

DESIGN OF EFFICIENT LOW VOLTAGE HIGH CURRENT DC TO DC POWER SUPPLY

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ABSTRACT

The design of low voltage high current DC to DC power supply for 48V input is discussed in this section. The converter is built using single switch forward converter. Synchronous rectifiers are used for secondary side rectification. The voltage conversion ratio of the converter is high. Transformer based topologies are a proper choice for converters requiring such conversion ratio. A new bifurcated transformer winding arrangement is proposed in this thesis. The suitability of the proposed winding arrangement in improving the efficiency of the power supply is given. The magnetic design of the proposed bifurcated secondary winding arrangement is given. The loss distribution and the experimental waveforms of the power supply are presented.

KEY WORDS: Synchronous rectifiers, bifurcated transformer, Magnetic Elements, Inductor

1. INTRODUCTION

The converter is designed for the specification given in Reference [3], [4]. The thesis attempts to meet the steady state requirement of the power supply. The key specifications of the power supply are given below,

1. Input voltage $V_g = 48\text{ V}$,
2. Output voltage $V_o = 1.5\text{ V}$,
3. Output current $I_o = 50\text{ A}$,
4. Efficiency $\eta > 80\%$.

The single switch forward converter topology is used to make this power supply. The circuit schematic of the power supply is shown in Fig. 1. As can be seen from Fig. 1, the transformer has one primary 1 N and two secondary windings, 22 NN ab . The two secondary windings of the transformer are connected in parallel with proper polarity as shown in Fig. 1. The transformer is reset using third winding 3 N [3],[4]. (It may be noted that, the earlier design (12V/1.5V) employed resonant reset method). The synchronous rectifiers $61'$, 22 SS are used in the secondary side for rectification. The role of synchronous rectifiers in reducing the conduction loss in the power supply was explained in section 3.5.

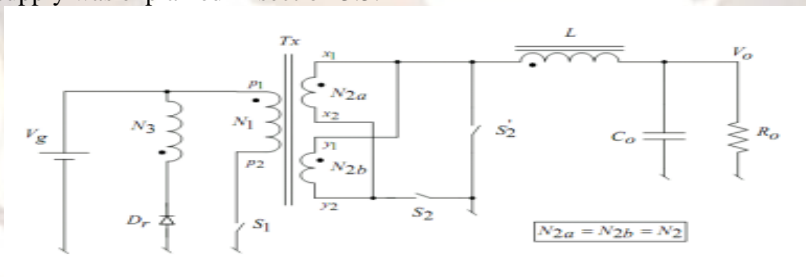


Fig. 1 Circuit schematic of the 48V input converter.

2. DESIGN OF THE OUTPUT FILTER INDUCTOR

The specifications of the inductor are,

1. Inductor current $I_{avg} = 20\text{ A}$,
2. Current ripple factor $\delta_i = 20\%$,
3. Nominal duty ratio $D = 0.375$,
4. Switching frequency = 100 kHz .

The area product method is used to design the inductor [2]. The required area product of the inductor is given by,

$$A_p = \frac{2E}{K_c K_c B_m J}$$

The required number of turns N and the required air gap l_g are obtained using following equations,

$$N = \frac{l_l}{\mu_c B_m}$$

$$l_g = \frac{\mu_0 A_c N^2}{L}$$

The required inductance for the above specification is [4],

$$L = \frac{(1-D)R_o T_s}{\delta_i}$$

$$L = \frac{(1-0.375) \times 75 \times 10^{-3} \times 10 \times 10^{-6}}{0.7} = 2.34 \mu H$$

The energy handled by the inductor is,

$$E = \frac{1}{2} L I^2$$

$$E = \frac{1}{2} \times 2.34 \times 10^{-6} \times (24)^2 = 674 \mu J$$

The area product of the core is calculated using,

$$A_p = \frac{2 \times 674 \times 10^{-6}}{1.1 \times 0.6 \times 0.28 \times 10^{-6} \times 6.5} = 1122 \text{ mm}^2$$

An E-I 22/6/16 core could be used. The area product of the core is $A_p = 1478 \text{ mm}^4$ and the core area is $A_c = 78.3 \text{ mm}^2$. The required number of turns is obtained using Eq.

$$N = \frac{2.34 \times 10^{-6} \times 24}{78.3 \times 0.28 \times 10^{-6}} = 2 \text{ Turns}$$

The air gap length is calculated using Eq.

$$l_g = \frac{4 \times \pi \times 10^{-7} \times 78.3 \times 10^{-6} \times (2)^2}{2.34 \times 10^{-6}} = 0.168 \text{ mm}$$

Air gap of 0.084mm is provided to each limb of the core.

The required cross sectional area of the winding is determined as follows,

$$a_w = \frac{27.5}{6.5} = 4.2 \text{ mm}^2$$

The required cross sectional area of the winding is obtained by using four conductors in parallel. The cross sectional area of each conductor is,

$$a_{wx} = \frac{4.2}{4} = 1.05 \text{ mm}^2$$

The conductor of height 0.2mm and width 5.25mm is used.

The resistance of inductor winding is,

$$R_{dc} = \frac{\rho (MLT) N}{a_w}$$

$$R_{dc} = \frac{2 \times 10^{-5} \times 60 \times 3}{4.2} = 0.86 \text{ m}\Omega$$

The copper loss in the inductor winding is given below,

$$P_{cu} = I_{rms}^2 R_{dc}$$

$$P_{cu} = 416 \text{ mW}$$

To ease the manufacturing of the windings, the number of turns of the inductor is reduced. Using a bigger core reduces the number of turns. A modified E 43/10/28 core is used. The E 43/10/28 core is shown in Fig. 2. The core dimensions are shown in figure.

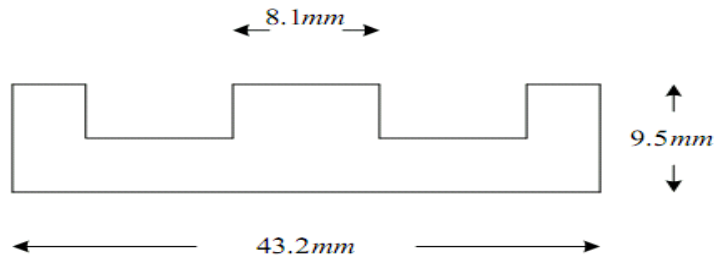


Fig.2 E 43/10/28 core

The modified core is shown below,

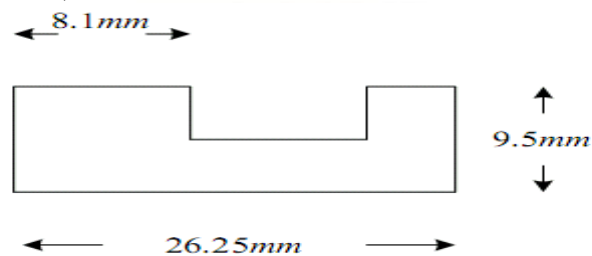


Fig. 3. E 43/10/28 core modified as U 25/10/28 core

The modified U-U 25/10/28 core has the area product of $A_p = 24240\text{mm}^4$ and the core area is $A_c = 112.5\text{mm}^2$. The current ripple factor in the inductor is increased to $\delta_i = 0.3$. The required inductance for the modified current ripple is $L = 1.25\mu\text{H}$.

The number of turns of the inductor is calculated using.

$$N = \frac{1.25 \times 10^{-6} \times 23}{112.5 \times 0.28 \times 10^{-6}} \approx 1 \text{ Turn}$$

The air gap length is calculated using.

$$l_g = \frac{4 \times \pi \times 10^{-7} \times 112.5 \times 10^{-6} \times (1)^2}{1.25 \mu\text{H}} = 0.113 \text{ mm}$$

Air gap 0.05mm is provided to each limb of the core.

The operating current density of the winding is $J = 2.65\text{A/mm}^2$. The copper loss in the windings is $P_{cu} = 60\text{mW}$. The core loss in the inductor is $P_e = 0.17\text{W}$.

2.1 DESIGN OF THE FORWARD CONVERTER

The forward converter is designed for the following specification.

1. Input voltage $V_g = 48\text{V}$,
2. Output voltage $V_o = 1.5\text{V}$,
3. Output current $I_o = 20\text{A}$,
4. ripple factor $\delta_i = 30\%$,
5. Output voltage ripple factor $\delta_v = 1\%$,
6. Switching frequency = 100 kHz.

For the above specification the required value of filter elements are,

1. Output filter inductance $L_o = 1.25\mu\text{H}$,
2. Output filter capacitance $C_o = 7 \times 220\mu\text{F}$.

The output filter capacitance is selected based on the voltage ripple and the ripple current rating of the capacitor.

The output voltage of the converter is given by,

$$V_o = \frac{2V_g}{1 + \frac{L}{\mu_0 \mu_r C_o}} \approx \frac{2V_g}{1 + \frac{L}{\mu_0 \mu_r C_o}}$$

In forward converters, which use conventional transformer winding arrangements, the output voltage is given by

$$V_o = \frac{N_2}{N_1} D V_g$$

The constant (12) in our converter is introduced on account of the proposed bifurcated winding arrangement. The main advantage of the proposed secondary winding arrangement is, that it requires only the half the number of turns of any one of the winding to get the same turns ratio.

For the above voltage specification, the turns ratio of the transformer is $\frac{N_2}{N_1} = \frac{1}{6}$ and the nominal operating duty ratio is $D = 0.375$

A prototype power supply was built for the following specifications,

1. Input voltage $V_g = 48V$ (nominal),
2. Output voltage $V_o = 1.5V$ (nominal),
3. Output current $I_o = 20A$ (nominal).

A typical condition (as measured) is given below,

Input voltage	Output voltage	Input current	Output current	Efficiency
V_g	V_o	I_{in}	I_o	η
48V	1.5V	0.765A	19.6A	80%

Table No.1

2.2 EXPERIMENTAL RESULTS

The experimental results of the prototype are given in this section. It is expected that, in future the operating voltage of all CPU's will still reduce. Therefore, to validate the suitability of the proposed power converter configuration, the power supply was tested at output voltages less than 1.5V and the obtained efficiency shown.

The efficiency of the converter (without the gate drive loss) for the output voltages 1.5V, 1.25V, 1V for various outputs current is given in Figs respectively. The key voltage and current waveforms of the power supply for 1.5V output are given in

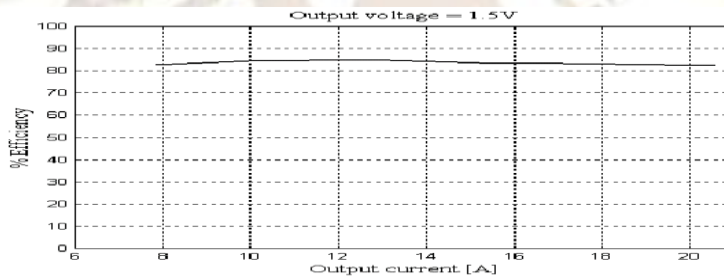


Fig. 4. % Efficiency Vs Output current [A] for Output voltage = 1.5V

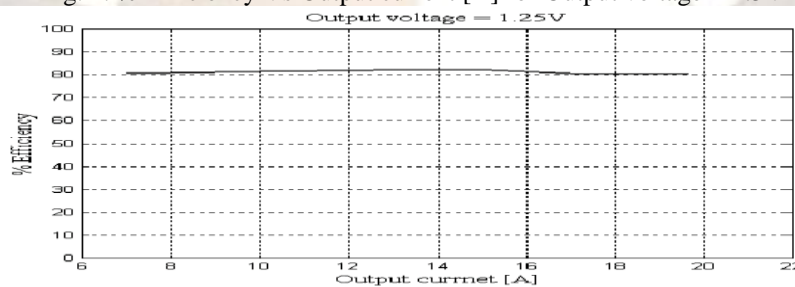


Fig. 5. % Efficiency Vs Output current [A] for output voltage = 1.25V

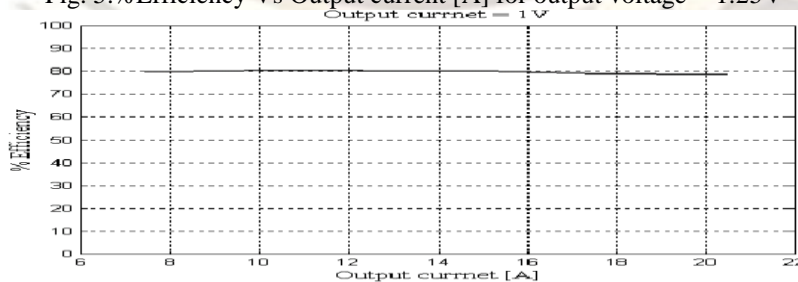


Fig. 6. % Efficiency Vs Output current [A] for output voltage = 1V

The measured ripple in the output voltage is 1% (2.2%) > of the output voltage. This is higher than the specified steady state ripple voltage. The specified ripple voltage can be achieved by using a high frequency low ESR capacitor.

5. SUMMARIES

Design methodology for converter requiring large voltage conversation ratio is demonstrated for a 48V input power supply. A new bifurcated secondary winding arrangement is proposed for such applications. The advantages of the proposed transformer winding arrangement over the conventional winding arrangement are,

- Large voltage transformation ratio with less number of primary winding turns,
- Less volume of the core for same VA rating compared to other winding arrangements.

The design methodology for the proposed winding arrangement is given. The same is validated by experiment. The loss distribution in the converter is presented. The forward converter used in this power supply is reset using third winding reset method.

6. CONCLUSION

The basic objective of this thesis was to develop highly efficient DC to DC converter for low voltage, high current applications. Design methods to increase the efficiency of the power supply without using any soft switching techniques were proposed and verified through two prototype converters.

Two circuit configurations were proposed for 12V and 48V input voltage specification for the CPU power supplies respectively. They are,

1. Interleaved forward converter with coupled inductor for 12V input power supply,
2. Forward converter using bifurcated secondary winding arrangement for 48V input power supply.

The organization of this thesis are given as follows,

In chapter 2, the general magnetic design principles for low voltage, high current converters were discussed. The method for selecting proper core material, core shape and the physical dimensions of the conductor suitable for such applications is given. The advantages of planar magnetic devices for low voltage, high current power supply is presented. An analytical method for selecting the current density in the conductors to limit the copper loss is proposed and used. The manufacturing method for planar windings of both low current (primary) and high current (secondary) windings are outlined.

The design methodology for 12V input power supply is discussed in chapter 3. The power supply is made with two forward converters operating in parallel with coupled output filter inductor. The interleaved gating method for the converters is employed. The advantage of interleaved gating scheme in reducing the stress on the filter elements is highlighted. The role of synchronous rectifier to increase the efficiency of low voltage, high current power supplies is presented. The loss based design method for the magnetic elements is proposed and carried out. The loss distribution in the power supply is presented. The forward converter transformer is reset using the resonant reset method. This reset method makes use of the parasitic elements of the converter. The analytical expression for the resonant reset method is given in the appendix. The simulation and experimental results are also presented for the reset method.

In chapter 4, design methodology for converter requiring large voltage conversation ratio is demonstrated for a 48V input power supply. A new bifurcated secondary winding arrangement is proposed for such applications. The advantages of the proposed transformer winding arrangement over the conventional winding arrangement are,

- Large voltage transformation ratio with less number of primary winding turns,
- Less volume of the core for same VA rating compared to other winding arrangements.

The design methodology for the proposed winding arrangement is given. The same is validated by experiment. The loss distribution in the converter is presented. The forward converter used in this power supply is reset using third winding reset method.

In general, in the thesis the power supplies are designed using following guidelines.

1. Loss based design of magnetic elements

The core loss and the copper loss in the magnetic elements are selected based on the maximum allowable loss in them. There need not be any direct rule in selecting the maximum operating flux density and maximum operating current density. The loss distribution in each magnetic element is designer's choice.

2. Reduction of the switching loss

The switching loss in the converter are reduced by,

- a. Operating the converter at high duty cycle,
- b. Reducing the switching times.

a. Operating the converter at high duty ratio reduces the crest factor of the current flowing through the switches. This reduces the switching loss. The conduction loss is reduced by using low $R_{ds(on)}$ MOSFET.

b. Fast gating reduces the switching loss and increases the gate control power. Suitable compromise is made to keep the over loss less.

The major contributions of this thesis are,

1. Design methodology with inverse coupled inductor demonstrated for 12V input power supply using interleaved forward converter topology,
2. Design methodology for high turns ratio converter demonstrated for 48V input power supply using forward converter topology.

Both these design procedures have been validated through appropriate steady state performance tests.

In conclusion, the following are the recommendations for a highly efficient low output voltage, high current DC to DC power supply,

1. Using proper core size for the VA rating,
2. Using proper switches to reduce the gate drive power loss,
3. Manufacturing the planar windings using multilayer PCB process (this reduces the number of high current contacts and its associated loss),
4. Low output voltage ripple specification can be met by using proper high frequency, low ESR capacitor.

Future scope exists in the innovative design methods to achieve challenging dynamic requirement

7. REFERENCES:

1. Umanand L, Bhat S R, "Design of magnetic components for switched mode power supplies," New Age International Pvt. Ltd, 2001
2. Jia Wei, et al., "Comparison of three topology candidates for 12V VRM," IEEE APEC 2001, pp.245-251.
3. Intel Corporation, "VRM 9.0 DC-DC converter design guidelines," April 2001.
4. Intel Corporation, "A-D2D, Server distributed power 48V input (Advanced) DC to DC converter design specification".
5. Kaiwei Yao, et al, "Tapped-inductor buck converters with a lossless Clamp circuit," IEEE APEC 2002, pp. 693-698.
6. Peng Xu, Fred C. Lee, "Design of high-input voltage regulator modules with a novel integrated magnetics," IEEE APEC 2001, pp. 262-267.

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Short Biography



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