Research on anode power supply of low-power Hall thruster

JIA Hangyu1, QU Chengzhi1, JI Yuhui1, ZHOU Guangrui1, WU Suliang1

1Aerospace Science and Technology, Shanghai Space Power Research Institute, Shanghai, Province, 200245, China

*Corresponding author’s e-mail: wangduo@nsfz.net

Abstract: Based on the small power, small size, and high-efficiency micro-thrust requirements of micro-satellites, this paper mainly studies the anode power supply topology suitable for micro-satellites. The flyback converter and the secondary voltage doubler structure are used to achieve high gain. At the same time, in order to improve the efficiency, the resonant soft switching technology is used to achieve valley opening through the resonance of the transformer leakage inductance and the capacitor to realize the soft switching of the switch tube and the diode. This article developed a 250W experimental prototype, and conducted a series of no-load and full-load tests under closed-loop steady-state operation, which can realize the zero-voltage turn-on of the switch tube and the zero-current turn-off of the diode. The efficiency is up to 93.7% under full load conditions, while the output ripple is small and there is no oscillation, and the device stress is small, which proves to be suitable for use in the anode power supply of micro satellites.

1. Introduction
In recent years, with the vigorous development of global commercial aerospace, the market for microsatellites has continued to expand. Compared with other spacecraft, they are small in size and light in weight. At the same time, they have low commercial development costs and short cycles. They have been widely used in communications, remote sensing, navigation, and deep space exploration. Due to its high specific impulse, high efficiency, no pollution, high control accuracy, and high safety, the Hall electric micro thruster has gradually become the most technologically competitive choice of micro satellite propulsion system. The thrust of the Hall thruster is proportional to its input power, and it is the anode power supply of the power processing unit (PPU) that determines its input power, and its power can account for more than 90% of the PPU[1-2]. The wide application of microsatellites puts forward new requirements for low-power, small-size, and high-efficiency anode power supplies.

2. Topology selection
Flyback converter is a commonly used circuit topology. It is often used in low-cost power supplies with an output power of 5~150W. It consists of a MOSFET, a transformer and a secondary diode. Its main advantage is that it does not need a secondary filter inductor like other topologies. The flyback transformer has the dual functions of a transformer and an inductor so that it has a lot of advantages in volume and cost. However, there are fewer applications in high-boost applications due to restrictions on switching tube voltage stress and converter efficiency. Literature [3]-[4] proposed that the use of a voltage doubler unit structure to obtain a higher boost ratio and reduce device stress through the combination of a capacitor and a diode is a relatively simple and efficient way to increase the gain. Therefore, it is considered that the secondary side uses a double voltage rectifier circuit as shown in Figure 1 to obtain a higher boost capacity.
The topology formed by combining the flyback converter and the double voltage rectifier circuit is shown in Figure 2. In order to further improve efficiency, consider applying soft switching technology to reduce switching losses. Soft switching technology mainly includes PWM soft switching technology and resonant soft switching technology. The former generally implements soft switching such as phase-shifted full-bridge soft switching technology through control strategies; the latter implements soft switching through the resonance of inductors and capacitors, and its representative is LLC resonant soft switching. Considering the choice of the topological structure of the resonant soft switching technology, the literature [5]-[6] describes in detail the principle design and parameter optimization of the resonant soft switch. The leakage inductance and capacitor resonance of the flyback transformer are used to achieve soft switching, and the excitation of the transformer The inductance and leakage inductance are equivalent as shown in figure 3, resulting in a high-efficiency boost topology.

In Figure 3, Lm is the magnetizing inductance, and Lr is the equivalent leakage inductance of the secondary side. Lr and Cb form the secondary side resonant circuit, and Lm and Cds form the primary side resonant circuit. When the switching tube is turned on, energy is transferred from the primary side to the secondary side through the transformer. The primary side's magnetizing inductance stores energy, and the secondary side Lr and capacitor Cb resonate to charge the capacitor Cb; when the switching tube is turned off, it is stored in Lm and Cb. The energy is output to the load through the diode D2, and the transformer transfers energy during the on and off periods of the switch tube, which improves the utilization rate of the transformer.

3. Materials and Methods

3.1 Working mode
The converter works in discontinuous current mode (DCM). In steady state operation, the converter has six working modes in one switching period of Ts. The main working process of each working mode is as follows.
Figure 7. Mode 4 Figure 8. Mode 5 Figure 9. Mode 6

Mode 1 $[t_0 \sim t_1]$ At $t_0$, the switch tube $V$ is turned on and the drain-source voltage $u_{ds} = 0$, so that the tube realizes the zero voltage switching (ZVS) turn-on. $V$ turns on, the excitation current increases linearly, $L_r$ and $C_b$ resonate and VD1 turns on. Then $i_{VD1}$ starts to charge $C_b$ and the voltage $u_{Cb}$ gradually increases. At the same time the primary current $i_p$ is equal to the sum of the excitation current and the resonance current.

At $t_1$, VD1 turns off, the resonance of $i_{VD1}$ decreases to zero and then VD1 turns off. The voltage of $C_b$ reaches the maximum value $U_{Cbm}$, and modal 1 ends. In this process, part of the primary energy is stored in $L_m$, and the other part is transferred to $C_b$ in the form of resonance.

$$i_{VD1}(t) = I_{VD1m}\sin[w_1(t - t_0)]$$

$$U_{Cbm} = NU_{in} + I_{VD1m}\sqrt{L_r/C_b}$$

(1)

In the formula: angular frequency $w_1 = 1/\sqrt{L_r/C_b}$; $I_{VD1m}$ is the maximum current flowing through VD1.

Mode 2 $[t_1 \sim t_2]$ $V$ continues to conduct and VD1 and VD2 are both turned off. The secondary side resonant working state ends; the resonant current is zero; $u_{Cb}$ remains unchanged, and the excitation current still rises linearly. At $t_2$, V turns off, and the excitation current reaches the peak value $I_{pm}$.

State 2 ends. The period of $t_0$ to $t_2$ is the on-time $T_{on}$ of V. Then $I_{pm} = U_{in}T_{on}/L_m$.

Mode 3 $[t_2 \sim t_3]$ At $t_2$, $V$ is turned off and $i_p$ no longer increases. At this time, $i_p$ starts to charge $C_{ds}$ and $u_{ds}$ gradually rises. At $t_3$, VD2 is turned on and working mode 3 ends. In this mode, the $i_p$ energy is large and can be considered to remain unchanged.

Mode 4 $[t_3 \sim t_4]$ VD2 is turned on and VD1 is turned off. The energy stored in $L_m$ and $C_b$ is transferred to the load, and $i_{VD2}$ and $u_{Cb}$ gradually decrease.

$$u_{Cb}(t) = U_{Cbm} - \frac{1}{C_b}\int_{t_3}^{t} i_{VD2}(t)dt$$

$$i_{VD2}(t) = I_{pm} / N - I_{pm}(t - t_3) / (NT_{off})$$

(2)

At $t_4$ time, $i_{VD2}$ decreases to zero, diode VD2 ZCS turns off, and working mode 4 ends. The period from $t_3$ to $t_4$ is recorded as $T_{off1}$.

Mode 5 $[t_4 \sim t_5]$ Both VD1 and VD2 are turned off, $u_{Cb}$ remains unchanged. At $t_4$, $i_p = 0$, $L_m$ and $C_{ds}$ resonate; $u_{ds}$ begins to decrease, and $i_p$ flows in the reverse direction. At $t_5$, $u_{ds}$ decreases to zero and working mode 5 ends. Its resonance frequency is:

$$w_2 = 1/\sqrt{L_m/C_{ds}}$$

(3)

Mode 6 $[t_5 \sim t_6]$ At $t_5$, the body diode of $V$ turns on, and $i_p$ still has a negative value at this time. The circuit no longer works in the quasi-resonant state. The input voltage is applied to both ends of $L_m$ and $i_p$ begins to rise linearly. At $t_6$, $i_p$ rises to zero, and working mode 6 ends. At this point, one work cycle is completed and the next work cycle is entered. In actual work, the duration of mode 3 and
mode 6 is relatively short.

It can be seen from the working modal analysis that the forward and flyback converter realizes the zero voltage turn-on of the switching tube and the zero current turn-off of the secondary diode, which greatly reduces the switching loss.

3.2 Device stress and gain analysis

3.2.1 Current stress analysis

The current stress of the diode $D_1$ is $I_{V_D1}$. According to the ampere-second balance, in the steady state the amount of charge flowing into the capacitor $C_b$ is equal to the amount of charge flowing out in a switching cycle, then

$$\int_{t_0}^{t_1} i_{V_D1}(t) dt = \int_{t_0}^{t_1} i_{V_D2}(t) dt$$  \hspace{1cm} (4)

Combine (1) (2) (4) that

$$I_{V_D1m} = \frac{w T_{off1}}{4N} I_{pm}$$  \hspace{1cm} (5)

Diode $D_2$ is the output diode, and the maximum current $i_{V_D2m}$ flowing through it is

$$I_{V_D2m} = \frac{I_{pm}}{N}$$  \hspace{1cm} (6)

3.2.2 Voltage stress analysis

The maximum reverse voltage that the diodes $D_1$ and $D_2$ bear are both output voltages. When $D_1$ is turned on, the diode $D_2$ bears the maximum reverse voltage $V_o$. When $D_2$ is turned on, the diode $D_1$ also bears the maximum reverse voltage $V_o$. The switch tube $V$ bears a maximum reverse voltage of $2V_{in}$ when it is turned off.

3.2.3 Gain analysis

When the switch tube is turned on, the output voltage is

$$U_1 = \frac{1}{T_{off1}} \int_{t_0}^{t_1} u_{cb}(t) dt$$  \hspace{1cm} (7)

When the switch tube is turned off, the output voltage is

$$U_2 = \frac{NU_{in} T_{on}}{T_{off1}}$$  \hspace{1cm} (8)

The output voltage is

$$U_o = U_1 + U_2$$  \hspace{1cm} (9)

The combined voltage gain is

$$K = \frac{U_o}{U_{in}} = N + \frac{T_{on}^2}{L_m C_b} - \frac{NL_m C_b}{12 T_{on} T_{off1}}$$  \hspace{1cm} (10)
3.3 Soft switch realization conditions

3.3.1 Diode zero current turn-off condition
When the converter works in the DCM mode, that is, the current drops to zero before the switch tube is turned on again, the diode $D_2$ can automatically realize zero-current shutdown. When the on-time is longer than the secondary side resonant half cycle, diode $D_1$ can also achieve zero current turn-off, so the condition for $D_1$ to achieve soft switching is

$$T_{on} > \pi \sqrt{L_r C_b}$$

(11)

3.3.2 Switch tube zero voltage turn-on conditions
The converter adopts the quasi-resonance method to realize the zero voltage turn-on of the switching tube. At the bottom of the resonance voltage of $u_{ds}$, if the primary current can be changed from negative to zero, that is, the reflected voltage when the switching tube is turned off is required to be greater than or equal to the input voltage, then the switching tube can realize zero voltage turn-on. So the conditions for the switch tube to realize soft switching are

$$\frac{U_2}{N} > U_{in}$$

(12)

4. Results & Discussion

4.1 Simulation
In order to verify the theoretical feasibility, the Saber software was used for simulation verification. The designed input voltage $U_{in}$ is 37~45V, the rated voltage is 42V, the steady-state output voltage is 250V~320V (adjustable), the rated output is 320V, the maximum output power is 280W, the switching frequency is 50~150kHz, the transformer turns ratio is 1:4, $L_m$ is 20uH, $L_r$ is 0.4uH, $C_b$ is 2.7uF, output capacitance $C_o$ is 30uF, MOS tube is an ideal device.

The experimental simulation waveforms are shown in the figure 10 below, which are the driving signal waveform, the drain-source voltage of the switch tube, the diode VD1 and the diode VD2 in order. The experimental results are consistent with the theory, and the zero voltage turn-on of the switch tube and the zero current turn-off of the two diodes are realized.

![Figure 10. Saber simulation waveform](image)

4.2 Experiment
Build a physical prototype according to the above indicators and conduct experimental tests. The test waveforms under the conditions of rated input 42V and rated output 320V are as follows.
Figure 11 shows the voltage and current waveforms at both ends of the MOS tube. It can be seen from the figure that the intersection of voltage and current is close to 0 when the switching tube is turned on, which realizes the zero-voltage turn-on soft switching of the switching tube and reduces the turn-on loss.

Figure 12 shows the voltage and current waveforms at both ends of the diode D1. It can be seen from the figure that the voltage is 0 when the current is not 0. The soft switching of the diode is realized through the resonance period and the loss is reduced.

Figure 13 shows the voltage and current waveforms at both ends of the diode D2. It can be seen from the figure that the voltage is 0 when the current is not 0, and the circuit works in DCM mode, which realizes the diode's zero-current turn-off soft switch and reduces the loss.

Analog output no-load test, when the input voltage is 37V, 42V, 45V, the output voltage is 250V and 320V under no-load conditions, the test data is shown in Table 1. The test results under no-load and full-load start conditions are shown in Table 2, and the test results of stepping the load from no-load to full-load and switching from full-load to no-load are shown in Table 3.

| Table 1 No-load output performance test |
|------------------|----------------|------------|-------------|-------------|----------|
| Vin/V | Iin/A | Vout/V | Iout/A | Vref/V |
|------------------|----------------|------------|-------------|----------|
| 37.0 | 0.02 | 250.71 | 0 | 1.68 |
| 37.0 | 0.04 | 320.70 | 0 | 2.16 |
| 42.0 | 0.05 | 250.82 | 0 | 1.68 |
| 42.0 | 0.04 | 320.70 | 0 | 2.16 |
| 45.0 | 0.04 | 250.68 | 0 | 1.68 |
| 45.0 | 0.04 | 320.70 | 0 | 2.16 |

| Table 2 No-load and full-load startup test |
|------------------|----------------|------------|-------------|-------------|--------|
| Vin/V | Vout/V | Vout/V | Iadj/ms | Vout/V | Iadj2/ms |
|------------------|----------------|------------|-------------|-------------|--------|
| 37 | 250 | 22 | 128 | None | 175 |
| 37 | 320 | 30 | 140 | None | 180 |
| 42 | 250 | None | 140 | None | 154 |
| 42 | 320 | 28 | 120 | None | 172 |
| 45 | 250 | None | 101 | None | 154 |
| 45 | 320 | 30 | 100 | None | 164 |

| Table 3 Test situation of load step |
|------------------|----------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Vin/V | Load step | Vmax Voltage | Imax/A | Vout/V | Iout/A | Iout/A | Vout/V | Iout/A |
|------------------|----------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 37 | Zero—>Full | 133 | 27.8 | 85.5 | 152 | 198 | 6.1 | 354 | 2.56 | 344 | 7.4 |
| 37 | Full—>Zero | 141 | 19.4 | 95.5 | 100 | 186 | 5.5 | 450 | 1.92 | 452 | 7.6 |
| 42 | Zero—>Full | 133 | 27.8 | 74.5 | 158 | 210 | 6.3 | 350 | 2.36 | 344 | 7.2 |
| 42 | Full—>Zero | 139 | 19.0 | 73.5 | 100 | 208 | 6.0 | 428 | 1.96 | 434 | 7.2 |
| 45 | Zero—>Full | 133 | 26.6 | 58 | 99 | 208 | 6.0 | 352 | 2.44 | 342 | 7.0 |
| 45 | Full—>Zero | 137 | 19.4 | 69.0 | 153 | 208 | 5.8 | 412 | 2.04 | 414 | 7.0 |

Vout is the output voltage, VDSmax is the maximum voltage between DS of MOS tube Q1, IDSmax is the maximum current when MOS tube Q1 is turned on, Vos is the output voltage overshoot (Vos1 is no
load, \(V_{os2}\) is full load), \(t_{adj}\) is the output voltage setup time (\(t_{adj1}\) is no load, \(t_{adj2}\) is full load), \(V_{Cb}\) is the voltage of capacitor \(C_b\), \(I_{Cb}\) is the current of capacitor \(C_b\); \(V_{D1max}\) is the maximum voltage of \(D_1\), \(I_{D1max}\) is the maximum current of \(D_1\), \(V_{D2max}\) is the maximum voltage of \(D_2\), and \(I_{D2max}\) is the maximum current of \(D_2\).

According to the no-load test conditions in Table 1, the input voltage is in the range of 37V~45V. According to the constant voltage reference, the output voltage can be stabilized at 250V/320V, the output has no oscillation, and the performance is normal.

It can be seen from Table 2 and Table 3 that there is no overshoot under full load conditions, and the voltage establishment time is short. When the input voltage is 37V~45V, and the output voltage is 250V and 320V respectively, the bus voltage is at the input voltage during the no-load and full-load load switching process. When it is 37V, the overshoot is the largest, when no load is switched to full load, the overshoot is 85.5V, and the recovery time is 152ms; when full load is switched to no load, the overshoot is 95.5V, and the recovery time is 100ms, and the dynamic performance is excellent.

Analog output full load test and the output voltage is tested for the full load of 250V and 320V when the input voltage is 37V, 42V, 45V. The test data is shown in Table 4.

| Input voltage \(V_{in}\)/V | Input current \(I_{in}\)/A | Input current ripple \(I_{in,ripple}\)/A | Output voltage \(V_{out}\)/V | Output current \(I_{out}\)/A | Output current ripple \(I_{out,ripple}\)/A | Constant pressure benchmark \(V_{ref}\)/V | Output voltage ripple \(V_{ou,ripple}\)/V | Efficiency \(\eta\)/% |
|--------------------------|----------------------|-------------------------------|---------------------------|-----------------|-------------------------------|-----------------------------|-------------------|-----------------|
| 36.986                   | 6.370                | 1.11                          | 250.79                    | 0.862           | 0.20                          | 1.68                        | 7.1               | 91.75           |
| 36.975                   | 8.313                | 1.16                          | 320.90                    | 0.875           | 0.21                          | 2.16                        | 5.2               | 91.35           |
| 41.985                   | 5.55                 | 1.12                          | 250.70                    | 0.868           | 0.15                          | 1.68                        | 5.2               | 93.39           |
| 41.979                   | 7.123                | 1.20                          | 320.95                    | 0.873           | 0.21                          | 2.16                        | 7.7               | 93.70           |
| 44.978                   | 5.207                | 1.08                          | 251.20                    | 0.865           | 0.18                          | 1.68                        | 7.9               | 92.77           |
| 44.982                   | 6.671                | 1.12                          | 320.7                     | 0.868           | 0.15                          | 2.16                        | 5.2               | 92.76           |

According to the full load test, the input voltage is in the range of 37V~45V. According to the constant voltage reference, the output voltage can be stabilized at 250V/320V and the output has no oscillation, and the performance is normal. Adjust the resonant capacitor \(C_d\)s in Figure 1.4 to change the resonant frequency of the resonant capacitor and the transformer magnetizing inductance, so that the converter achieves a zero-voltage turn-on state when the converter has a rated input of 42V, a rated output of 320V, and a full load. Therefore, it can be seen from Table 2. It can be seen that when the input voltage is 42V, the output voltage is 320V, and the efficiency is the highest under full load, it is 93.7%.

5. Conclusions

On the basis of theoretical analysis, simulation analysis and physical prototype design are carried out. For the new type of flyback soft-switching converter in the closed-loop working state, the no-load and full-load tests of the converter in the steady-state mode are carried out, and the dynamic mode is tested. No-load startup, full-load startup and output load steps are tested. The test results realize the soft switching of the switch tube and the secondary diode. The output voltage is equivalent to the series output when the switch tube is turned on and off due to the voltage doubler structure. Compared with the simple flyback converter, the device stress is small and the output gain is High, a series of dynamic tests show that the closed-loop topology is stable and the dynamic performance is good. It is the preferred topology for the anode power supply of the micro satellite.

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