Design of Processor Power Supply

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Abstract. A design of a power products onboard for industrial processor power supply is introduced. The power supply topology adopts full bridge circuit topology and double current synchronous rectifier. It selects the power devices and analyzes the main influence on the power loss of power efficiency, and then completes the design of the power supply products. The final results show that the electrical performance parameters consistent with the expected effect of customers, and has been applied in industrial processor power supply equipment successfully.

Introduction

With the continuous development of microprocessors and digital signal processors, the requirement of power supply for chips is getting higher and higher. Whether it is power density, efficiency and dynamic response, there are new requirements. Especially, the output voltage is getting lower and lower, but the current is getting bigger and bigger. The output voltage will be reduced from 3.3V to 1.1-1.8V, or even lower. From the point of view of power supply, microprocessors and digital signal processors etc. are loads of power supply, and they are dynamic loads, which means that the load current will change greatly in an instant, from 13A/us in the past to 30A/us to 50A/us in the present, which requires a converter with low output voltage, high current and good dynamic response.\textsuperscript{[1]}

According to the customer's demand, the SYNQOR semi-brick power supply module products are replaced by domestic ones. Before the product hardware design, it is necessary to estimate the efficiency of the half-brick module power supply with nominal 48V input 5V/60A output in order to ensure the feasibility of product design. This product design takes SYNQOR brand PQ60050HZ60 as the reference to complete the task of replacing domestic modules. The following is the efficiency demonstration of the semi-brick module power supply for customer needs. According to the customer's needs and considering the voltage bus requirements of communication power supply, the efficiency feasibility of the half-brick module power supply with nominal 48V input 5V/60A output is demonstrated.

Requirement Description

Electrical Performance Requirements

Specific electrical performance parameters according to customer requirements are as follows

1. Input voltage range: 40V-70V;
2. Output voltage: 5V;
3. Output current: 60A;
4. Efficiency: $\geq$91% (48V or 40V input, full load output);
5. Working temperature: -40°C to 80 °C;
6. Module volume: 61 mm long; 57.9 mm wide; 12.7 mm high (half-brick module).
**Requirement Description**

According to the current high-current output circuit topology, the design mainly considers the full-bridge, half-bridge, voltage and current-fed full-bridge topology. Because the current and voltage-fed topology (referring to the SYNQOR power supply topology) is used to drive complex processing, and after the synchronous rectifier circuit is used at the output, it is difficult to solve the logic timing error of the drive circuit when the machine is shut down. In theory, no additional filter inductance is needed for output, but without filter inductance, the output voltage ripple has obvious voltage collapse, which affects the normal use of power supply and the output voltage ripple is very large. And the device complexity of the two-stage circuit is high, the device density in half-brick volume (61 mm long; 57.9 mm wide; 12.7 mm high) is high, and the technology level of the device is required higher, so full bridge circuit is chosen to realize product design.

**Introduction to the Principle of the Scheme**

(1) Voltage-fed full-bridge topology

As shown in Fig. 1 voltage-fed full-bridge circuit, the voltage-fed Buck full-bridge converter is connected in series with the Buck converter in front of the full-bridge circuit converter, and the output is directly output to the filter capacitor after rectifier. Thus, the DC output voltage is the peak value of the transformer secondary voltage (ignoring the conduction voltage drop of the rectifier), so that the full-bridge switching tube can maintain about 100% duty cycle output without pulse width modulation. Stable output can be achieved only by pulse width modulation of switch in Buck circuit.

![Figure 1. Voltage-fed Full Bridge Circuit.](image1)

(2) Full-bridge synchronous rectification (central tapping)

The Q1 and Q4 of the full bridge synchronous rectifier half-wave rectifier circuit in Fig. 2 are one pair, driven by the same set of signals, and turn on or off at the same time; Q2 and Q3 are another pair, driven by another set of signals, and turn on or off at the same time. Two pairs of switching pipes are cut off in turn, forming positive and negative alternating pulse current in the primary winding of the transformer. The energy is transmitted to the output through the transformer, and half-wave rectification using central tap at output.

![Figure 2. Full-bridge synchronous rectifier half-wave rectifier circuit.](image2)
(3) Full Bridge Synchronized Rectifier (Double Rectifier)

The Q1 and Q4 of full bridge synchronous rectifier circuit in Fig. 3 are one pair, driven by the same set of signals, and turn on or off at the same time; Q2 and Q3 are another pair, driven by another set of signals, and turn on or off at the same time. Two pairs of switching tubes turn off in turn, forming positive and negative alternating pulse current in the primary winding of transformer. The energy is transmitted to the output through full bridge transformer. The output end uses double current rectification mode. The number of winding turns at the output end of transformer is less than that of half-wave rectifier in central tap mode, and the realization is less difficult. The output efficiency of low-voltage and large-current is higher. This rectification mode is recommended for designing low voltage and high current converters\(^{[2]}\).

![Figure 3. Full Bridge Synchronized Rectifier Circuit.](image)

Based on the above analysis, the efficiency analysis and calculation of this product is based on the full bridge topology output current doubler synchronous rectifier circuit form\(^{[3]}\).

**Analysis and Calculation of Product Efficiency**

**Electrical Performance Indicators of Products**

- Power output power: \( P_o = 300 \text{W} \);
- Minimum input voltage: \( V_{in_{\text{min}}} = 40 \text{V} \);
- Nominal input voltage: \( V_{in} = 48 \text{V} \);
- Maximum input voltage: \( V_{in_{\text{max}}} = 70 \text{V} \);
- Output voltage: \( V_o = 5 \text{V} \);
- Output current: \( I_o = 60 \text{A} \);
- Frequency of power supply operation: \( f = 200 \text{KHz} \);

**Loss Analysis of Power Devices**

(1) Transformer design

The ratio of primary side to secondary side turns of transformer is \( N_{ps} \);

The number of turns on the primary side of the transformer is \( N_p \);

The number of secondary edge turns is \( N_s \);

The theoretical maximum duty cycle is \( D_{\text{max}} = 0.8 \);

The theoretical turn ratio is \( N_{ps1} \), and it is calculated as follows:
\[ N_{ps1} = D_{max1} \frac{V_{inmin}}{V_o} = 6.4 \]  

After taking the integer, the actual turn ratio is: 

\[ N_{ps} = 6 \]

According to the actual turn ratio, the maximum duty cycle is calculated as follows: 

\[ D_{max} = \frac{V_o N_{ps}}{V_{inmin}} = 0.75 \]  

The apparent power of the transformer is: 

\[ P_s = \left( \frac{1}{\eta} + 1 \right) P_o = 600VA \]  

Ferrite material is used for magnetic material. The minimum area of required magnetic material is calculated by area method as: 

\[ AP = \left[ \frac{P 10^4}{K_0 K_f B_m j} \right]^{1.14} \]  

Where in \( \eta \) is the transformer prediction efficiency, the typical value is 0.98. \( K_0 \) is the magnetic core window utilization coefficient, the typical value is about 0.4. \( K_f \) is the waveform coefficients which is the ratio of RMS to mean value, \( K_f = 4 \) of the square wave. \( B_m \) is the working flux density of transformer, the value of soft magnetic ferrite is between 0.2T and 0.4T. \( f \) is the switching frequency of transformer, the typical value of this product is 200 kHz. \( j \) is the current density coefficient of transformer winding, the current density is 500A/cm\(^2\) at the allowable temperature rise of 25°C~35 °C.

The calculation shows that: \( AP \approx 0.2 \text{cm}^4 \)

In order to make the winding coil window area margin larger, the magnetic material of EQI30 is selected and the magnetic material manual is consulted. By inquiring the manual of magnetic materials, it is concluded that: \( A_w = 50 \text{mm}^2; A_e = 100 \text{mm}^2 \), from the above calculation results, it can be concluded that: \( AP_1 = A_w A_e > AP \), It meets the design requirements.

In the case of nominal 48V input voltage, when the switching tube works at the maximum duty cycle, the minimum turns of the primary winding of the transformer are calculated as follows: 

\[ N_{pmin} = \frac{V_{in} D_{max}}{2A_e B_m f} = 4.5 \]  

After taking integer turns, the original winding turns of transformer are: 

\[ N'_s = \frac{N_s}{N_{ps}} = 1 \]  

The actual magnetic induction intensity is calculated as follows: 

\[ VB_m = \frac{V_{inmin} D_{max}}{2A_e N'_p f} = 0.125T \]  

The results show that: \( VB_m \leq 2B_m \)
Calculating Iron Loss of Transformer

According to the magnetic material manual, the magnetic material works at 200 KHz at 100 °C and the magnetic flux density is 0.125 T, the unit volume loss of soft ferrite core is as follows:

\[ P_v = 0.15 \times 10^{-3} \text{W/mm}^3 \]

It is found that the volume of the core is \( V_{fe} = 4170 \text{mm}^3 \). According to the formula calculation, the transformer iron loss is as follows:

\[ P_{fe} = P_v V_{fe} \left( \frac{f}{100 \text{kHz}} \right)^{1.55} \left( \frac{\Delta B_m}{0.2T} \right) \approx 1.2 \text{W} \quad (8) \]

(2) Calculating Copper Loss of Transformers

The effective values of the primary winding and the secondary winding are respectively:

\[ I_{prms} = \frac{1.07 P_o}{V_{in\text{min}}} \approx 8.1 \text{A} \quad (9) \]

\[ I_{srms} = I_o = 60 \text{A} \quad (10) \]

The DC resistance values of the primary coil and the secondary coil are respectively:

\[ R_p = 5 \times 10^{-3} \Omega; \quad R_s = 0.8 \times 10^{-3} \Omega; \]

Then it can be seen that the copper loss of the primary winding of the transformer is as follows:

\[ P_{pcu} = I_{prms}^2 R_p \approx 0.33 \text{W} \quad (11) \]

The copper loss of the secondary coil is as follows:

\[ P_{scu} = I_{srms}^2 R_s \approx 2.88 \text{W} \quad (12) \]

The total copper loss of transformer coils is:

\[ P_{cu} = P_{pcu} + P_{scu} = 3.2 \text{W} \quad (13) \]

The total loss of transformer is:

\[ P_T = P_{cu} + P_{fe} = 4.4 \text{W} \quad (14) \]

(3) Design and calculation of output inductance \(^[4][5]\)

According to the design requirements, the output current variation rate is about 20%, then the output inductance is calculated at the lowest voltage input as follows:

\[ L = \frac{\left( V_{in\text{min}} / N_p - V_o \right) D_{max}}{\lambda I_o f / 2} \approx 0.2 \mu\text{H} \quad (15) \]

The EQI14 magnetic material is selected according to the magnetic material manual, in which the effective magnetic cross section area is \( A_{ej} = 30.3 \text{mm}^2 \); Take the variation of magnetic induction intensity \( \Delta B = 0.2 \text{T} \);

\[ N_L = \frac{L(I_o - \frac{\lambda I_o}{2})D_{max}}{\Delta B A_{ej} 2f} \approx 3.3 \quad (16) \]

Take \( N_L \) as an integer and get \( N_L = 4 \).
Calculating Iron Loss of Inductance

According to the magnetic material manual, the magnetic material works at 200 KHz at 100 °C and the magnetic flux density is 0.2T, the unit volume loss of soft ferrite core is as follows:

\[ P_{vl} = 0.15 \times 10^{-3} \text{W/mm}^3 \]

It is found that the volume of the core is \( V_{fe} = 641 \text{mm}^3 \), the transformer iron loss is as follows:

\[ P_{fe} = P_{vl} V_{fe} 2^{1.55} \approx 0.28 \text{W} \quad (17) \]

Calculating Copper Loss of Inductance Coil

The winding impedance of the tested inductance is:

\[ R = 1.5 \times 10^{-3} \Omega \]

Then the copper loss of a single inductance coil is as follows:

\[ P_{Lcu} = I_o^2 \frac{D_{max}}{2} R_L = 1.89 \text{W} \quad (18) \]

The total loss of the output filter inductor is as follows:

\[ P_L = 2(P_{fe} + P_{Lcu}) = 4.34 \text{W} \quad (19) \]

(4) Loss Analysis of Power MOS Transistors in Full Bridge Circuit with Primary Edge

Determine the voltage stress of the switch, and the input voltage is 40V-70V. Because of the topological circuit, the voltage stress of the switch is reduced by 70% and the switch of 100V is selected. Determine the Current Stress of Switching Tube.

The peak value of the primary current is:

\[ I_{peak1} = \frac{I_o + \frac{1}{2} I_o}{N_{ps}} = 11 \text{A} \quad (20) \]

The effective value of the primary current is:

\[ I_{rms1} = \sqrt{\frac{D_{max}}{2} I_o} \approx 6 \text{A} \quad (21) \]

IR brand MOSFET is Selected, the original side of the double-tube parallel connection mode is used, and the bridge arm using eight switch tubes is used, the model is IRFH7184, the main parameters of a single switch tube are as follows:

\[ R_{DS(on)} = 4 \times 10^{-3} \Omega \; ; \; V_{DS} = 100 \text{V} \; ; \; I_D = 128 \text{A} \; ; \; T_s = 9.9 \text{ns} \; ; \; T_f = 3.9 \text{ns} \]

The switching loss of the single arm (four switches) of the primary switch is as follows:

\[ P_s = \frac{1}{2} V_{in} I_{peak1} T_s f + \frac{1}{2} V_{in} I_{peak1} T_f f \approx 2.2 \text{W} \quad (22) \]

The main switching loss of the primary switch is:

\[ P_{sw} = 2P_s = 4.4 \text{W} \quad (23) \]

The conduction loss of the single arm of the original switch tube (four switches) is as follows:

\[ P_{on} = I_{rms1}^2 R_{DS(on)} = 0.256 \text{W} \quad (24) \]

The total conduction loss of the primary switch is:

\[ P_{on} = 2P_{on} = 0.512 \text{W} \quad (25) \]

The total loss of the primary switch is:

\[ P_{spall} = 4.9 \text{W} \]

(5) Loss Analysis of Power MOS Transistors in Subside Rectifier Circuits
Determine the voltage stress of the switch. According to the maximum 70V input voltage of the power supply, the ratio of the primary side to the secondary side of the transformer is 6, then the maximum voltage stress of the output rectifier is as follows (resonance voltage peak caused by leakage inductance at transformer output is ignored): 

\[ V_{DS_{\text{max}}} = \frac{V_{\text{in, min}}}{N_{PS}} \approx 12V \]  

(26)

Then it is concluded that the voltage withstand of the output rectifier should be greater than 12V. The current stress of the switch is calculated as follows:

The peak value of the output current is:

\[ I_{\text{peak}2} = \left(1 + \frac{1}{2} \lambda \right) I_o = 66A \]  

(27)

The effective value of the output current is:

\[ I_{\text{rms1}} = \sqrt{\frac{D_{\text{max}}}{2}} I_o = 35.5A \]  

(28)

IR brand MOSFET is Selected, the output adopts 4-tube parallel connection mode, Q5 and Q6 use 8 MOSFETs, the model is IRFH8318, The main parameters of a single switch are:

\[ R_{DS_{\text{(on)}}} = 2.5 \times 10^{-3} \Omega; \ V_{DS} = 30V; \ I_D = 120A; \ T_{r1} = 33ns; \ T_{f1} = 12ns; \]

The switching losses of the single arm (four switches) of the output rectifier are as follows:

\[ P_s = \frac{1}{2} V_{DS_{\text{max}}} I_{\text{peak}2} T_{r1} f + \frac{1}{2} V_{DS_{\text{max}}} I_{\text{peak}2} T_{f1} f = 4W \]  

(29)

The total switching loss of the output rectifier is: 

\[ P_{\text{all}} = 2P_s = 8W \]  

(30)

The conduction loss of the output single arm rectifier is as follows:

\[ P_{\text{on}} = I_{\text{rms1}}^2 R_{DS_{\text{(on)}}} = 0.75W \]  

(31)

The total conduction loss of the output rectifier is: 

\[ P_{\text{on,all}} = 2P_{\text{on}} = 1.5W \]  

(32)

The total loss of the output rectifier is: 

\[ P_{\text{stall}} = 9.5W \]

Analysis of Product Efficiency Accounting Results

According to the above calculation results, and the predicted control circuit loss is \( P_{\text{control}} = 4W \), the calculating efficiency of product wear and tear for each part of the product is as follows:

\[ \eta_{\text{all}} = \frac{P_o}{P_o + P_s + P_f + P_{\text{stall}} + P_{\text{all}} + P_{\text{control}}} \approx 91.7\% \]  

(33)

Conclusion

From the efficiency estimation results, it can be seen that with the development of semiconductor technology and the maturity of planar transformer design technology, the efficiency analysis results of this product are similar to that of SYNQOR semi-brick power supply module PQ60050HZ60. Based on the full bridge topology, the output current doubler synchronous rectifier circuit scheme can meet the expected requirements of customers. The theoretical analysis and calculation of efficiency lay a good theoretical foundation for the next practical prototype debugging.
Reference


