Design of Phase-Shifted Full-Bridge Switching Power Supply Transformer

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ABSTRACT: The design of the switching power supply transformer, applied to the phase-shifted full-bridge inverter circuit as an example, is discussed in this paper. First, the main circuit of the phase-shifted full-bridge inverter is presented, and the basic design considerations from references are reviewed. Then the design processes are presented step by step, in which the detailed calculations are provided. Finally the testing data of some samples is given, and some suggestions are offered to get best efficiency and performance, which is helpful for practical design and production.

KEYWORD: Power Transformer; Switching Power Supply; Phase-Shifted Full-Bridge

1 INTRODUCTION

In recent years, high-frequency switching power supply is more widely used in applications. Due to limitations of the core material, the operating frequency of conventional high-frequency transformer is much low, usually around 20kHz.With the development of power technology, miniaturization, high frequency and high power density have become the direction of the research and development trends in switching power supply areas. Transformer is a main component in switching power supply, and its importance on system performance is instantly increasing nowadays. How to design a proper transformer has become the main technology of switching power supply.

The design cases of the bipolar switching power supply transformers are less seen, or the volume of most transformers is great. For this reason, we studied the design of phase-shifted full-bridge switching power supply transformer, hoping to provide a useful reference for the optimized design of the bipolar switching power supply transformers.

2 PHASE-SHIFTED FULL-BRIDGE CONVERTER CIRCUIT

2.1 *Main circuit*

A phase-shifted full-bridge converter circuit of switching power supply is shown in Figure 1. Q_1 and Q_3 are two of the same type MOSFET, called leading-legs, used to realize zero-voltage switching (ZVS). Each MOSFET has a capacitance in parallel,

which is C_1 and C_2. Q_2 and Q_4 are two of the same type high-speed IGBT, called lagging-legs, used to realize zero current switching (ZCS). There is no capacitance needed in parallel with IGBT in lagging-legs. Each lagging-leg has a diode in serial, that's D_1 and D_2, for blocking reverse voltage and reverse current across the power switch in 0 state. C_3 is the blocking capacitor and L is the resonant inductance, including the main transformer leakage inductance. $D3\sim D_6$ are rectifier diodes, forming full-wave rectifier circuit. L_f is the output filter inductor and C_4 is the output filter capacitor.
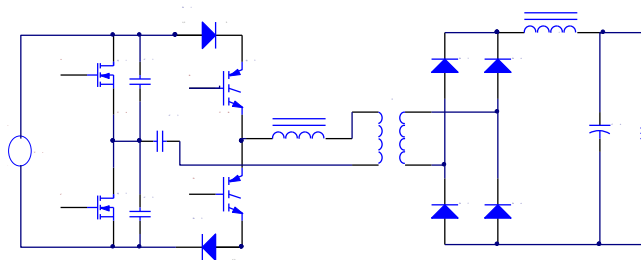

Figure 1 Main circuit structure diagram of the converter

2.2 *Features*

High-power MOSFET and high-speed IGBT are used in the circuit, which could reduce power consumption, increase the switching speed and reduce transformer size. Soft-switching technology, like Zero-voltage switching (ZVS) and zero current switching (ZCS) are used instead of the traditional hard-switching technology. The voltage of switches is zero when the switches turn on, while the current through the switches is zero when the switches cut

off. Therefore switching voltage, current stress, surge and noise of power transistor are greatly reduced, leading to lower power consumption.

3 DESIGN OF SWITCHING POWER SUPPLY TRANSFORMER

High frequency transformer is the main part of the whole switching power supply. It directly related to the successful or not of the design of switching power supply.

3.1 Design principles of switching power supply transformer

3.1.1 Temperature Rise

The working temperature of the transformer is clearly stated in safety criteria. Absolute temperature of Class A transformer must be less than 90℃, and that of Class B transformer should not exceed 110℃. Therefore, the temperature rise must be designed within the specified range, and that is the criteria of transformer design.

3.1.2 Cost

Since the transformer is an important part of the switching power supply, its cost is also a major consideration. Trading off on the cost, size, quality of the transformer, getting optimized performance, is the main task of the switching power supply design.

3.2 Design Specifications of Switching Power

The following information is the design specification for a 2200 watts transformer, operating at 34kHz, using Ap, Area Product approach. For a typical design example, assume with the following specification of supply transformer:

Input voltage, $V_{in} = 380V$
Input frequency, $f_L = 50HZ$
Output voltage, $V_o = 220V$
Output current, $I_o = 10A$
Operating frequency, $f_s = 34kHz$
Output power, $P_o = 2200W$
Estimated efficiency, $\eta = 0.9$
Input power, $P_{in} = P_o / \eta = 2444\ W$
Maximum temperature rise, $\Delta T = 50℃$

In the actual design of transformer, iron consumption must be less than the allowable, to ensure the reliability of the transformer.

3.3 Core selection of switching power supply transformer

From performance requirements of the transformer, core material is basically considered only from Permalloy alloys, ferrite material, cobalt-based amorphous alloy and nanocrystalline alloys. The price of Permalloy alloys and cobalt-based amorphous alloy are high, which are several times around the price of ferrite material. The saturation flux density (Bs) of them is not very high, and the process is complex. Therefore, through comprehensive performance comparison of these materials, we chose ferrite material for its high saturation magnetic flux density Bs, good temperature stability and low prices. PC40 material from TDK Corporation is selected to make switching power transformers, which permeability up to 2300H/m, saturation magnetic induction Bs value at 25 ℃ for 510mT, 60 ℃ for 480mT, 100 ℃ for 390mT,and high resistivity for 6.5Ω • m.

3.4 Parameter calculation of switching power supply transformer

3.4.1 Total apparent power of transformer

Total apparent power of Transformer, Pt, depends on the output power Po of the transformer and the form of the rectifier circuit as shown in Table 1.

Table 1. Form of the rectifier circuit and total apparent power of transformer. [1]

Type	Total apparent power
Full-bridge Circuit Bridge Rectifier	$P_t = P_o (1 / \eta + 1)$
Half-bridge Circuit Full-Wave Rectifier	$P_t = P_o (1 / \eta + \sqrt{2})$
Push-pull Circuit Full-Wave Rectifier	$P_t = \sqrt{2} P_o (1 / \eta + 1)$

In which, η, is the transformer efficiency.

Our case uses a full bridge-circuit bridge rectifier,
so
$$P_t = P_O \left(\frac{1}{\eta} + 1 \right) = 2200 \left(\frac{1}{0.9} + 1 \right) = 4644W \quad (1)$$

3.4.2 Operating flux density

Operating flux density is a very important parameter in the design of switching power supply transformer. It depends on the core material, structure, frequency, temperature, core unsaturated and other factors. If the value is too small, the size, weight and turns of the switching power supply transformer would increase, and the leakage inductance would also increase. According to practical experience, the maximum operating flux density, Bm, is generally set within the range of 0.15 ~ 0.25T in self-cooling mode, while in air-cooled mode, It is usually set within a larger number of 0.3 T ~ 0.4 T.

3.4.3 Establish Area Product (Ap)

The value of Area Product, Ap, is selected applicable to or close to Ap calculated value of magnetic materials, structure and core specifications.

Area Product of switching power supply may be stated as:

$$Ap = AeAw = \frac{P_t}{K_f K_m f_s B_m J} \qquad [2] \qquad (2)$$

where A_e is effective area of the center pole , cm²

A_w is core winding window area, cm²

K_f is waveform coefficient. The value of square wave is 4 and the value of sine wave is 4.44.

K_m is filing factor of window. It is related with wire thickness, winding process, the leakage inductance and stray capacitance, generally ranging from 0.2 to 0.4.

f_s is frequency of transformer switching.

J is current density, generally ranging from 2 ~ 5A/mm². Current density can be made bigger for air cooling

In this example, K_f=4.0; K_m=0.4;f_s=34KHz;and J = 5A/mm².

The value of operating flux density, Bm, varies larger in the formula. In this example, EE cores of TDK material (PC40) are selected. Its operating frequency is 34KHz and temperature rise is 50℃. It is working in air cooling mode. Theoretical calculations on core in references are much larger. Dual core is selected to reduce the size of transformer. As TDK Core data sheet shown in table 2, we use the following two kinds of cores. One is EE42/42/21 dual core, whose area product is 10cm⁴. Another is EE55/55/21 dual core, whose area product is 28.1cm⁴.They both exceed the theoretical calculations of area product of core.

Table 2. Part date sheet of TDK Core

Core	Ae	Aw	Ap	$2 \times Ap$
	mm²	mm²	cm⁴	cm⁴
EE55/55/21	354	397	14.05	28.1
EE42/ 42/21	182	275	5.0	10.0"

3.4.4 Calculate winding turns

Primary winding turns of transformer is given by the following equation:

$$N_1 = \frac{V_{inmax}}{4 f B_m A_e} \qquad [3] \qquad (3)$$

where

V_{inmax} = maximum input voltage of transformer

Secondary voltage is given by the following equation:

$$V_{smax} = \frac{V_{omax} + V_D + V_{Lf}}{D_{max}} \qquad (4)$$

where V_{smax} = maximum secondary voltage; V_{omax} = maximum output voltage; V_D = voltage of rectifier diode; V_{Lf} = voltage of output filter inductor; D_{max} = maximum duty ratio.

Primary-secondary turns ratio can be calculated as follows: $K = \frac{V_{inmin}}{V_{smax}}$ $\qquad (5)$

where

V_{inmin} = minimum input voltage of transformer.

Secondary winding turns of transformer is given by the following equation:

$$N_2 = \frac{N_1}{K} \qquad (6)$$

According to the formula above, several sets of data calculations are done. Voltage parameters requirement and turns ratio calculation are shown in table 3. And transformer design and calculation parameters are shown in table 4.

Table 3. Form of input voltage and primary-secondary turns ratio calculated.

Parameters	Vinac	Vindc	Vo	Vsmax	K
	V	V	V	V	
The first case	380±10%	440~585	198~242	288	1.53
The second case	380±15%	420~618v	180~280	333	1.26

where Vinac=AC input voltage; Vindc=DC input voltage; Vo= the output DC voltage range.

Table 4. Form of transformer design and calculation parameters.

Parameters	EE42/42/21	EE42/42/21	EE55/55/21
Bm(T)	0.3	0.25	0.2
AP(cm⁴)	5.69	6.83	8.54
N1	40	48	32
K	1.53	1.53	1.26
N2(k=1.53)	27	32	20
N2(k=1.26)	32	38	27

3.4.5 Winding wire selection

Secondary winding area can be calculated as follows:

$$A_2 = \frac{I_2}{J} = \frac{10}{5} = 2mm^2 \qquad (7)$$

Primary winding area can be calculated as follows:

$$A_1 = \frac{I_1}{J} = \frac{I_2 / K}{J} = \frac{10/1.26}{5} = 1.59mm^2 \qquad (8)$$

Taking into account the skin effect of high frequency current, the wire diameter should be selected to follow the principle of a diameter less than twice the penetration depth. When the wire diameter is less than twice of the maximum diameter decided by the penetration depth, it can be taken around the strands or flat copper winding. The penetration depth can be calculated as follows:

$$\Delta = \sqrt{\frac{2}{\omega\mu\gamma}} = \sqrt{\frac{2}{2\pi \times 34 \times 10^3 \times 4\pi \times 10^{-7} \times 58 \times 10^6}} \qquad (9)$$
$$= 0.36mm^2$$

where ω =angular frequency; μ= wire permeability; and γ = wire conductivity. For copper wire, $\mu = 4\pi \times 10^{-7}$H/m and $\gamma = 58 \times 10^{-6}$S/m.

According to the results, the wire diameter should be selected less than 0.72 mm^2.

4 PRODUCTION AND TEST OF SWITCH POWER TRANSFORMER

The production of high frequency transformer winding mainly refers to the windings of the transformer. Windings structure would affect the performance of transformer, reliability and the amount of wire. Two questions need to be considered. The first is how to minimize leakage inductance and the second is to reduce the eddy current consumption. These would help to improve the power conversion efficiency, reduce the surges of voltage, and improve the reliability of the inverter switches. In this example, sandwich structure is applied in the transformer windings.

According to the results of calculation and the actual project experience, the calculated parameters were adjusted and modified. No air gap was set between the cores. Several sets of transformers parameters were shown in Table 5.

Table 5. Form of transformer parameters.

Parameters	The first set	The second set	The third set
Dual core	EE42/42/21	EE42/42/21	EE55/55/21
Primary Turns	40	45	40
Secondary Turns	32	40	32

Set I:
No air gap between the cores. The inductance of the primary winding was 14.26mH, Q was 205. The inductance of the secondary winding was 9.16mH, Q was195.The leakage inductance was 4.8μH

Testing after 5 minutes, the temperature of the transformer winding was 49℃, and the cooling fin temperature of the power tube was 41 ℃

Ten minutes later, the temperature of the transformer winding rose to 109℃, and the cooling fin temperature of the power tube was 52 ℃

Transformer coils and cores were very hot. The core was saturated apparently. From here you could learn, Bm value of 0.3 was too large.
Set II:
No air gap between the cores. The inductance of the primary winding was 12mH, Q was 106. The inductance of the secondary winding was 10mH, Q was 104.The leakage inductance was 1.45μH.

Testing after 5 minutes, the chip temperature of the power tube was 82 ℃. The chip temperature of the rectifier diode was 77 ℃, and the temperature of the transformer winding was 78 ℃.

Thirty minutes later, the chip temperature of the power tube was 100 ℃. The chip temperature of the rectifier diode was 77 ℃, and the temperature of the transformer winding was 82 ℃.

Efficiency measured at light-load was above 88%, and which at heavy-load was above 90%.
Set III:
No air gap between the cores. The inductance of the primary winding was 6.53mH, Q was 335. The inductance of the secondary winding was 4.31mH, Q was 352.The leakage inductance was 12.5μH.

Testing after 10 minutes, the chip temperature of the power tube was 70℃. The chip temperature of the rectifier diode was 72 ℃, and the temperature of the transformer winding was 80 ℃.

30 minutes later, the chip temperature of the power tube was 80 ℃. The chip temperature of the rectifier diode was 80℃, and the temperature of the transformer winding was 88 ℃.

Efficiency measured at light-load was above 90%, and which at heavy-load was above 91%.

5 CONCLUSIONS

From the above data, we can conclude that, in the design and production of switching power supply, dual core transformer can be used to reduce the size of the transformer. If smaller size is required, but efficiency is not most concerned, the second set transformer can be tried. If high efficiency is required, the third set transformer is appropriate. The size of the third set, of course, is slightly larger than those of the second set, but compared to those of single-core transformer, it has been reduced a lot. Of course, in the actual product design, it is necessary to slightly adjust the transformer parameters to achieve maximum efficiency and optimum performance.

6 ACKNOWLEDGEMENTS

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