage(V) | 12.04      | 12.01      | 12.15      | 11.89      | 11.98      | 12.09      | 12.13      | 11.91      |
| Output current(A) | 2.5        | 25.1       | 2.49       | 2.46       | 2.51       | 2.45       | 2.48       | 2.52       |
| Efficiency (%)   | 85.5       | 88.8       | 84.7       | 88.1       | 86.3       | 85.9       | 83.8       | 86.0       |

4.2. Experimental analysis of improved switching tube loss suppression method

The experimental conditions in Section 3.1 are selected. The current and voltage waveform of the power switching tube of the ZCT-PWM circuit in the double-pulse width modulation mode is shown in Figure 5. The statistical results of the input current, voltage, output current, voltage and working efficiency under different input working conditions are shown in Table 2.

Table 2. The efficiency of DP circuit with different input voltages

| Parameter        | Case 1     | Case 2     | Case 3     | Case 4     | Case 5     | Case 6     | Case 7     | Case 8     |
|------------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Input voltage (V) | 18.02      | 20.05      | 22.37      | 25.26      | 26.11      | 27.43      | 30.09      | 31.98      |
| Input current (A) | 17.6       | 15.9       | 14.3       | 12.2       | 12.1       | 11.2       | 10.4       | 9.8        |
| Output voltage(V) | 12.04      | 12.01      | 12.15      | 11.89      | 11.98      | 12.09      | 12.13      | 11.91      |
| Output current(A) | 2.5        | 2.51       | 2.49       | 2.46       | 2.51       | 2.45       | 2.48       | 2.52       |
| Efficiency (%)   | 94.7       | 94.3       | 94.7       | 95.1       | 95.3       | 96.1       | 96.5       | 95.9       |

From simulation and experiment results that the ZCT PWM soft switching circuit can realize double PWM zero current switching tube under open and shut off, through the contrast table 1 and table 2, we can see compared with the traditional switch tube loss suppression method, the modified method under the wastage of the switch tube, circuit has dramatically improved the work efficiency.

5. Summary

This article from the perspective of reduce the loss of the opening of the switch tube shut off is analyzed and studied the traditional suppression method and the modified suppression method of inhibition effect, through mathematical analysis it is concluded that through the optimization of absorbing circuit and can
effectively reduce the traditional suppression method the opening of the switch tube impact current in
the circuit, the circuit parameters of resonant circuit parameters optimization can achieve improved ZCT
PWM soft switching circuit of the main opening of the switch tube zero current and zero voltage turn
off, and the two methods through the experiment on the switch tube power inhibition effect is verified,
the results show that the modified method of the wastage of the switch tube is smaller, The working
efficiency of the circuit has been improved obviously.

References
[1] Wei Huaru, Zhang Junhong, GAO Wei, Feng Jin, Li Jun. Research on current Harmonic
Suppression based on Bipulse width Modulation of voltage-controlled DC-DC converter [J].
Ship Electric Technology, 2008, 38 (11): 37 - 42.
[2] Ma Yu. High-frequency Study of low-power DC-DC converters [D]. Zhejiang University, 2018.
[3] Xu Sheng. Buck Circuit Research based on SiC power device [D]. Xidian University, 2017.
[4] Zhang Chunli. Analysis of operating Mode of soft switch Bidirectional DC converter [J]. Science
and Technology Innovation and Productivity, 2016 (12): 65 - 68.
[5] Lv Qing, Wang Lu, WANG Haojiang, GAO Wei. Loss analysis of ZVZCT-PWM SEPIC
converter [J]. Ship electricity technology, 2013, 33 (12): 17 - 19.
[6] GAO Wei, Zhang Junhong, Zhao Jinghong. Experimental Analysis of a large - power modified
Buck converter with wide - width voltage [J]. Journal of electrical technology, 2011, 26 (S1):
23 - 28.