Research on a new converter topology for energy transmission between spacecrafts

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Abstract. A novel power converter based on dual-transistor forward converter topology is proposed to meet the requirements of high power transmission between spacecrafts. Compared with the traditional two-transistor forward converter, this converter eliminates the secondary filter inductance and the diode of the rectifier. Theoretical analysis and experimental results show that the new topology reduces the use of magnetic elements, improves the power density of the converter, and improves the parasitic oscillation and reverse recovery of the rectifier diode. The new topology can better meet the requirements of power supply system for high reliability, reducing device stress, increasing the availability of key devices, optimizing system structure and so on.

1. Introduction

Large complex spacecraft systems can be constructed through multiple spacecrafts onboard networking. By using the energy transfer technology between spacecrafts, on-orbit networking of different spacecrafts power supply systems can be realized, so as to achieve system power expansion, energy comprehensive utilization, energy supply under failure, and improve the reliability of the whole system. The energy transfer technology between spacecrafts can connect the power supply system between two spacecrafts through power converter, and use its transformation and regulation function to achieve the purpose of energy transmission between the two power supply systems\cite{1,2}.

At present, there are few researches on power converters applied to energy transmission between spacecrafts. Reference \cite{3-4} refers to the case of energy transmission from docking target spacecraft to manned spacecraft using 500W power converter. With the continuous expansion of energy transmission power between spacecraft, it is necessary to further expand the power level of power converter. The increasing demand also brings a series of problems such as topology selection, device stress, power density and so on\cite{1,5-7}.

Compared with industrial power supply, aerospace power supply has a special working environment, which requires higher reliability of equipment, and is restricted by device selection and other constraints, and the available topology structure is also limited. At present, the main topological forms are single-ended forward circuit, flyback circuit, dual-transistor forward circuit, push-pull circuit, half-bridge circuit, full-bridge circuit and so on\cite{2}. Among them, the dual-transistor forward converter topology (shown in Figure 1.a) has the characteristics of no-bridge-arm through and transformer bias, low voltage stress of switch, easy modular design and so on. Based on the basic topology of 1.a, a method of generating 2kW converter by using four 500W dual-transistor forward
converters in input-parallel-output series (IPOS) for energy transfer between spacecrafts is proposed in reference [8], as shown in Figure 1.b. The technical advantages of IPOS topology lie mainly in [9-13]: 1) the output voltage pulsation frequency is four times as high as the actual power transistor switching frequency, which reduces the volume weight of the input and output filters; 2) the power loss of the power devices is dispersed and the electrical stress of the power switching devices is reduced; 3) the equivalent duty cycle of the secondary rectifier side voltage is increased and the transmission is reduced. The dynamic response of the output current is fast; 4) The continuous current mode operation of the converter is easy to be realized because of the short time of continuous current.

![Diagram of IPOS topology and converters](image1)

**Figure 1.** Basic topology and IPOS topology of two transistor forward converter.

The circuit in Figure 1 has serious reverse recovery and voltage oscillation problems when the output current is large, as shown in Figure 2. $V_{D5}$ and $I_{D5}$ are the voltage and current waveforms of the secondary rectifier diode, $V_{D6}$ and $I_{D6}$ are the voltage and current waveforms of the secondary rectifier diode. It can be seen from the diagram that the voltage oscillation on the diode will lead to the problems of high voltage stress, difficult selection and large on-loss. In high voltage and high current applications, this problem will further exacerbate the contradiction of device selection.

![Simulation waveforms of double transistor forward converter](image2)

**Figure 2.** Double transistor forward converter simulation waveform.

On this basis, a new forward converter topology is proposed to meet the needs of energy transmission between spacecraft. The original topology and device stress are further optimized. The principle and characteristics of the converter are analyzed and studied in detail.

2. **New topology of dual transistor forward converter**

Considering the capacitance of rectifier secondary junction, the output can be equivalent to current source because of the existence of filter inductance. During the commutation period of rectifier diode, the resonant mode of resonant inductance and diode junction capacitance is the cause of voltage oscillation. If the output is a voltage source rather than a current source, the voltage source can clamp
the diode voltage and essentially eliminate parasitic oscillations. The topology derivation process is as follows: the output filter inductance can be omitted because the transformer leakage inductance realizes the reuse of the resonant inductance and the filtering function; and the secondary-side continuous-current diode is always in the cut-off state because of the parallel connection between the secondary-side continuous-current diode and the output filter capacitor, thus further eliminating the continuous-current diode. The topology of the new dual transistor forward converter are shown in Figure 3.

The novel dual-transistor forward converter consists of switching transistor Q1 and Q2 (D1 and D2 are body diodes respectively), transformer T, (Lm is transformer excitation inductance), primary reset diode D3 and D4, inductance Lr (can be supplied by transformer leakage inductance), secondary diode D5, filter capacitor C0 and load resistance Ro. By controlling the on-off of switches Q1 and Q2, the working state of the converter is changed. When Q1 and Q2 are turned on, the power supply energy is transferred to the load and the transformer is magnetized forward; when Q1 and Q2 are turned off, the transformer is magnetically reset through diodes D3 and D4.

Compared with the traditional two-transistor forward converter, the circuit has a simpler circuit topology, the number of components is equal to the two-transistor flyback converter, but the operation mode is similar to the two-transistor forward converter. The converter directly transfers energy from the primary side to the secondary side during switching on, which is different from the indirect energy transfer mode in which the flyback topology releases energy from the transformer to the secondary side during switching on. Therefore, the topology combines the advantages of forward topology and flyback topology.

![Figure 3. Basic topology and IPOS topology of new dual transistor forward converter.](image1)

3. Principle analysis of the new converter

![Figure 4. The main working waveforms of the new double transistor forward converter.](image2)
Ideally, the switching speed of Q1 and Q2 switches is identical without considering the parasitic parameters of switches and diodes. Figure 4 is the main working waveforms of the new dual transistor forward converter. Modal analysis is as follows.

3.1. Mode 1 [t0, t1]

The working mode is shown in Figure 5 (a). At t0 time, the switch tube Q1 and Q2 are switched on, and the resonant inductor current iLr is zero, that is, iLr (t0) = 0. After t0 time, +V_in is added between the two points of a and b of the original side bridge arm, the iLr increases, the power energy is transferred to the load, and the transformer is magnetized forward. According to the Lr volt-second balance relation of inductance, the primary current of transformer at t1 time can be obtained by equation (1):

\[
i_{Lr}(t_1) = \frac{V_{in} - \frac{n_z V_o}{n_1}}{L_r} (t_1 - t_0)
\]

(1)

If the primary polarity of the transformer is up-positive and down-negative, the secondary diode D5 of the transformer is turned on. At this time, the voltage on the excitation inductance Lm of the transformer is clamped, so the Lm constant voltage charging is carried out in the process. According to the Lm volt-second balance relation of inductors, the excitation current of transformer at t1 time can be obtained by equation (2):

\[
i_{Lm}(t_1) = \frac{n_z V_o}{L_m} (t_1 - t_0)
\]

(2)

t1 time, Q1 and Q2 turn off, this mode ends. The modal conduction time is (3):

\[t_{01} = DT_s\]

(3)

D is the duty cycle of switching cycle.

3.2. Mode 2 [t1, t2]

The working mode is shown in Figure 4 (b).

t1 time, Q1, Q2 turn off, iLr flows through diode D3, D4. At this point, -V_in is added to the original bridge arm, and iLr begins to drop. According to the inductance Lr and Lm volt-second balance, t2 time iLr and iLm can be obtained by (4) and (5):

\[
i_{Lr}(t_2) = \frac{-V_{in} - \frac{n_z V_o}{n_1}}{L_r} (t_2 - t_1) + i_{Lr}(t_1)
\]

(4)

\[
i_{Lm}(t_2) = \frac{n_z V_o}{L_m} (t_2 - t_0)
\]

(5)

At this stage, the iLr is always greater than the excitation current iLm, so there is always a positive current flow through the primary side of the transformer, and the secondary diode D5 continues to turn on. At t2, iLr drops to the same value as iLm, and this mode ends.

The modal conduction time is (6):

\[t_{12} = DT_s\]

(6)

\[
D_1 = \frac{V_{in} - \frac{n_z V_o}{n_1}}{L_r} (\frac{1}{L_r} + \frac{1}{L_m}) \cdot \frac{V_{in} - \frac{n_z V_o}{n_1}}{n_1} \cdot D = \frac{V_{in} + \frac{n_z V_o}{n_1}}{L_r + \frac{n_z V_o}{L_m}} (\frac{1}{L_r} + \frac{1}{L_m}) \cdot \frac{V_{in} + \frac{n_z V_o}{n_1}}{n_1} \cdot D
\]

(7)
3.3. Mode 3 \([t2, t3]\)

The working mode of the circuit is shown in Figure 5 (c). At \(t2\), because \(i_L \) equals \(i_{Lm}\), the transformer's primary and secondary edges are removed, and the \(L_m\) is no longer clamped, and the transformer is magnetically reset. At this point, \(-V_{in}\) is added to the original bridge arm, and \(i_L\) drops with \(i_{LM}\). The secondary side is supplied by the output capacitor for the load. At \(t3\), both \(i_L\) and \(i_{Lm}\) dropped to zero, and this mode ended.

The modal conduction time is (8):

\[
t_{3,3} = D_s T_s
\]

(8)

\[
D_s = \frac{n_p}{n_s} \frac{V_{in}}{V_m} (D + D_s) \frac{L_r + L_m}{L_m} \approx \frac{n_p}{n_s} \frac{V_{in}}{V_m} (D + D_s)
\]

(9)

\[
s_{TD} t_{223} = n_r (D + D_s) \frac{L_r + L_m}{L_m} \approx n_r \frac{V_{in}}{V_m} (D + D_s)
\]

(10)

\[
\frac{1}{2} (t_2 - t_i) I_{DS}(t_i) = I_L
\]

(10)

\[
I_{DS}(t_i) = \frac{n_r}{n_r} \left[ I_L(t_i) - I_{LM}(t_i) \right]
\]

(11)

According to formula (10) and (11), the formula of the gain of the converter is obtained.

\[
G = \frac{V}{V_m} = \frac{L_r + MN^2}{2NL_r} + \left( \frac{L_r + MN^2}{2NL_r} \right)^2 + M
\]

(12)
According to the gain expression, the gain curves under different parameters can be drawn, as shown in Figure 6 (a), (b), (c), (d). It can be seen from the gain characteristic curve that the converter gain decreases with the increase of switching frequency $f_S$ and inductance $L_r$, increases with the increase of load $R$, and is nonlinear with the transformer turn ratio $N$.

$$N = \frac{n_T}{n_i} \quad M = D^2 T R = \frac{D^2}{f_s} R$$ \hspace{1cm} (12)

4. Test verification
A model is established for simulation analysis. The simulation conditions are as follows: the input voltage $V_i$ is 100V, the output power $P_o$ is 500W, and the working frequency $f_s$ is 100kHz. In the figure, $V_{gs}$ is the driving signal, $V_{ab}$ is the output voltage waveform of the original side, $V_{Q1}$ is the voltage waveform of the two ends of the switch $Q_1$, $V_{D5}$ is the voltage waveform of the two ends of the secondary side diode, and $I_{D5}$ is the current waveform of the secondary side diode. The simulation results are shown in Figure 7. It can be seen from the graph that the simulation analysis is consistent with the theoretical analysis.

Figure 6. Gain characteristic curve of double transistor forward converter.

Figure 7. Simulation waveforms of converter.
In order to verify the correctness of the theory and simulation analysis, the converter is verified by experiments. The experimental conditions coincide with the simulation conditions. Figure 8 shows the experimental waveforms of dual transistor forward converter under 100V input condition. Among them:

Figure 7 (a) shows the waveforms of Vgs1 and Vgs2 driving signals of two MOS transistors, and the corresponding leakage source voltage VQ1 and VQ2 of the MOS transistors. Obviously, it can be seen from the diagram that the voltage at both ends of two MOS transistors is zero during switching on, and the voltage at both ends during switching off is 100V, that is Vin, which is ideally analyzed. Because of the junction capacitance of the switch, the voltage at both ends of the MOSFET decreases to 0 after the junction capacitance is completely discharged.

Figure 7 (b) is the waveform of the voltage at the two ends of the diode side diode D5 and the current iD5 passing through the D5. As can be seen from the diagram, due to the existence of diode junction capacitance, the diode charges backward, and the forward current drops to zero. The reverse recovery performance of diodes is improved.

Figure 8 (c) is the waveform of driving signal Vgs1, inductance current IL and transformer side diode D5 current iD5, which is consistent with the theoretical analysis.

Figure 8 (d) is the waveform of the voltage at the two ends of the diode side diode D5 and the current iD5 passing through the D5. As can be seen from the figure, due to the existence of diode junction capacitance, the diode charges in the reverse direction, and the forward current drops to zero. The reverse recovery performance of diodes is improved.

![Figure 8](image)

**Figure 8.** Test waveforms of double transistor forward converter at input voltage of 100V.

### Table 1. The comparison between the improved IPOS topology and the original IPOS topology device.

|                     | Switch tube voltage | Switch tube current | Primary diode voltage | Primary diode current | Rectifier diode voltage | Rectifier diode current | Freewheeling diode voltage | Freewheeling diode current |
|---------------------|---------------------|---------------------|-----------------------|-----------------------|-------------------------|-------------------------|-----------------------------|-----------------------------|
| Original IPOS topology | 100V                | 8.7A (rms)          | 100V                  | 0.35A (avg)           | 150V^a                  | 6.6A (avg)              | 75V                         | 13.4A (avg)                 |
| Improved IPOS topology | 100V                | 10.6A (rms)         | 100V                  | 7.5A (avg)           | 55V                    | 20A (avg)              | /                           | /                           |

^a Calculated by 2 times voltage spikes
According to the power level requirement, four power modules are selected to be combined in series and parallel. Under rated operating conditions, the device stress of the improved IPOS topology and the original IPOS topology are compared as shown in Table 1. It can be seen that the improved IPOS topology uses capacitive filter, reduces the use of magnetic components, and improves the power density of the converter. The problem of parasitic oscillation and reverse recovery of rectifier diode is improved, and the volume of converter is reduced by non-continuous diode.

5. Conclusions

Aiming at the requirement of high power transmission between spacecrafts, the topology optimization of power converter is studied. Based on the analysis and comparison of the IPOS topology of the dual-transistor forward converter, a new dual-transistor forward converter is proposed. The principle and characteristics of the converter are analyzed and verified in detail. The analysis and experimental results show that the new IPOS topology reduces the use of magnetic components, improves the power density of the converter, improves the parasitic oscillation and reverse recovery of rectifier diodes, and meets the requirements of high reliability of Aerospace Power supply, reducing device stress, increasing the availability of key devices and reducing the volume of equipment.

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