Multi-output forward converter based on power distribution control

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Abstract. The cross regulation rate affects the voltage accuracy of the multi-output power supply. To fundamentally improve the cross regulation rate of the multi-output forward converter, a control strategy based on power distribution is proposed. The real-time voltage and real-time current of each output end are sampled by ARM to obtain real-time load, the expected output power is calculated according to the expected output voltage of each path, and the conductance of the main switch and the secondary rectifier are calculated according to the working principle and hardware parameters of the forward converter on time, so that each output gets the desired voltage. The experimental results show that the multi-output forward converter using power distribution control has a cross regulation rate of less than 1% and a load regulation rate of less than 0.4%. The designed forward converter can not only effectively improve the cross regulation rate, but also have better load regulation.

1. Introduction
The magnetic core of the forward converter has no air gap, the transformer has high inductance value, small copper loss, and high degree of winding coupling, which makes the conversion efficiency of the forward converter high; the energy storage inductor and rectifier diode can effectively attenuate ripple. Therefore, the single-tube forward converter is suitable for low voltage and high current applications. The multi-output forward converter can meet the conditions of low voltage and high current, but the voltage drop of its output rectifier diode and the power distribution of the transformer are important factors that affect its cross-regulation rate. Therefore, how to improve the cross-adjustment rate of the multi-output forward conversion has become an important direction of power electronics technology research[1].

At present, the strategies for improving the cross regulation of multi-output forward converters mainly include: optimization of transformer design, weighted voltage control, auxiliary output with linear regulator, synchronous control of main and auxiliary circuits, all of which can improve cross-adjustment rate[2-5]; and the power distribution control strategy is only applied to the flyback converter, which can fundamentally improve the cross regulation of the dual output flyback converter[6]. Fundamentally improve the cross regulation of the forward converter, a multi-output forward converter based on power distribution control is designed.
2. System composition and control and strategy

2.1. System composition

The main circuit of the multi-output forward converter based on power distribution control[7] is shown in Figure 1. In Figure 1, $U_S$ is the input DC voltage, $U_{O1}$, $U_{O2}$ and $U_{O3}$ are the output DC voltage, $S_{W1}$ is the main switch, $S_{W2}$, $S_{W3}$ and $S_{W4}$ are synchronous rectifier switches.

As shown in Figure 1, ARM samples the output voltages $U_{O1}$, $U_{O2}$, and $U_{O3}$ and the load currents $I_{O1}$, $I_{O2}$, and $I_{O3}$ in real time to obtain real-time loads $R_{L1}$, $R_{L2}$, and $R_{L3}$ in a multi-output forward converter. Combined with the desired output voltage $U_E$, the expected power $P_E$ of multiple outputs is calculated. In order to make the obtained power $P_O$ equal to the expected power $P_E$, the PWM wave duty ratio is calculated by controlling the switches $S_{W1}$, $S_{W2}$, $S_{W3}$ and $S_{W4}$ to achieve the power distribution requirements of each output.

![Figure 1. Schematic diagram of power distribution control strategy](image)

2.2. Strategy based on power distribution control

The three output rated voltages and currents of the forward converter designed this time are: $U_{O1}=24V$, $I_{O1}=3A$; $U_{O2}=12V$, $I_{O2}=2A$; $U_{O3}=5V$, $I_{O3}=1A$; multi-channel with power distribution control. The output forward converter achieves the purpose of constant voltage, and the real-time load is obtained by sampling the output voltage and output current of each path, the required output power is calculated from the real-time load and rated voltage of each path, and the corresponding secondary side is calculated from the output power of each path the duty cycle of the switch tube makes the secondary power distribution equal to the required output power. Therefore, the output power of each channel is reasonably distributed, and the problem of cross-adjustment rate is effectively solved.

Control principle: as shown in Figure 1, firstly, the input voltage $U_S(t)$, output voltage $U_{O1}(t)$, $U_{O2}(t)$, $U_{O3}(t)$ and load current $I_{O1}(t)$, $I_{O2}(t)$, $I_{O3}(t)$ are sampled by ARM in real time to obtain the real time load $R_{L1}$, $R_{L2}$ and $R_{L3}$.
Given the expected voltages $U_{E1}$, $U_{E2}$ and $U_{E3}$, the expected output power $P_E$ and average current $I_{AV}$ of each circuit can be calculated as:

$$P_E = \frac{U_{E}^2}{R_L}$$

$$I_{AV} = \frac{U_{E}}{R_L}$$

The forward converter works in discontinuous mode, as shown in Figure 2, which is the current waveform of its energy storage inductor. The peak current value $I_{max}$ of the energy storage inductor $L$ in the figure is equal to twice the average current $I_{AV}$ in its charge and discharge time $t_2$.

$$I_{max} = 2I_{AV}$$

According to the volt-second balance[8], the relationship between the charging time $t_{on}$ of the energy storage inductor and its discharge time $t_{off}$ is as follows:

$$\left\{ \begin{array}{l}
\frac{V_{on}}{L}t_{on} = I_{max} \\
V_{E}t_{off} = V_{on} - V_{E} = K
\end{array} \right.$$ 

$$\Rightarrow t_{on} = \frac{t_{off} V_{E}}{V_{on}} = \frac{V_{E}}{V_{on} \times n - V_{E}} = K$$

In the above formula: $K$ is the ratio of charging time $t_{on}$ and discharging time $t_{off}$ of energy storage inductor, $V_E$ is the desired output voltage, $L$ is the value of energy storage inductance, $V_{on}$ is the...
voltage value across the energy storage inductor, \( V_S \) is the input voltage, and \( n \) is the transformer turns ratio.

The relationship between the average current \( I_{AV} \) in the charging and discharging time \( t_2 \) of the energy storage inductor and the average current \( I_L \) in a cycle \( t_3 \) is:

\[
\frac{t_2}{T} I_{AV} = I_L \Rightarrow \frac{K+1}{K} \frac{t_{on}}{T} I_{AV} = I_L
\]

(6)

In the above formula: \( T \) is the period of the switching components.

According to the power distribution control, the power obtained by the output distribution is equal to the expected power, which is equivalent to the period average current \( I_L \) of the energy storage inductor equal to the expected average current \( I_{AV} \) of the output. From equation (6), the on-time relationship of the output switching components can be obtained:

\[
\frac{V_S \times n \times t_{on}}{V_L \times T} = \frac{1}{2L} I_{AV}
\]

(7)

The conduction time \( t_{on} \) of the three output switching components is:

\[
t_{on} = \frac{2 I_{AV} TV_L L}{V_{on} V_n n} = \frac{2 P_L TL}{V_{on} V_n n}
\]

(8)

\[
L < L_C = \frac{(V_o + V_f)(1 - D_{min})T}{I_{O(max)}}
\]

(9)

\( P_L \) is the expected output power.

The on-time \( t_o \) of the main switch components is equal to the maximum on-time \( t_{max} \) of the real-time three output switching components.

Finally, the corresponding PWM wave output from the ARM is used to drive the four-way switching components on and off, so that the power distribution value of each side of the secondary side is equal to the expected value. Therefore, the output voltage is stabilized, and the problem of cross-regulation of the multi-output forward converter is fundamentally solved.

3. System hardware and programming

The input DC voltage of this design is 48V ~ 72V, the output voltage is 24V / 3A for one channel, 12V / 2A for two channels, and 5V / 1A for three channels; the efficiency is greater than 90%.

3.1. System hardware design

The hardware design of this system mainly includes the design of the transformer, magnetic reset circuit, drive circuit of the main switching components, sampling circuit, ARM control circuit and auxiliary power circuit, etc., which only selects the value of the output energy storage inductor and the selection of high frequency transformer parameters and analyze.

3.1.1. Energy storage inductor design.

In discontinuous mode, the energy storage inductance value is based on the formula:

\[
L < L_C = \frac{(V_o + V_f)(1 - D_{min})T}{I_{O(max)}}
\]

(10)

\( L_C \) is the critical inductance, \( D_{min} \) is the minimum duty cycle of the rectifier, \( I_{O(max)} \) is the maximum output current, \( V_f \) is the conduction voltage drop of the secondary rectifier.
The inductance $L_1$ of the three-output energy storage inductor is $30\mu H$, $L_2$ is $20\mu H$, and $L_3$ is $10\mu H$.

3.1.2. High frequency transformer design.
According to the range of transformer switching frequency and power, select the appropriate core model[9-10], considering the cost factor, choose PC40 material, soft ferrite core, the specification is EC39.

The high-frequency transformer turns ratio is: $n_1$ is 2, $n_2$ is 4, $n_3$ is 10; the magnetic reset circuit uses the third winding magnetic reset technology, the turn ratio $n_4$ is 1; the number of primary turns $N_P$ is 22 turns, the number of secondary turns $N_S$ is 11 turns, $N_{S2}$ is 5 turns, $N_{S3}$ is 2 turns, magnetic reset winding turns $N_{S4}$ is 22 turns.

3.2. System software design
This design selects STM32F103C8T6 as the main control chip and integrates rich peripheral functions such as ADC, DMA, TIM, and GPIO.

As shown in Figure 3, in the program flow chart of the function, first, after the system initialization is completed, the three-output voltage $U_{O1}(t)$, $U_{O2}(t)$, $U_{O3}(t)$ and load current $I_{O1}(t)$, $I_{O2}(t)$, $I_{O3}(t)$ are sampled in real time and then the three-output real-time load $R_L$ and expected output power $P_E$ are calculated. Then, through the power distribution strategy, the on-time of the three-output switch is calculated and compared with each other. The longest turn-on time is $t_{max}$, the main switch turn-on time $t_s$ is equal to $t_{max}$, because the transformer has primary and secondary leakage inductance can not be avoided, so the turn-on time can be appropriately adjusted according to the desired voltage, so that the output voltage is closer to the expectation voltage. Finally, the system outputs four PWM wave control switching components to meet the power requirements of the three outputs.

![Figure 3. program flow chart](image-url)
4. System experiment result test

According to the design and programming of theoretical parameters, the correctness of the control strategy is verified through Saber simulation. Test the cross adjustment rate and load adjustment rate to get the experimental results and observe the control effect of the power distribution control.

4.1. Cross regulation test

When the input voltage is set to 60V, the two output loads of output channels UO1 and UO2 are kept in a light load state, and the output load RL of UO3 channel changes from heavy load to light load. The experimental data is shown in Table 1.

It can be obtained from Table 1 that the cross-adjustment rate of UO1 and UO2 is 0.083%, and the load adjustment rate of UO3 is 0.4%.

Table 1. Test values of UO1, UO2 affected by UO3 load changes

| RL1/Ω | RL2/Ω | RL3/Ω | UO1/ V | UO2/ V | UO3/ V |
|-------|-------|-------|--------|--------|--------|
| 48    | 50   | 5     | 23.99  | 12.01  | 4.99   |
| 48    | 50   | 10    | 23.99  | 12.00  | 4.99   |
| 48    | 50   | 25    | 23.99  | 12.01  | 4.99   |
| 48    | 50   | 35    | 23.98  | 11.99  | 4.98   |
| 48    | 50   | 50    | 23.98  | 11.99  | 4.99   |

Similarly, the test values of UO1 and UO3 affected by UO2 load changes can be obtained. The experimental data is shown in Table 2. It can be obtained from Table 2 that the cross regulation of UO1 and UO3 are 0.083% and 0.4%, and the load regulation of UO3 is 0.083%.

Table 2. Test values of UO1, UO3 affected by UO2 load changes

| RL1/Ω | RL2/Ω | RL3/Ω | UO1/ V | UO2/ V | UO3/ V |
|-------|-------|-------|--------|--------|--------|
| 48    | 50   | 6     | 23.99  | 12.01  | 4.99   |
| 48    | 50   | 8     | 23.99  | 12.00  | 4.99   |
| 48    | 50   | 12    | 23.99  | 12.01  | 4.99   |
| 48    | 50   | 24    | 23.98  | 11.99  | 4.98   |
| 48    | 50   | 48    | 23.98  | 11.99  | 4.99   |

For the same reason, it can be concluded that UO2 and UO3 are affected by UO1 load changes. The experimental data is shown in Table 3.

Table 3. UO2, UO3 are affected by UO1 load change test value

| RL1/Ω | RL2/Ω | RL3/Ω | UO1/ V | UO2/ V | UO3/ V |
|-------|-------|-------|--------|--------|--------|
| 8     | 50   | 50    | 24.02  | 12.01  | 5.00   |
| 12    | 50   | 50    | 24.00  | 12.00  | 4.99   |
| 16    | 50   | 50    | 23.98  | 11.99  | 4.98   |
| 24    | 50   | 50    | 23.99  | 11.99  | 4.98   |
| 48    | 50   | 50    | 23.98  | 11.99  | 4.99   |

From Table 3, it can be obtained that the cross-adjustment rates of UO2 and UO3 are 0.083% and 0.4%, and the load adjustment rate of UO1 is 0.083%.

5. Conclusion

The experimental results show that the design method of the multi-output forward converter based on power distribution control is reasonable and feasible. With this control method, the cross regulation of the multi-output forward converter is fundamentally improved, and the cross regulation of the circuit output is less than 1%, and the power supply stability and voltage accuracy are improved.
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